Performance Analysis of Minicell-based Manufacturing System for

Mass Customization

Fazleena Badurdeen*, Bader Meriden and Smitha Thuramalla

Department of Mechanical Engineering,

University of Kentucky

Lexington, KY 40506, USA

*Corresponding author,

Email: badurdeen@engr.uky.edu

Phone: 1-859-257-6262 Ext.436

Fax: 1-859-323-1035
1. INTRODUCTION

Customer expectations have changed significantly over the past several years and manufacturers in many industries are no longer able to meet customer requirements through mere product differentiation. Customers now demand better quality products customized to meet their individual requirements while still providing fast delivery and low cost. In light of these changes, mass customization, which is defined as ‘the low-cost, high-volume, efficient production of individually customized offerings’ [Pine (2007)], has emerged as an important source of competitive advantage.

Davis introduced the term mass customization through his 1987 book *Future Perfect* [Davis (1987)]. Later, Pine and several others [Pine (1993), Victor, Boynton and Pine (1993), Gilmore and Pine (1997)], did some seminal work that contributed to the popularization of the concept in the 1990’s. Advances in information and manufacturing technologies have brought about tremendous opportunities for mass customization to a point where, nowadays literally, ‘anything that can be digitized can be customized’ [Pine (2007)]. Many examples of successful mass customization ranging from shoes and clothing to hearing aids and computers demonstrate the feasibility of the strategy and has increased its popularity.

Successful mass customization requires superior capabilities to integrate customers to achieve co-design through effective product configurator systems, efficient product variant management as well as organizational structures and processes [Åhlström and Westbrook (1999), Moser (2007)] that are capable of taking product specifications and transforming them into customized finished products. In this context, the need for
highly flexible and responsive manufacturing systems that can produce the customized products within a short time and at competitive prices cannot be over emphasized.

Companies follow different strategies to mass customization with customer involvement occurring at varying levels. The earlier in the value chain customer involvement takes place, the more challenging are the manufacturing capabilities needed for successful mass customization. For example, with standardized customization [Lampel and Mintzberg (1996)], often also referred to as assemble-to-order customization, customer involvement in co-design occurs at the assembly stage where customers select from different options for the features for product configuration (e.g.: Dell, Flyte bicycles, many automobile manufacturers). Existing manufacturing strategies such as lean manufacturing can be extended for application to this type of customization by eliminating all non-value adding activities and to enable achieving cost efficiencies. With lean manufacturing, production leveling is applied to facilitate mixed model scheduling based on sales projections [Ohno (1998)]. The diversity in customer requirements and high product variety make demand forecasting very difficult in mass customization. Some form of order consolidation and subsequent release to the shop floor is plausible when applying lean strategies for standardized customization.

On the other hand, in a fully customized environment where ‘pure customization’ [Lampel and Mintzberg (1996)] takes place, customers get involved early in the design stage enabling a more custom offering to be designed, and produced, by incorporating individual needs. Pure customization requires highly automated agile manufacturing systems, for example, with CAD/CAM systems to design and fabricate the fully customized products. While this form of customization has been practiced in the
business-to-business (B2B) context for many years, the number of companies engaged in
pure customization in the business-to-customer (B2C) segment is still limited, possibly
due to the challenges involved in offering fully customized products in large scale at
competitive prices.

Customization through intervention at the fabrication/production stage in the
value chain—tailored customization according to the Lampel and Mintzberg (1996)
terminology—is less challenging than pure customization but still permits achieving a
greater fit to customer needs than with standardized customization. In practice, however,
many companies appear to follow a mix of tailored and standardized customization by
custom fabricating options for one, or a few, major features and offering pre-fabricated
options for other features. Adidas’s offering of customized shoes (miadidas), customized
eye glasses, as well as the National Bicycle Industrial Company case [Kotha (1995)] are
eamples of companies that can be classified under this category.

Direct application of lean manufacturing for tailored customization is not feasible
given the impact on upstream processes due to demand fluctuations, and therefore, the
difficulties in production leveling. On the other hand, the use of fully automated
manufacturing systems could increase product cost quite significantly. This paper
presents a modular manufacturing system design using ‘minicells’ that has potential to
deliver the flexibility and responsiveness required for efficient tailored customization (or
a combination of tailored + standard customization) by extending and adapting group
technology concepts. The performance of minicells under stochastic demand conditions
and approaches to integrate minicells with final assembly cells to explore the potential of
extending the application of lean manufacturing principles is also examined.
The remainder of the paper is organized as follows. An overview of the minicell concept and how minicells can be integrated with the entire manufacturing system is presented in section 2. Alternate strategies to design minicells and the design methodology are briefly discussed in section 3. A numerical example is used to demonstrate the performance of minicells, compared to traditional cells, under stochastic demand conditions through simulation modeling in section 4. Conclusions and future research activities planned are presented in section 5.

2. MINICELLS FOR MASS CUSTOMIZATION

In most situations, customization of a product is often possible by customizing the fit, function and/or aesthetics of one, or a few, main features. For example, a high degree of customization of a shoe can be achieved with a well-fitted last that matches the customer’s foot shapes to provide superior comfort. In the case of a bicycle, this may be achieved through the customization of the frame, based on customer anthropometry, to ensure a comfortable ride. Thus, a bicycle mass customizer may offer multiple options for most of the features such as the frame, handle bar, fork and seat (for example, with the product structure shown in Figure 1). The frame will be the ideal candidate for fabricating to customer specifications to achieve higher customization. Other features can have multiple options, varying depending on material, design, size, etc., that are pre-fabricated and assembled with the custom fabricated frame to produce the customized offering.
Badurdeen (2005) proposed the development of a modular, multi-stage manufacturing configuration for mass customization for use when one or more features are fabricated to order. Combining the variety of options (custom fabricated and pre-fabricated options) for a mass customized product’s features can give rise to a large number of product variants. However, these variants are likely to vary from each other only in terms of one, or a few, different options. Therefore, though the demand for each product variant itself could be highly dynamic, the demand for options is likely to be less volatile. Due to this reason, the options and their processing requirements have been used to develop a new type of manufacturing cells known as *minicells* [Badurdeen (2005), Badurdeen and Masel (2007a, 2007b)].

The design of minicells begins with an option-machine matrix (as opposed to the product/part-machine matrix used for traditional cells) which is formed using information from process plans for custom fabricated options (an example is shown in Figure 2 indicating the machines needed for each option). To achieve greater modularity in the system designed, the minicell configuration is developed by starting with the option-machine matrix and dividing it into sub-matrices. Minicells are then formed within each sub-matrix, or stage, by grouping the machines required for processing a sub-set of
operations for a group of options (methodology discussed in section 3). The result is a network of minicells where all the custom fabricated options for a product variant (simply referred to as a product variant here onwards) will be routed to the required minicells to complete processing.

<table>
<thead>
<tr>
<th>Feature 1</th>
<th>Feature 2</th>
<th>Feature 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Options</td>
<td>Machines</td>
<td></td>
</tr>
<tr>
<td>O11</td>
<td>M1</td>
<td>1</td>
</tr>
<tr>
<td>O12</td>
<td>M2</td>
<td>1 1 1</td>
</tr>
<tr>
<td>O13</td>
<td>M3</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>O21</td>
<td>M4</td>
<td>1 1 1</td>
</tr>
<tr>
<td>O22</td>
<td>M5</td>
<td>1 1 1</td>
</tr>
<tr>
<td>O23</td>
<td>M6</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>O24</td>
<td>M7</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>O25</td>
<td>M8</td>
<td>1 1 1</td>
</tr>
</tbody>
</table>

**Figure 2: Option-Machine Matrix**

The minicells, as described above, are only used to produce custom fabricated options. The final customized product offering will later have to be assembled using the pre-fabricated options and custom fabricated options. The overall manufacturing system configuration illustrating the integration of minicells, as well as traditional cells used to produce the pre-fabricated options, with final assembly is shown in Figure 3.
Synchronized order launching at the final assembly and minicells will be required to ensure custom options are available for final assembly at the required time. Traditional manufacturing cells can be used to produce pre-fabricated options which can be fed to final assembly, for example through a supermarket system, for replenishment on an as-needed basis.

3. MINICELL DESIGN METHODOLOGY

In traditional cellular manufacturing, each cell is dedicated to a different product family whereas a minicell is dedicated to producing an option family [Badurdeen (2005)]. Two different approaches have been proposed by Badurdeen and Masel (2006) to divide the
option-machine matrix into multiple stages, an example of which is illustrated in Figure 4 [for detailed description of the methods see Badurdeen and Masel (2006)].

With Strategy A, the matrix is divided vertically to assign the machines into multiple stages (Stage A1 and Stage A2 in Figure 4). With Strategy B, the matrix is divided into stages based on the features available. For example, in Figure 4, each feature is assigned to a separate stage. With both methods, the options within each stage are then grouped to form option families and minicells. For each product variant, the options to be custom fabricated are then routed to the necessary minicells, in each stage, as per customer specifications.

Genetic Algorithm-based Design Approach

Badurdeen (2005) and others (2006, 2007b) have used genetic algorithm (GA) models to design the best minicell configuration for a given problem when multiple features of the mass customized product are fabricated after receiving the customer order. For
successful mass customization, companies need to be able to deliver customized products at a low cost with short turnaround times. Reducing the time between receiving and completion of all orders (makespan) and total machine requirements for the minicell configuration have been taken as objectives for optimization in minicell design.

Different, but deterministic, demand scenarios have been used to test the GA results and develop robust minicell designs. The GA-based design methodology is outlined in Figure 5 (see Badurdeen and Masel (2006, 2007b) for details) which is briefly described below.

![Figure 5: Minicell Design Methodology](image-url)
The number of stages for the design and the maximum number of minicells per stage are user defined. For the GA, a chromosome (with \( m \) genes) is used with Strategy A to represent cutoff point selection to divide the matrix into stages (user defined for Strategy B based on number of features and how they are to be assigned). Another chromosome with \( m \) blocks (\( m = \# \) of stages) of \( n \) genes (\( n = \# \) of options) each is used to represent the number of minicells in each stage and assignment of options to minicells. The initial population of \( p \) (= population size) chromosomes is determined randomly.

They assumed an 8-hour work shift to estimate machine capacities to process the daily demand and consolidated orders on a daily basis for release to the shop floor. When scheduling orders in minicells, setup times have been taken to be sequence-independent and as included in processing times. They used the Campbell, Dudek and Smith (1970) heuristic to schedule jobs in the first minicell and a first-come-first-served basis for the remaining minicells. Chromosome fitness function value is weighted based on the relative importance assigned to minimizing makespan and machine capacity. A mix of single cut-point and swapping crossover strategies and random mutation of genes has been applied to perform the genetic operations. The GA is terminated after the required number of generations.

**Performance of Minicells**

Badurdeen and Masel (2006, 2007b) have used separate GA models to design minicells following both strategies (A and B). Their findings on minicell performance have shown encouraging results, particularly when demand variability is high. Despite the network-type configuration, where product variants must travel to multiple minicells
to be processed, minicells have shown better, or similar, results with respect to makespan, machine requirements, and average flow/lead time compared to traditional manufacturing cells.

4. **MINICELL PERFORMANCE UNDER STOCHASTIC DEMAND**

Previous analyses on minicells, designed using the GA models, have been limited to experimentation using deterministic demand scenarios. However, with mass customization, customer demand is highly variable and unpredictable. Ascertaining minicell flexibility to provide consistent performance under such stochastic demand conditions is a vital step in improving the design and implementing this type of cells in mass customization environments. The simulation models designed and the experimentation conducted to evaluate performance under such conditions is explained in this section. For a given problem, robust minicells (and traditional cells for comparison) are first designed using GA models developed by Badurdeen and Masel (2006, 2007b). Simulation models are then formulated for each design using the software Arena™ to test performance under dynamic demand conditions, as illustrated in Figure 6.

![Figure 6: Procedure for Testing Minicell Performance for Stochastic Demand](image-url)
**Mass Customization Example**

A numeric example is used in this paper to demonstrate the experimentation conducted to evaluate minicell performance under stochastic demand conditions. A mass customized product where three features are fabricated-to-order, with three different options for each is considered (see Figure 7(a)). These options will be fabricated in minicells. The option-machine matrix for the problem (in terms of processing time in minutes) is shown in Figure 7(b).

![Figure 7: (a) Product Structure and (b) Option-Machine Matrix for Example](image)

A total of 27 product variants can be generated by combining the custom fabricated options and the average daily demand for them are given in Table 1 (the product variants are identified by the option number chosen for each feature. For example, the variant 11.22.33 has option 11 for feature 1, option 22 for feature 2 and option 33 for feature 3). These values are used to compute machine capacities required in each minicell (or traditional cell). The actual demand is assumed to be normally distributed about this average demand.
Table 1: Average Daily Demand for Product Variants

<table>
<thead>
<tr>
<th>Product Variant</th>
<th>Demand</th>
<th>Product Variant</th>
<th>Demand</th>
<th>Product Variant</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.21.31</td>
<td>8</td>
<td>12.21.31</td>
<td>5</td>
<td>13.21.31</td>
<td>10</td>
</tr>
<tr>
<td>11.21.32</td>
<td>3</td>
<td>12.21.32</td>
<td>2</td>
<td>13.21.32</td>
<td>2</td>
</tr>
<tr>
<td>11.21.33</td>
<td>3</td>
<td>12.21.33</td>
<td>2</td>
<td>13.21.33</td>
<td>5</td>
</tr>
<tr>
<td>11.22.31</td>
<td>2</td>
<td>12.22.31</td>
<td>10</td>
<td>13.22.31</td>
<td>3</td>
</tr>
<tr>
<td>11.22.32</td>
<td>4</td>
<td>12.22.32</td>
<td>4</td>
<td>13.22.32</td>
<td>4</td>
</tr>
<tr>
<td>11.22.33</td>
<td>3</td>
<td>12.22.33</td>
<td>1</td>
<td>13.22.33</td>
<td>2</td>
</tr>
<tr>
<td>11.23.31</td>
<td>7</td>
<td>12.23.31</td>
<td>10</td>
<td>13.23.31</td>
<td>6</td>
</tr>
<tr>
<td>11.23.32</td>
<td>8</td>
<td>12.23.32</td>
<td>8</td>
<td>13.23.32</td>
<td>6</td>
</tr>
<tr>
<td>11.23.33</td>
<td>7</td>
<td>12.23.33</td>
<td>9</td>
<td>13.23.33</td>
<td>4</td>
</tr>
</tbody>
</table>

For the GA, the number of stages in the configurations was set to three with a maximum of 2 minicells per stage. The minicell configurations designed following Strategy A and Strategy B are shown in Figure 8 and Figure 9, respectively. The options assigned to each minicell in each stage, the number of units of each type required and the resulting network of minicells is shown in the figures.

(a) Minicells, Options and Machine Requirements

(b) Flow in Minicells

Figure 8: Details of Minicell Configuration Designed using Strategy A
As minicells are designed by adapting and extending group technology principles, traditional manufacturing cells are also designed for the same problem using a separate GA [see Badurdeen and Masel (2006)]. The machine requirements for a two traditional cell configuration, product variants assigned to each cell and the number of machines required and the flow in traditional cells is shown in Figure 10.

**Figure 9: Details of Minicell Configuration Designed using Strategy B**

- Minicell # M/c: Options (11, 12) and (21, 22, 23)
- Stage 1: Options B(1), C(1), D(1), E(1), F(1), G(1)
- Stage 2: Options B(1), C(1), D(1), E(1), F(1), G(1)
- Stage 3: Options B(1), C(1), D(1), E(1), F(1), G(1)

**Figure 10: Details of Traditional Cells Designed**

- Traditional Cell # M/c: Options (11, 12) and (21, 22, 23)
- Cell 1: Variants (11.21, 11.22, 11.23, 12.21, 12.22, 12.23, 13.21, 13.22, 13.23)
The minicell and traditional cell designs were then tested to evaluate their performance under different demand scenarios. For each scenario, the actual demand is computed such that it is \( N \sim (\mu = \text{average daily demand}, \sigma = x\% \text{ of average daily demand}) \). The average flow time to process product variants in minicells, makespan after testing with 15 different actual demand scenarios (each with \( x=10 \)) are summarized in Table 2. The total number of machines required for each type of designs is also shown.

**Table 2: Performance of Minicells and Traditional Cells**

<table>
<thead>
<tr>
<th>Design</th>
<th>Total Machines</th>
<th>Average Flow Time (hrs)</th>
<th>Makespan (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minicell Strategy A</td>
<td>11</td>
<td>3.03</td>
<td>5.25</td>
</tr>
<tr>
<td>Minicell Strategy B</td>
<td>21</td>
<td>1.75</td>
<td>2.85</td>
</tr>
<tr>
<td>Traditional Cells</td>
<td>14</td>
<td>2.58</td>
<td>4.03</td>
</tr>
</tbody>
</table>

As can be observed, minicells designed by strategy B give much better results, in terms of makespan and average flow time, though the machine requirements are higher as result of the duplication.

**Simulation Model Design and Performance Analysis**

The simulation models to test the performance of minicell configurations and traditional cells, designed above, under stochastic demand conditions was developed using the simulation software Arena™.

For simulation models, the demand was set to be stochastic and normally distributed. Simulation time was set to 8 hours and product variants (entities in the simulation) were generated as a batch and released to the system to be processed on the cells on a first-come-first-served basis. Just as in the GA models, setup times were
assumed to be sequence-independent and included in processing times. Material handling time was neglected and the ‘station’ and ‘route’ blocks in Arena™ were used to model this.

The simulation models were tested under different demand scenarios to evaluate volume flexibility of minicell designs. Three scenarios with average daily demand shown in Table 1 and standard deviations =10%, 50% & 100% (denoted as L10%, L50% and L100%) and two other scenarios by doubling the average daily demand and with standard deviation = 50% & 100% (denoted as H50% and H100%) were tested using the simulation models. All the models were run for five replications each. The variation of average flow time and average makespan (across all replications) for the two minicell designs and traditional cells is presented in Figure 11 and Figure 12, respectively.

In all cases, including the scenarios with increased average daily demand and higher variability, minicells designed by strategy B show consistently better results. However, it appears that minicells by strategy A are not as good, and perform poorly, compared to traditional cells.
For the H100% scenario, none of the designs is able to complete processing the total demand generated and work-in-process inventory remains in the system after the 8-hour period. This explains the ceiling of 8 hours for average makespan with H100% for all models.

The variation in average flow time and makespan with stochastic demand is consistent with the pattern observed with GA results (using deterministic demand data) shown in Table 2. The disparity in the actual values can be attributed to the variation in the demand quantities. The results indicate that minicells by strategy B offer greater flexibility to process the custom fabricated options in the mass customized products within a shorter time (i.e. lower average flow times) compared to using traditional cells. In all cases, except the H100% scenario where all product variants are not completed, this design also enables completing processing the entire batch of orders for the day (i.e. makespan) within a shorter time.
Machine utilization statistics are useful when evaluating the usage of machines to identify bottleneck resources in the different designs. This information can also be useful to incrementally modify the designs to achieve better performance. The variation in the utilization of machines in different minicell designs and traditional cells is shown in Figure 13, Figure 14 and Figure 15.

![Figure 13: Variation in Machine Utilizations with Minicells Type A](image)

In Figure 13 and Figure 14, machines are identified by the stage number ("SG"), the minicell it belongs to ("Min") and the type of machine ("A", "B", etc.). For traditional cells, the cell number ("Cell1", "Cell2") and machine type are denoted.
Except with the H100% scenario, the designs possess sufficient machine capacity to produce the fabricated-to-order options of the product. However, as variability is
increased even further to the H100% level, machine A turns out to be the bottleneck with all designs. In addition, machine E, too, is operating at capacity with the minicell designs. The option-machine matrix reflects the sequence of machines in the process plans. Therefore, a bottleneck at the first machine (A) limits product variant entry to the manufacturing system leading to adverse impacts on time-based performance measures. Selective modification of machine capacity, for example by adding more machines of type A in minicells, can be explored to improve performance further, mainly with minicells designed by strategy B.

5. CONCLUSIONS AND FUTURE RESEARCH

The potential of using minicells (particularly with strategy B) to achieve higher flexibility to meet the dynamic demand experienced in mass customization and optimize the time-based performance measures is demonstrated in this paper. The minicell design methodology was illustrated with a numerical example for which simulation models were designed and performance was evaluated under stochastic demand conditions.

As described previously, minicells are only intended for the custom fabricated options. Pre-fabricated option must later be combined with fabricate-to-order options in final assembly (Figure 3). Due to the dynamic nature of daily demand in mass customization environments, the average flow time—and time between units or cycle time for minicell output—will be highly variable. However, in order to synchronize flow between minicells and final assembly, some operating rules must be developed, for example using fixed time buckets to transfer units, based on the nature of the mass customized product, process plans for custom fabricated options (i.e. time requirements
and difference in processing times for various options) as well as expected demand. Further research is needed to determine methods to optimally design and operate a minicell-based manufacturing system.

6. REFERENCES


