Re-articulating the role of process design to support mass customisation: the case of rapid manufactured custom-made fixtures

Daniel Eyers[1*], Hartanto Wong[1] and Shwe Soe[2]

[1]*Cardiff University Innovative Manufacturing Research Centre, Cardiff, UK*
[2]*The Manufacturing Engineering Centre, Cardiff University, Cardiff, UK*
** corresponding author: eyersdr@cf.ac.uk*

Abstract
Whilst the fulfilment of customised production affects the whole product realisation chain involving product design, process design and supply chain design, our assessment of the literature observes comparatively little attention has been given to process design. Within this area, this paper considers the opportunity for custom fixture manufacture, combining the power of modularity with the technologies of Rapid Manufacturing. Several examples are presented illustrating significant improvements in quality, fixture cost and overall time to market can be achieved through this approach.

Keywords: Fixtures, Mass Customisation, Rapid Manufacturing

Introduction

The pursuit of a mass customisation (MC) strategy not only increases the choices available to a customer, but also the range of variety which a manufacturer must manage. Significant proliferation of part and product varieties together with more random arrivals of customer orders resulting from fulfilment of these individualised products requires sufficient flexibility and rapid response capability. This brings direct consequence on the whole product realisation chain. The steps involved in the product realisation chain can be grouped into three areas involving *product*, *process* and *supply chain* design activities (Ellram et al., 2006; Fine, 2000; Lu and Wood, 2006)

- *Product design* is subdivided into activities of architectural choices (for example, integrality vs. modularity decisions) and detailed design choices (for example, performance and functional specifications for the detailed product design)
- *Process design* involves understanding the characteristics of the product to determine the appropriate manufacturing systems development (decisions about plant and operations systems design) and manufacturing processes (decisions about the process technologies and equipment to be used which also include more specific details such as the design of tools and fixtures, together with the sourcing, outfitting and testing those tools and fixtures.
- *Supply chain design* is divided into the supply chain architecture decisions and logistics/coordination system decisions. Supply chain architecture decisions include for example, sourcing decisions, structuring the relationships among the supply chain members. Logistics/coordination decisions include the inventory, delivery and information systems to support ongoing operations.

To implement MC strategies successfully, it is imperative that each of the three activities discussed above is reengineered utilising innovative ideas beyond the predominantly mass production orientated way of thinking. Much research has been devoted to enhance firms capabilities in supporting MC strategies which can actually be linked to the three development activities involved in the product realisation chain.

In this paper, a literature review suggests that the vast majority of research on MC, especially that published in the operations management domain, has focused predominantly on aspects related to product design and supply chain or logistics design. Very little attention devoted to process design seems to correspond with a common misperception suggesting that this part of the chain is less critical in comparison to the other elements. This is certainly untrue as the adoption of a MC strategy would have implications on processes, which may be evidenced by an exponentially increased number of process variations including diverse machines, tools, fixtures, setups, and so on. A cost-effective process design is therefore an absolute necessity to achieve a winning MC strategy. The dearth of existing research focusing on the important role of process design to accommodate MC motivates this study.

This paper primarily aims to rearticulate the important role of process design by specifically showcasing an innovative application of custom-made fixture design and production to support MC strategies. Fixtures are a vital component in the continuous effort to improve manufacturing efficiency whilst simultaneously adhering to the specified quality standards. Fixtures are utilised in manufacturing production whenever a component must be located and held with respect to a machine-tool or measuring device, or with respect to another component, as for instance in assembly or welding.

Conventionally, fixtures are made of plastic or metal, and are produced by a fabricating or machining process. The lead times are variable and can often extend to several weeks for production of moderately complex fixtures. For these conventional processes, lead time and cost increase as the fixture becomes more complex. Further limitation arises since both *design for manufacturability* and *design for assembly* rules apply to fixtures, and resultantly optimal fixture designs are often sacrificed to satisfy machining or fabricating constraints.

The MC of goods may necessitate the manufacture of new fixtures for individual products. This is apparent in situations where customisation results in changed geometries in the final product, resulting in the existing fixtures no longer being suitable for the manufacturing processes. Development of new fixtures will require the skills of a designer who is familiar with manufacturing processes, together with the fabrication of new fixtures which is both time consuming and expensive. Resultantly, conventional fixture design and production processes are typically unsuitable in MC environments.

Based on the findings of industrial case research, a custom-made fixture design and manufacturing technique is introduced. Traditionally, good fixture design was heavily reliant on the experience of toolmakers, and was a time-consuming, labour intensive and expensive process. However, since fixtures are used throughout manufacturing, much work has been undertaken in the development of Computer Aided Fixture Design (CAFD) (Pehlivan and Summers, 2008). In this paper, we explore a new technique for fixture production which combines the advantages of CAFD and the capabilities of modularity together with the opportunities offered by technologies of Rapid Manufacturing (RM). In this approach, using modular beam structures a support system is created, whilst the custom-built fixture element is produced using RM processes. A much shorter lead time afforded by this technique could allow the production of fixtures to be *postponed* as late as possible minimising costs associated to product design revisions. A number of examples are presented illustrating significant improvements in quality, fixture cost and overall time to market can be made using this new approach.

The contribution of this paper to the existing literature lies in the following respects. Firstly, this paper attempts to fill the gap in the existing operations management literature by focusing on process design. Our case study on customised fixture design and production may represent an area that, despite its critical role in the whole product realisation chain, has so far been overlooked. Secondly, this paper also contributes to increasing the number of empirical studies which are currently dominated by conceptual studies. We believe that empirical studies are important to enhance understanding of MC enablers, answering the 'how' question in achieving many desirable characteristics. Thirdly, our study can also be seen as one of the very few studies that try to enhance the awareness of academics and practitioners within the operations management domain on the potentials of exploiting advanced manufacturing technologies such as RM in overcoming existing limitations. We hope that this will foster intensification of technology-informed operations management research

This remainder of this paper is organised as follows. In the next section, a systematic review of the operations management literature pertaining to MC is presented, classifying each paper by either product design, process design or supply chain execution. This quantitative assessment of MC is supported by a qualitative review of the literature to familiarise the reader some of the main motivations for MC. In the third section, we introduce the concept of Rapid Manufacturing, and using several case studies illustrate the opportunity for its usage in the manufacture custom fixtures.

Literature review

The growing importance of mass customisation

The literature on MC is rich and fast growing. MC's research presence is entering its third decade, and the interest in this subject is increasing. Considering only *customisation*, an earlier study using the ABI/INFORM database and reported in Lampel and Mintzberg (1996) indicated that from 1971 to 1980, an average of only twenty articles on customisation appeared annually; from 1981 to 1990, 234 articles; and after 1990, 2,324. To compare, we used the same database on a keyword search to identify that *mass customisation* received zero publications in the 1970's, one in the 1980's, 293 in the 1990's and from the millennium until the end of 2008, 442. Given the concept was coined in literature by in 1987 by Davis (1987), the literary silence during the first two decades is to be expected; for the current decade in totality it is plausible that publications will surpass 500. In presenting these findings, we are mindful that ABI/INFORM does not fully represent an entire population of MC literature, but is useful in describing indicative growth.

The central motivation for businesses to adopt a MC strategy has often been attributed to increasing business competitiveness, and thereby gaining an advantage over rival companies. By providing customers products which meet their requirement, MC has been heralded as being "the New Frontier in Business Competition" (Pine 1993). Porter (1998) identifies two core strategies for the achievement of a competitive advantage – price and differentiation. Differentiation can be vertical (typically differentiating on product quality), or horizontal (differentiating on product attributes). For mass production it may be difficult to increase the horizontal differentiation without incurring greater costs of manufacture. However, for companies pursuing a MC strategy this is the primary focus, and therefore competitiveness is theoretically increased.

However, achieving competitiveness through differentiation is only sensible if customers actually desire customised goods. Throughout the 20th Century, mass production dominated manufacturing, providing standardised goods made cost-effectively by exploitation of economies of scale. Whilst this approach has reduced costs for the mass market, such homogenous markets are observed to be in decline (Hart, 1995) and increasingly, customers are demanding products which meet their individual needs, verified in consumer products e.g. (Piller et al., 2004), and is also readily evident in industrial situations (Arabe, 2002).

Product realisation chain

While each of the three activities in the product realisation chain is of equal importance, we are not aware of any previous studies reviewing interests of the MC research community within the operations management domain in addressing each activity. This motivated us to carry out a review with the aim of assessing how the existing studies on MC have paid attention to each of the three activities in the product realisation chain.

A review was conducted of publications which appear in journals that represent major research outlets in the field of operations management. Our sample consists of 173 academic papers published in journals such as: *International Journal of Production Research, International Journal of Production Economics, International Journal of Production and Operations Management, Journal of Operations Management, Production and Operations Management, Management Science, Omega, European Journal of Operational Research, International Journal of Flexible Manufacturing Systems, IEEE Transactions on Engineering Management.*

Due to the limited space, it is not our intention to list all the reviewed publications in this paper. Several examples discussed in the following, however, would be useful for the reader to follow our line of thought in developing the classification. Studies addressing *product design* can generally be classified into one of the three following groups. Research that belongs to the first group examines architectural designs to accommodate MC, which also includes studies analysing the concept of modularity. Examples include papers by Tsai and Wang (1999), Duray et al. (2000), and Mikkola (2007). The second group relates to product line design and considers the number of product varieties to represent the level of customisation (see e.g. Alptekinoglu and Corbett, 2008; Dobson and Yano, 2002; Mendelson and Parlaktürk, 2008). Finally, the last group concerns aspects related to the elicitation of customer requirements or customer involvement (see e.g. Franke and Piller, 2004; Randall et al., 2007; Terwiesch and Loch, 2004).

Studies addressing *process design* can generally be classified into one of the two groups. The first group consists of conceptual studies emphasising the importance of flexibility or reconfigurability of manufacturing systems to accommodate MC. Examples of conceptual papers are Jiao et al. (2007) and Bi et al. (2008). The second group presents results obtained from empirical research, particularly in showcasing best practices in different industries. Several papers which present successful applications of postponement or product delayed differentiation such as Feitzinger and Lee (1997), Dapiran (1992), and Brown et al. (2000) belong to this group. We note, however, that although postponement can be considered as one innovative approach addressing process design, there are numerous studies on postponement that do not really address process design but are more closely related to supply chain design as presented in Pagh and Cooper (1998) and Yang and Burns (2003). Finally, studies focusing on *supply chain design* generally concentrate on aspects such as supply chain structure to accommodate MC (Rudberg and Wikner, 2004; Salvador et al., 2004), and MC implications on logistics (Fuller et al., 1993; Mason and Lalwani, 2008).

A quantitative summary of the review is presented in a Venn diagram depicted in Figure 1. As shown in the diagram, in addition to papers which concentrate on each of the three activities, some further papers are related to more than one activity. This is expected as the relation and/or interface between one activity and another also represents an important area of research. Finally we find several papers that should be located outside the three circles as although relevant for MC, they do not address the product realisation chain (e.g. papers discussing the (re)-definition of MC or presenting a literature review).

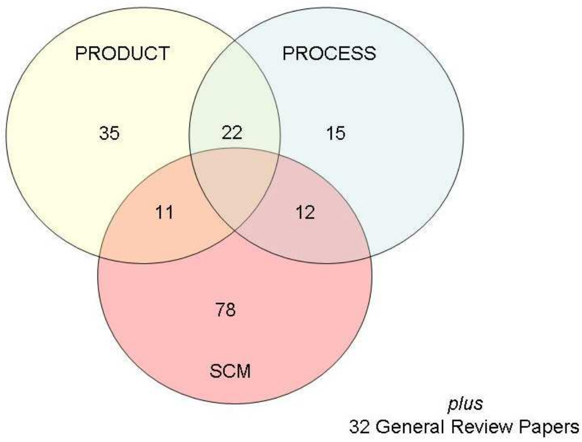

Figure 1: Quantitative review of mass customisation literature

Introduction to rapid manufacture of custom fixtures

RM is an emergent technique for manufacturing which has evolved from a family of technologies known as Rapid Prototyping (RP). RM is based on an additive layer manufacturing (ALM) technique to produce end-use products directly from 3D CAD model data. Many of the processes in RP and RM are the same, however the difference between RP and RM is the intended use of the fabricated part; either as a prototype (RP) or for an end-use product (RM). Though seemingly semantic, this subtle difference promotes RM as a commercially competitive range of technologies, which can be judged with other flexible manufacturing systems on attributes such as cost, materials and reliability.

In contrast to machining or forming processes, RM machines build objects by joining together layers of liquid, powder or sheet material, which consequentially eliminates tooling and mould requirements. As RM technologies do not require these initial fixed costs, the economics of manufacture support lower volume production, which Hopkinson et al (2006) state may eventually make unit-of-one manufacturing viable. At present, these technologies are gaining acceptance in numerous industries, including aerospace, motorsports, medical, furniture and arts/crafts; a comprehensive discussion is presented by Wohlers (2008). In these examples, RM is used to fabricate the final MC product, a concept which has been acknowledged to have received limited consideration in the literature (Eyers et al., 2008)

Rapid Manufactured custom fixtures (hereafter known as RM fixtures) aim to exploit these attractive manufacturing properties to produce sophisticated part geometries, but without incurring cost penalties through the loss of economies of scale attributed to low-volume manufacture. Instead of being the final MC product, RM fixtures can be viewed as MC enablers, supporting the creation of MC products manufactured using conventional technologies that necessitate fixtures.

For RM, the contact element interface between the fixing system and the product can be designed using 3D CAD software to form a model of the fixture. Unlike many conventional point-contact systems (where the connection between contact element and part is achieved at single 'points' of the fixture), RM fixtures are able to replicate the exact geometry to fit with the end use product. This has many advantages, especially for improving the quality of fit and also helps distribute the weight of the part over a greater area. Once designed, RM fixtures are converted from proprietary CAD files to a native RM format (known as STL), from which unattended, direct manufacturing can be achieved in a matter of hours. The duration of the manufacture is dependent on both the size of the fixture contact element being manufactured and the speed at which the machine builds. Importantly, increasing complexity of the part will neither affect the speed at which it is manufactured, nor the cost of manufacture. Such fabrication costs are predominantly based on time taken and material utilised. Furthermore, whilst all RM fixtures are unique to their particular application, many systems employ a modular approach to the securing and positioning of the fixture. Similar to some conventional techniques, standardised modular beams may be utilised in creating an overall structure to support the individual contact elements.

Concerning RM fixture manufacture we recognise there is already some literature already pertaining to the use RM (Pham and Dimov, 2001; Violante et al., 2007), however the focus of these engineering studies has been the technical considerations for the manufacture of fixtures. In this study, our focus is not the physical manufacture of the product, instead we are concerned with the application of RM fixtures for the enablement of customised manufacturing.

Rapid manufactured custom-made fixture case studies

The use of RM fixtures in the production of customised goods has numerous implications for manufacturing practitioners. One commercial technology suitable for this application is RapidFit, a system developed by Materialise. In this section we present case studies developed with Materialise that utilise their system to produce RM fixtures. RapidFit is a combined modular beam & plate approach to construct an overall supporting structure, together with RM produced contact elements which act as the interface between beams and the final product. Using sophisticated software, fixtures are created automatically based on a 3D model of the designed product (which can either originate from a designer's 3D model, or from 3D scan of the physical product). Fixtures are manufactured using either Laser Sintering or Fused Deposition Modelling, in either nylon or ABS (both of which are hard wearing yet relatively unlikely to damage the surface of the finished product), with engineering tolerances of 0.1mm.

In the following three case examples, fixtures are presented which enable the measurement of parts when located for assembly. Measurement fixtures are important aspects of the quality assurance for a product, and where product prototyping is undertaken during product development, fixture designs will be updated iteratively, necessitating both redesign & remanufacture. The three fixtures are used together in the assembly of the front of a car. One fixture is used to position the car's grill, a second to position the fender and a third (shown in Figure 2), more complicated fixture used to locate the front bumper

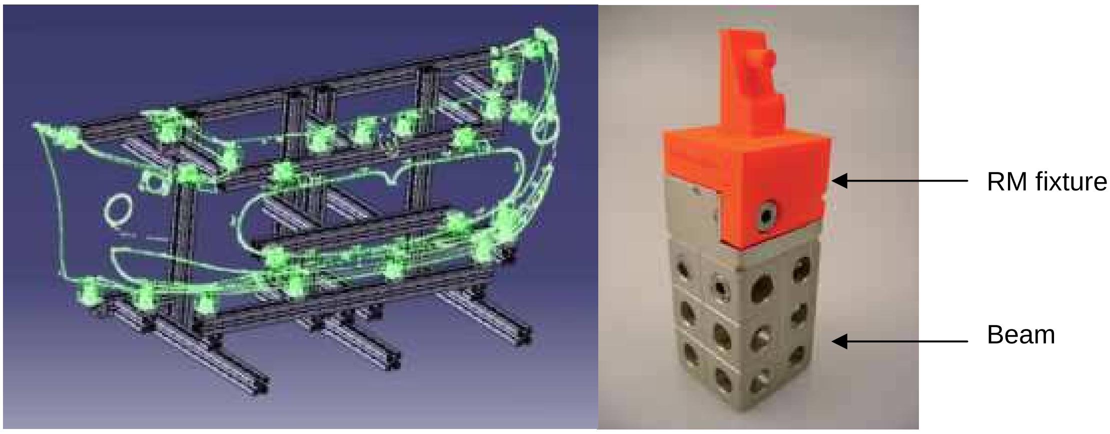

Figure 2: RapidFit bumper CAD model (left) & RapidFit fixture on Alufix modular beam (right)

The manufacture of fixtures would traditionally be achieved using conventional approaches such as machining aluminium or using beam and positioning kits. However, using RM, it is possible to construct suitable fixtures using Laser Sintering to form the contact element, shaped to the exact profile of the part, together with modular beams for assembly. In table 1, a brief comparison of each approach in terms of cost and lead-time is presented.

Table 1: Cost & lead-time comparison

	Contact Elements	**Rapid Fit+ (RM)**	**Machined Aluminium Supplier A**	**Machined Aluminium Supplier B**	**Beams & Positioning Kits**
Bumper	23	€12,525	€17,742	€17,500	€18,280
Fender	10	€6,200	€9,860	€8,500	€11,400
Grill	10	€4,900	€11,636	€6,475	€11,400
Total	43	€23,625	€39,238	€32,475	€41,080
% increase			+ 66%	+ 37%	+ 74%
Lead-time		3 weeks	6 to 8 weeks	6 weeks	6 weeks
Lead-time increase			+100 % to 166%	+100%	+100%

Each of the case studies presented has identified a large reduction in costs achieved through the use of RM for fixture manufacture. Whilst this is advantageous for all scenarios requiring fixture manufacture, cost reduction is particularly relevant to MC products where, unlike mass production, the cost of fixtures cannot be amortized over a large volume of products. A further advantage of the RM approach can be observed through a breakdown of the fixture cost, of which up to three quarters is resultant from the purchase of reusable modular beams. Resultantly, where the fixture needs to be revised, only the contact elements need to be remanufactured, hence the costs involved in overall fixture modification are significantly lessened.

One of the most interesting capabilities afforded by these RM fixtures is the ability to address responsiveness in manufacturing, as the manufacturing lead-time for customised fixtures can be halved. This provides interesting opportunities for multiple scenarios in the realisation of fixtures through RM, the first of which concerns postponement. In conventional manufacture, it is typical for the fixture design to be postponed as late as possible in design process, when product designs have been finalised and uncertainty is minimised. From the case studies it is apparent that RM fixtures can be created in up to half the time of conventional fixtures, which allows postponed manufacturing to be conducted even later into the design/manufacturing stages. Resultantly, manufacturers can be more confident of fixture requirements before committing to their production.

However, in situations where the customer is empowered to configure the geometry, it is likely the manufacturer will have no awareness of the geometric requirements in advance. A second scenario therefore exists since this voluntary postponement will not be an option, and instead the importance is on responsive manufacturing systems to fulfil the order on a timely basis. Consequently, the reduced manufacture times of RM fixtures will therefore be valuable in improving the overall responsiveness in terms of order fulfilment.

A final eventuality that is made possible due to the reduced costs of RM fixtures is the iterative production of multiple fixtures during product development. In this approach, fixtures are developed simultaneously with the component *before* the final product design is finalised. Whilst this will result in the need for multiple contact elements to be manufactured during the development of a single product, this technique can shorten overall product development since fixtures are produced simultaneously with the components. Although adopting such a strategy may seem wasteful in the development of multiple fixtures, this approach mitigates the risk of fully postponed fixture development, where delays in the production of the final customer item will occur if the fixtures prove unsuitable.

This flexibility and responsiveness is also important in the duplication of fixtures. Whilst highly customised demand implies a fixture will only be used on one item, the ability to easily reproduce identical fixtures is highly advantageous. In manufacturing it is common for fixtures to become damaged as a result of the working environment, necessitating the manufacture of new parts. With RM fixtures, their design may be held indefinitely in an electronic form, with manufacturing easily achieved by submitting as a job for the RM equipment.

The overall quality of the fixtures can be assessed on multiple criteria, however in this review we are particularly concerned with the geometric fit of the fixtures. As geometric customisation options increase, the complexity of the resultant finished part may become difficult (or indeed impossible) to manage using conventional approaches to fixture manufacture. This is particularly plausible where customers that are unfamiliar with the previously discussed ‘design for manufacture’ constraints are engaged in unassisted design. However, with RM fixtures, the contact element of the fixture is automatically generated from the 3D model of the customer product and directly manufactured using RM technologies, achieving an exact fit irrespective of the complexity of the geometry chosen by the customer. Considering both flexibility and costs of manufacture, it is particularly evident that as fixture complexity rises, the use of RM fixtures becomes increasingly worthwhile.

Conclusion

The intention of this paper has been to highlight the lack of research attention paid to process design as part of the overall product realisation chain for MC goods. From our assessment of the existing literature in the operations management domain it is readily evident that process design is an important research gap. Although it is arguably reasonable to find most studies related to process design published in the counterpart Manufacturing Technology or Engineering domain, very few studies addressing process design found in our review could indicate the lack of technology-informed operations management research. This is undesirable particularly in the context of MC since it is essential for the whole community to share ideas and knowledge for overcoming business as well as technical challenges in achieving a more ideal state of mass customisation era, where the provision of customised products can be realised at a comparable price and speed of equivalent standardised offerings.

In partial satisfaction of this omission, this paper presents a consideration of customised fixtures as a requisite element of process design, enabled using the emergent technologies of RM. From the case studies it is recognised that RM technologies may play an important role in this element of the product realisation chain, with potential to address issues of cost, responsiveness and quality. Whilst assessing the overall suitability of RM fixtures for general cases is outside the remit of this paper, the three examples shown illustrate benefits of an RM approach, particularly as fixture complexity increases or where iterative fixture development is required.

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