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APPLICATION OF ARTIFICIAL NEURAL NETWORK TECHNIQUES FOR DESIGN OF MODULAR MINICELL CONFIGURATIONS

Arvind Goyal
University of Kentucky, arvind12goyal@yahoo.com

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ABSTRACT

APPLICATION OF ARTIFICIAL NEURAL NETWORK TECHNIQUES FOR DESIGN OF MODULAR MINICELL CONFIGURATIONS

Artificial neural networks, so far, have not been used for designing modular cells. Therefore, Self-organizing neural network (SONN) is used in the present research to design minicell-based manufacturing system. Two previously developed methods were studied and implemented using SONN model. Results obtained are compared with previous results to analyze the effectiveness of SONN in designing minicells. A new method is then developed with the objective to design minicells more effectively and efficiently. Results of all three methods are compared using machine-count and material-handling as performance measuring criteria to find out the best method to design minicells and to analyze the performance of the newly developed approach.

KEYWORDS: Cellular Manufacturing, Minicell, Mass customization, Material Handling, Self-Organizing neural network.

Arvind Goyal

February 13, 2008

APPLICATION OF ARTIFICIAL NEURAL NETWORK TECHNIQUES FOR DESIGN OF MODULAR MINICELL CONFIGURATIONS

By

Arvind Goyal

Dr. Fazleena Badurdeen

Director of Thesis

Dr. Dusan P Sekulic

Director of Graduate Studies

Date: February 13, 2008

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THESIS

Arvind Goyal

The Graduate School
University of Kentucky
2008

APPLICATION OF ARTIFICIAL NEURAL NETWORK TECHNIQUES FOR DESIGN OF MODULAR MINICELL CONFIGURATIONS

THESIS

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Manufacturing Systems Engineering
in the College of Engineering at the University of Kentucky

By
Arvind Goyal
Lexington, Kentucky
Director: Dr. Fazleena Badurdeen
Assistant Professor of Mechanical Engineering
Lexington, Kentucky
2008

Dedicated to My Parents

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1 Introduction

1.1 Overview

Manufacturing is defined as “the application of tools and methods to convert raw materials into final consumable products”. The term “Manufacturing” is derived from Latin words called “Manu” and “factus” means made by hand (www.aptv.org/Factories). Almost all the things around us (furniture, ball point pens, bicycles, clothes, cars, tooth brush etc.) are the results of manufacturing in one way or the other. Thus manufacturing has its own importance and relevance right from the beginning.

Before the 19th century, each and every product was manufactured by hand in highly specialized manner by highly skilled labor that made cost of products too high, thus only upper segment of society was able to afford those products. Later on, increase in the demand pressurized manufacturers to produce these products in a shorter time and at less cost. Thus, manufacturing stepped into a new phase of “Mass production” through which it was possible to produce a single product in large volumes on time at very low cost. Henry Ford coined the idea of mass production and Ford Motor Company started manufacturing cars in large quantities at a fast pace and at low cost by developing assembly lines also termed as product flow lines (Ford, 1926). This was a revolution in the history of manufacturing and almost every company was striving to produce at mass production scale to reduce manufacturing cost and make profits.

Technological advances made customers more demanding and overtime they have sought to expect more variety from manufacturers to be able to choose product according to requirements. This was a very difficult move forcing manufacturers to make a compromise between volume and variety. Factors such as shrinking product life cycles, increase in product variety and customer expectations on continuous basis have been redefining competition in the market in the recent years (Irizarry *et al.*, 2001).

1.2 Mass Customization

Mass customization is defined as "the customization of the products and services for individual customers at mass production price" (Davis, 1987). Traditionally, customization and low cost were seen as two mutually exclusive terms and it was thought to be impossible to provide customized products to the individuals at mass production efficiencies. Advancement in technology and automation made customers more aware and more demanding. Nowadays customers want to customize the product they are going to buy according to their requirement and that too at lower cost.

Recently, Piller defined mass customization as "*Customer co-design process* of products and services with regard to *certain product features*. All operations are performed within a *fixed solution space*, characterized by stable but still flexible and responsive processes. As a result the *costs associated with customization* allow for a price level that *does not imply a switch in an upper market segment*" (Piller, 2004). Here, customer co-design indicates that customer works with manufacturer in value creation by defining, configuring, matching or modifying the product he/she is going to buy from the manufacturer (Piller, 2004).

The basic goal of mass customization is "to build customized products, even if the lot size is one, and to achieve customized/costs balance" (Pine, 1993). For most of the industries, markets are becoming fragmented into lower volumes and more customer driven products that have shortened product life cycle (Qiao *et al.*, 2002). Hence, mass customization is becoming an important aspect to survive in today's competitive world.

1.3 Challenges

Implementing mass customization is not an easy task. There are many issues directly or indirectly linked and need to be given a careful thought while implementing mass customization. One of the important challenges is the requirement of a dynamic stable manufacturing system. In other words, manufacturing operations and processes must be designed to serve a wide range of customers with changing product demand (Pine, 1993). Other related challenges are short setup times, small changeover times, shorter lead time etc.

Mass customization emphasis on “build to order” rather than “build to stock”. This poses another challenge that demands the system to change the traditional supply chain system. Suppliers must be able to supply the material just-in-time. Because the customer demand can not be predicted very well ahead, companies can not afford to stock raw-material or finished goods for very high variety of products they are offering to customers. Instead of supply-chain, a “demand-chain” is created for the mass customization environment (Gilmore *et al.*, 1997).

Information technology also plays a vital role and is another challenge in implementing mass customization (Ahlstrom *et al.*, 1999). It forms the basis to get information from the customer, making sure customer expectations are understood and interpret well and transferred correctly to manufacturing in minimum span of time. All these issues are very important for an effective implementation of mass customization.

Present research deals in designing a manufacturing system for mass customization environment capable of delivering high product variety at less cost. Therefore, other aspects though important to mass customization are not considered in the present study. Following section discusses various manufacturing strategies along with their drawbacks or limitations in a mass customization environment.

1.4 Manufacturing Systems

Mass production and Job shop manufacturing strategies are not able to meet the requirements of mass customization manufacturing environment. Mass production strategy can provide high-volume, low cost products but lacks in providing variety and flexibility. On the other hand, Job shop manufacturing can provide variety and flexibility but lacks in providing high productivity and efficiency.

Traditional cellular manufacturing has emerged into an effective manufacturing strategy over the last two decades. It helps in improving the productivity of the batch size and maintains the flexibility at the same time.

Figure 1-1 indicates exactly the position of cellular manufacturing system along with other manufacturing systems. As shown in this figure, Job shop that offers high-variety low-volume is at one extreme and mass production with high-volume low-variety is at the other end.

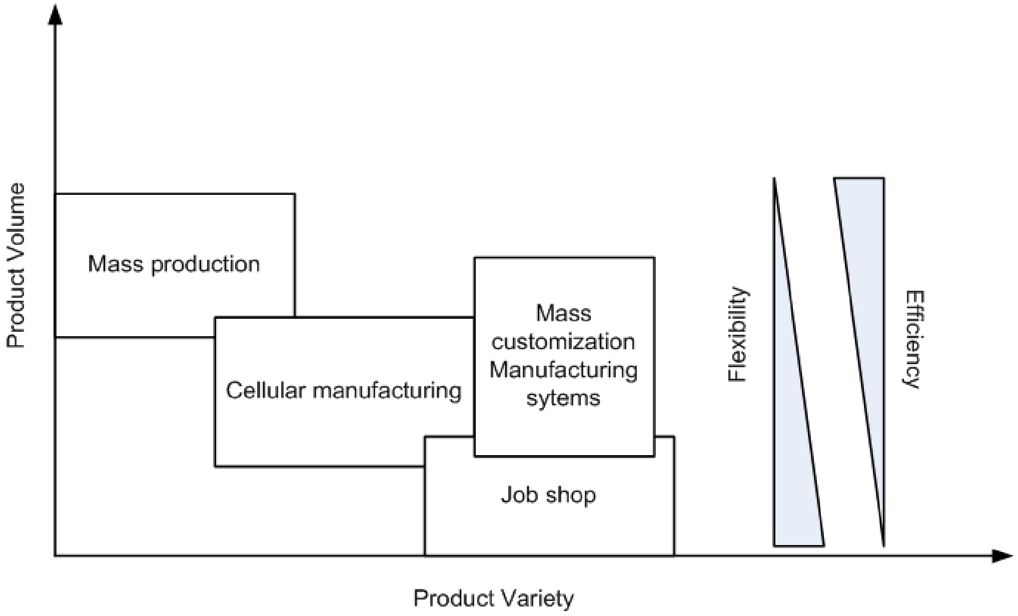


Figure 1-1: Product Volume-Variety indicating Manufacturing Systems

(Badurdeen, 2005)

Cellular manufacturing lies between these two manufacturing systems allowing medium to high volume production and reasonable variety. In cellular manufacturing, products with similar processing sequence are grouped together into product families. Then based on product families, cells are formed in such a manner that each cell can process at least one family of products. In other words, cellular manufacturing is a production system that provides benefits of flow-shop production systems while retaining the flexibility of job-shop production systems (Beaulieu *et al.*, 1997; Irizarry *et al.*, 2001; Soleymanpour *et al.*, 2002). This helps in handling variety to some extent by entailing the processing of similar parts by grouping the dedicated machines arranged in close proximity (Beaulieu *et al.*, 1997; Irizarry *et al.*, 2001; Soleymanpour *et al.*, 2002).

Mass customization, comparatively, demands for more flexible manufacturing systems. Figure 1-1 above, indicates the position of a manufacturing strategy capable of meeting mass customization manufacturing environment requirements more effectively and efficiently. As shown, there is a need of a manufacturing system that provides better flexibility and efficiency than traditional manufacturing cells.

Many methods for designing manufacturing cells to meet high-variety, low-volume manufacturing system environment have been proposed and discussed in the literature over the period of time. This includes traditional, virtual, dynamic, linked, and network cells. However, none of these have been explored in depth for their applicability to mass customization.

1.5 Introduction to Minicells

As explained in the previous section, traditional cells are not able to meet the mass customization requirements effectively. Hence, there is a need of manufacturing system that can allow better flexibility than the traditional cells. A typical traditional cell consists of product family and machines required to make the products in the product family. In 2005, Badurdeen came up with an alternative Method of designing small manufacturing cells, termed as “minicells”(Badurdeen, 2005).

Minicells for mass customization manufacturing are different from the cells used in traditional cellular manufacturing. Rather than dealing with products and machines, minicells deal with different options and machines needed for them. Figure 1-2 shows the traditional and mass customization product structures.

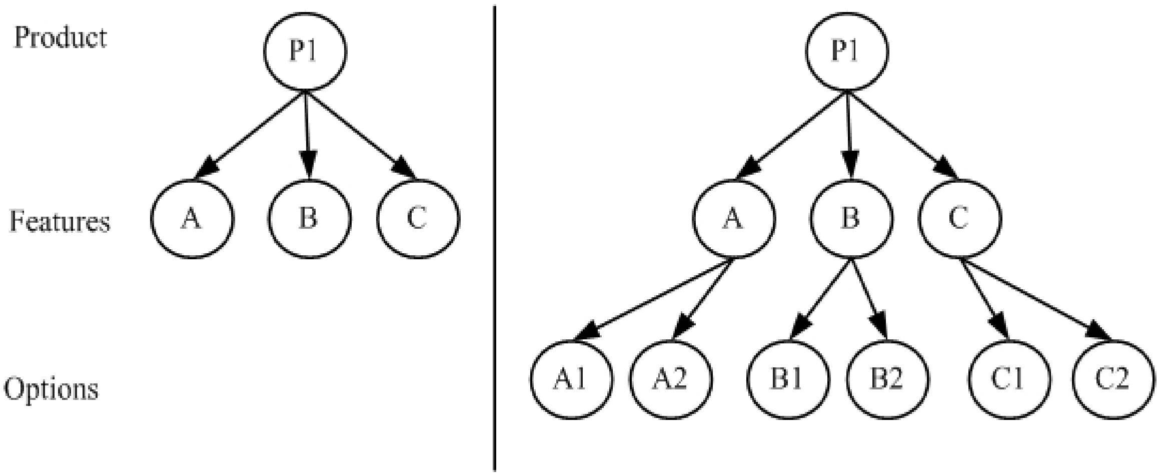


Figure 1-2: (a) Traditional and (b) Mass customization product structures (Badurdeen, 2005)

As shown in figure above, traditional product structures have products and features only, but in the present mass customization environment, large number of options is available for each customizable feature (Badurdeen *et al.*, 2007). It has been seen that many companies (e.g. Dell computers, Bally Engineered Structures, Airborne bicycles etc.) offer options-based customized products to the customers. Such type of customization is termed as "standardized customization" (Lampel *et al.*, 1996). Customer chooses one option for every customizable feature to get his/her own custom product.

Large number of product variants is possible in this way, thus providing high variety to customers. For example, if a product has 3 customizable features with feature 1 having 5 options, feature 2 with 10 options and feature 3 with 8 options, there can be 400 different product variants. If cells are designed considering product variants, then it would result in very large traditional cells. Large cells are difficult to manage and will result in longer lead times and high in-process inventory. Also, it is not advisable to have many cells because it can cause very high duplication of machines and require more space which will lead to high costs.

An alternative method is designing small cells based on options rather than product variants because of many benefits. First, options are less in number as compared to product variants. Secondly, the demand of options is likely to be less dynamic since it is sum of the demand of several product variants. This will lead to formation of small and simple minicells rather than complex cells that sometimes lead to chaos and make scheduling difficult. Such cells are termed as "minicells" and are dedicated to produce option families rather than product families.

Thus, Minicells can be defined as "*small manufacturing cells* which consist of one or multiple machines and are c*apable of processing options rather than features* either partially or fully". Generally, minicells are small in size and less complex than traditional cells in most of the cases but this can not be true in some cases depending on problem size. As discussed above, the concept of minicells was first introduced by Badurdeen (Badurdeen, 2005). In her research, Genetic algorithm (GA) based approach was used to design minicell configuration and it was concluded that minicells can work in a better way when compared to traditional cells in mass customization environment.

In 2007, Thuramalla used an alternative method to design minicell configuration. Two popular clustering algorithms, single linkage clustering (SLC) and average linkage clustering (ALC) were used to design minicell configuration. Similarity coefficients are calculated for each pair of parts or machines using "Jaccard similarity coefficient" and stored in a matrix which is further fed as input to ALC and SLC methods to identify part families or machine cells (Shafer, 1998). In SLC, two clusters get combined together based on the strongest link (max. similarity coefficient value) between them while in ALC; combination is based on the average value of similarity coefficients of all links between two clusters (Thuramalla, 2007).

1.6 Artificial Neural Networks

Artificial neural network (ANN) can be defined as “the interconnected group of artificial neurons that uses a mathematical model or computational model for information processing based on a connectionist method to computation” (http://en.wikipedia.org). Based on the information flowing through the network, ANN changes its structure and therefore is an adaptive system. Figure 1-3 shows a schematic representation of a simple generic ANN with three different layers: input layer, hidden and output layer. All these layers are made up of nodes. Nodes of the input layer accept input variables (independent variables) and their processing is done at the nodes in the hidden layers. An ANN can have a single or multiple hidden layers depending upon the complexity, size and nature of the problem to be solved. After being processed in the hidden layers, values are presented as output at one or more output nodes (dependent variables).

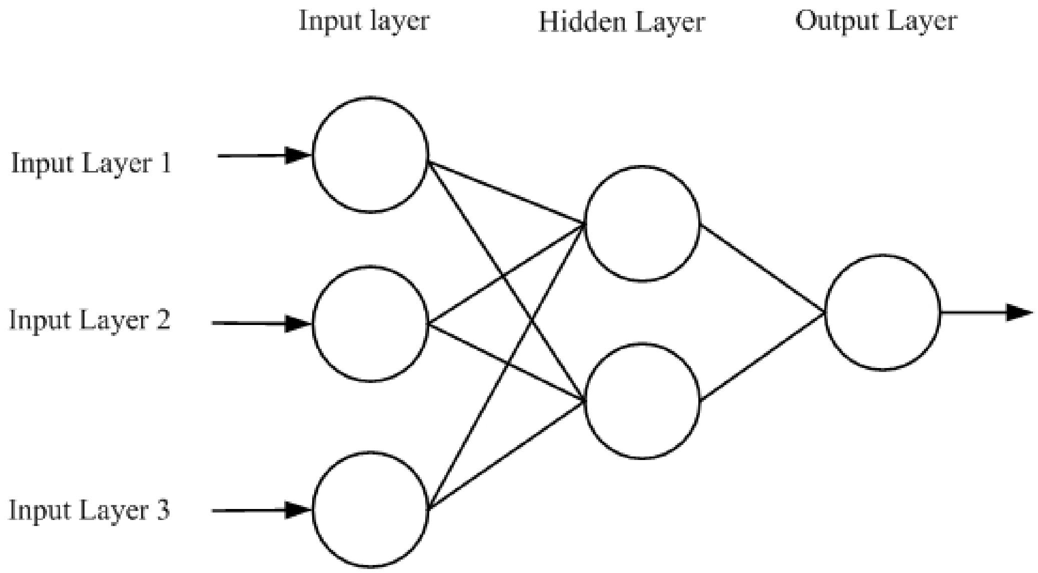


Figure 1-3: Schematic representation of Artificial Neural Network

ANN is very versatile tool applied in various fields such as archaeology, banking , credit card company, defense, engineering, environmental, finance & securities, manufacturing, marketing etc (http://www.palisade.com/neuraltools).

ANN is capable of solving different problems such as function approximation, clustering, prediction and classification problems. ANN learns in two different ways based on the problem that needs to be solved. The two learning modes in ANN are supervised learning and unsupervised learning. Supervised learning needs some initial data for the training and testing of the network. ANN learns from pre-existed data and then generates output for the new inputs. On the other hand, no initial data is required for unsupervised learning. Here network weights are modified according to some pre-specified rules of interaction. Clustering in neural networks is an example of unsupervised learning. When designing minicells, no data is available beforehand and therefore unsupervised learning in ANN can be used as one of the potential methods to design minicell configuration in mass customized environment.

1.7 Objectives

As discussed, minicell design for the mass customization manufacturing environment is an attempt made to blend the benefits of cellular manufacturing as well as job shop into it. As shown in figure 1, this kind of manufacturing system can be more suitable to mass customized environment when compared to either job shop or traditional cellular manufacturing system.

Minicells are a new concept. ANN has not been used to design modular cells. However, ANN techniques have previously been applied to from traditional cells. Therefore, there is a potential to extend ANN approach to form minicells. The objective of this research is to "design minicell configuration for mass customization environment using artificial neural networks". The primary aim is to analyze if ANN can provide comparative results to other techniques such as genetic algorithm and statistical clustering analysis that have already been used. To compare the results of different techniques, it is very important to design minicells using previously developed methods. Two methods have been developed so far (Badurdeen, 2005). Hence, the first objective is to design minicells following those two methods using ANN.

The second objective is to develop a new methodology which can provide better results in less time when compared to older methods. With this aim in mind, a new method which is a modified version of one of the previous methods is developed and is tested with four varied size test problems to compare the results with older ones.

Machine count and other time based performance measures have been considered in previous research for minicell design. However the amount of material handling involved/required with minicells configurations has not been investigated. Present study also fills that void by calculating amount of material handling required to process all product variants for every minicell configuration design developed for all problems. Therefore, this research will use the machine-count and amount of material handling as the performance measures to evaluate alternate minicell designs. Thus, the third and final objective of the present study is to develop some rules and a material handling calculator that can help in calculating material handling of all possible minicell configurations designed to find the optimal method based on the objectives and problem to be solved.

1.8 Thesis Outline

Following chapters will discuss in detail about the background and literature review related to the present research (chapter 2), methodology (chapter 3), results and discussion (chapter 4) and future work (chapter 5).

2 Literature Review

In this chapter, the literature related to current research is discussed. Section 2.1 gives a brief overview of mass customization (definitions and different models) followed by section 2.2 discussing about various existing manufacturing strategies for mass customization along with the limitations. In Section 2.3, the concept of minicells is discussed in detail. Section 2.4 gives benefits of cellular manufacturing. Section 2.5 then discusses the various cell formation techniques and related literature followed by Section 2.6 giving the brief description on artificial intelligence techniques and the history, applications and versatility of artificial neural networks (ANN). Finally, Section 2.7 reviews the application of ANN in cellular manufacturing, the meta-heuristics approach used in the current research for designing minicell configuration for mass customization.

2.1 Mass Customization

As indicated in chapter 1, the term “Mass Customization” anticipated by Toffler, Alvin (1970) was actually coined by a business consultant Davis, Stanley in his book “Future Perfect” in 1987 (Toffler, 1970; Davis, 1987). Consumers are no longer a homogeneous mass and due to this turbulence in the market, America who was dominating the business competition for the most of the 20th century through the system of mass production has begun to loose its market share in the late nineties (Pine, 1993). Since then, mass customization is seen as the most relevant way to meet the customer demand for individualized products.

The term “Mass Customization” has been defined in many different ways. According to Pine, “Mass customization is a new way of viewing business competition, one that makes the identification and fulfillment of the wants and needs of individual customers paramount without sacrificing efficiency, effectiveness, and low costs”. In simple words one can define mass customization as “to provide every customer with a product that matches his or her unique specifications” (Eastwood, 1996).

In 2001, Tseng and Jiao defined mass customization as “the technologies and systems to deliver goods and services that meet individual customers’ needs with near mass production efficiency” (Tseng *et al.*, 2001).

Many different definitions are stated by different authors in different ways and the literature so far has not established good conceptual boundaries for mass customization. Recently, Piller proposed a definition of mass customization to have a common understanding of this term. According to him, mass customization is “Customer co-design process of products and services, which meet the needs of each individual customer with regard to certain product features. All operations are performed within a fixed solution space, characterized by stable but still flexible and responsive processes. As a result, the costs associated with customization allow for a price level that does not imply a switch in an upper market segment” (Piller, 2004).

In the definition, customer co-design means involvement of the customer at the design stage. Various possible stages are possible at manufacturers end depending upon the level of involvement manufacturer can afford and offer to customer.

2.1.1 Customer Involvement Levels

Customization can be offered to the customer at different levels along the value chain. Many authors have worked extensively in this area and came up with their own different frameworks.

Pine suggests five stages termed as customized services, embedded customization, point-of-delivery customization, providing quick response and modular production as shown in Figure 2-1. Customized services stage can be defined as the level at which marketing and delivery department tailors the standard product before delivering it to customers, embedded customization is same as adaptive customization where customers are given choice to alter the products during use. Some extra work is done at the point of sale according to the needs of the customer in point-of-delivery customization, quick response customization is capable of very fast delivery of products to customers and modular production gives the privilege to configure standard products in a large variety of products (Pine, 1993; Da Silveira *et al.*, 2001).

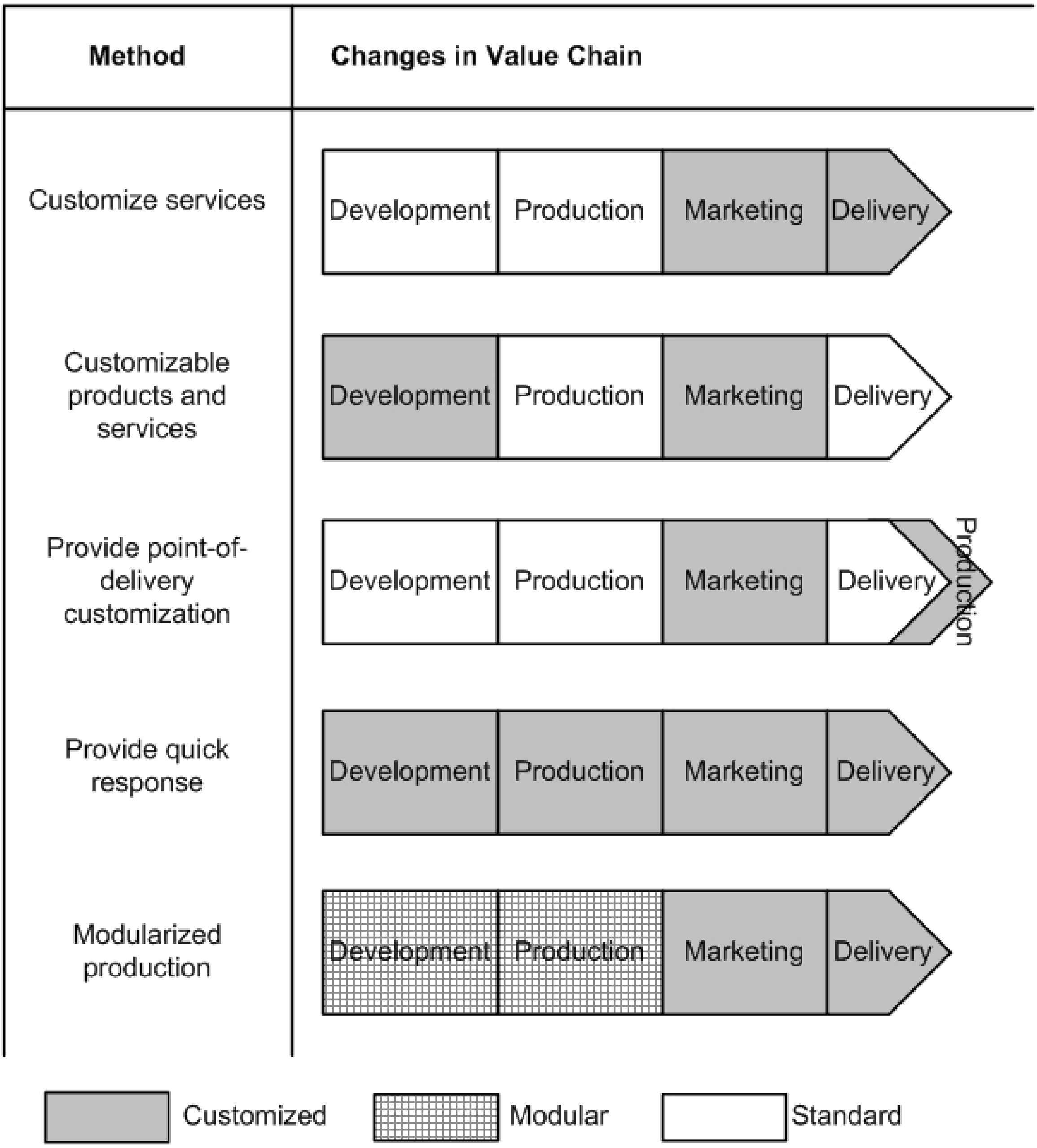


Figure 2-1: Customer Involvement Levels (Pine, 1993)

Lampel and Mintzberg, on the other hand also gave five levels of mass customization strategies shown in Figure 2-2 below involving different configurations of process: Pure standardization, segmented standardization, customized standardization, tailored and pure customization (Lampel *et al.*, 1996; Badurdeen, 2005).

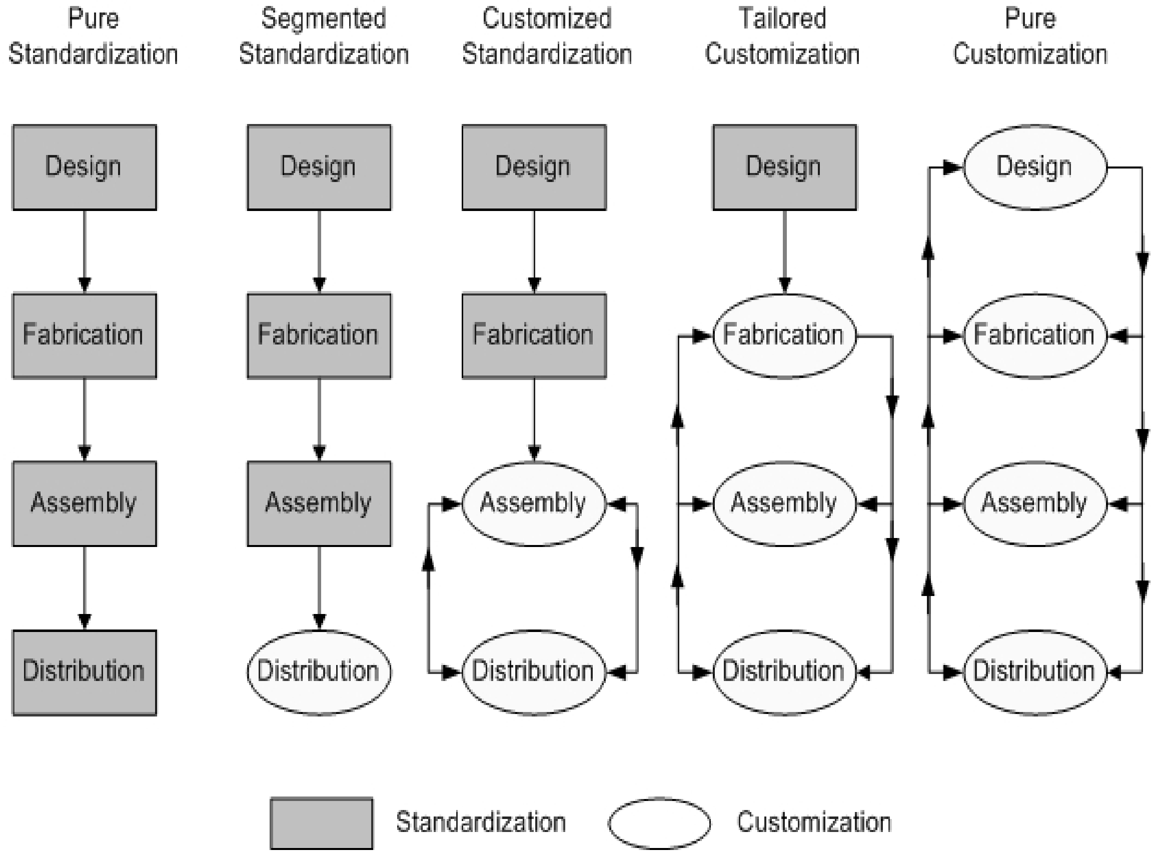
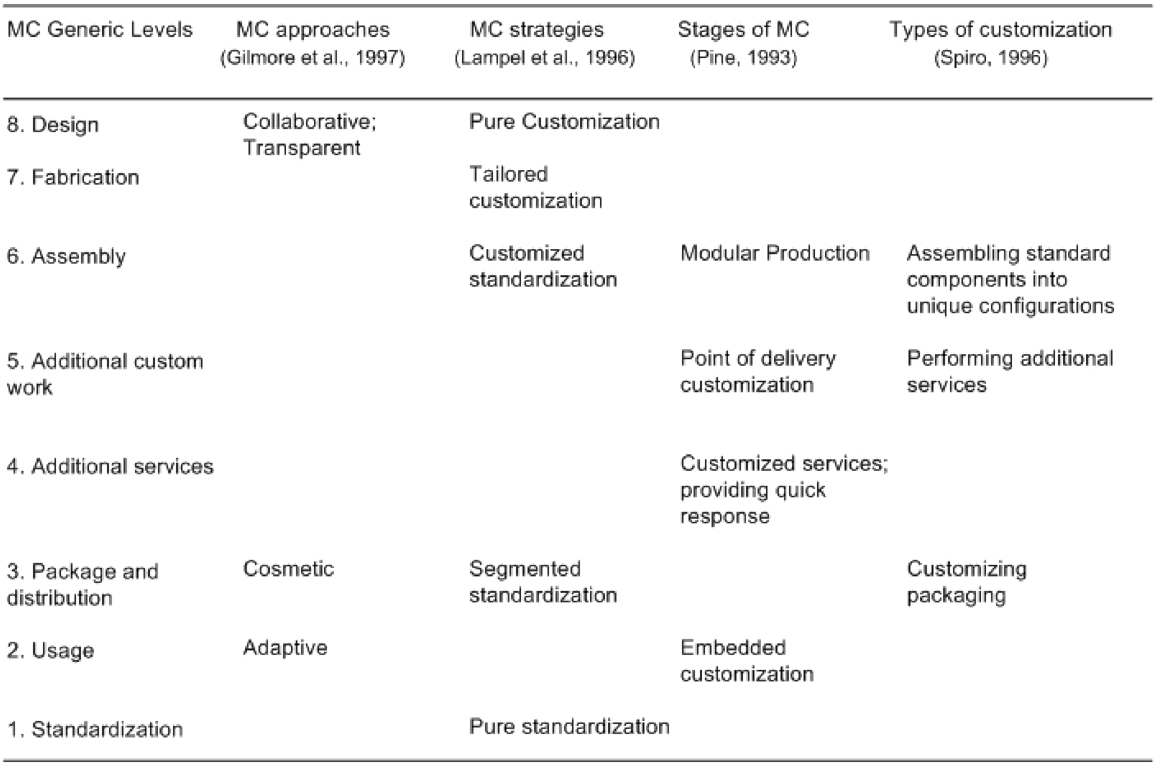


Figure 2-2: Continuum of Strategies (Lampel *et al.*, 1996)

Based on Gilmore and Pine studies, there can be four different levels of customization. First level is where designers have a dialogue with customers to understand what exactly customer is looking for in the product he/she is going to buy. This level of customization was termed as “Collaborative”. If customers are given choice to alter the products during use, then that level of customization was termed as “Adaptive”. Another level of customization is to pack the products especially for each customer and was termed as “cosmetic” and the fourth level is if products are adapted to individual needs with the terminology “transparent” given to it (Gilmore *et al.*, 1997; Da Silveira *et al.*, 2001).

Based on the levels of mass customization given by Pine and Gilmore, Pine, Lampel and Mintzberg and Spira (Spira, 1996), a table indicating generic levels of mass customization is developed (Da Silveira *et al.*, 2001)and is shown below in Figure 2-3.



MC Generic Levels	MC approaches (Gilmore et al., 1997)	MC strategies (Lampel et al., 1996)	Stages of MC (Pine, 1993)	Types of customization (Spiro, 1996)
8. Design	Collaborative; Transparent	Pure Customization		
7. Fabrication		Tailored customization		
6. Assembly		Customized standardization	Modular Production	Assembling standard components into unique configurations
5. Additional custom work			Point of delivery customization	Performing additional services
4. Additional services			Customized services; providing quick response	
3. Package and distribution	Cosmetic	Segmented standardization		Customizing packaging
2. Usage	Adaptive		Embedded customization	
1. Standardization		Pure standardization		

Figure 2-3: Generic Levels of Mass Customization (Da Silveira *et al.*, 2001)

2.2 Mass Customization Manufacturing Systems

Traditionally, manufacturing was done with the primary aim of producing standardized products in high volume and at low cost and these standard products were always instantaneously available to customers as manufacturers can produce these products well in advance and store them in inventory. Low volume, high mix operations on the other hand used to charge extra premium prices for the extra effort and customer has to wait for sometime before the customized product was actually delivered to him/her.

2.2.1 Mass Customization Manufacturing Systems Requirements

Mass customization no longer provides that categorization and now customers want the best of the best. They want to get the unique products at the same cost they were paying for standard products and demand instant deliveries (Eastwood, 1996). Failure to do so, results in loosing market share in today's highly competitive world. Customization has now got individualized. That is, it is being done on a lot size of one instead of on the market segments of the past. This builds up the pile of challenges manufacturing industries are facing nowadays. Listed below are the challenges that manufacturing industries are facing and striving for.

- High product mix (Irizarry *et al.*, 2001)
- Low cost (Wemmerlov *et al.*, 2000)
- Instant deliveries (Irizarry *et al.*, 2001)
- Competitive business (Pine, 1993)
- Customer involvement (Individualization) (Pine, 1993; Lampel *et al.*, 1996)
- Shrinking product life cycles (Irizarry *et al.*, 2001)
- Increase in customer expectations (Irizarry *et al.*, 2001)

This leads to the need of developing a manufacturing strategy that is capable of meeting the requirements of mass customization environment. Over a period of time, many different manufacturing strategies like JIT, lean manufacturing, agile manufacturing and cellular manufacturing are proposed and implemented in various industries. A brief overview of all these practices is given below.

2.2.2 Lean Manufacturing

Lean manufacturing is one of the manufacturing strategies that can help in reducing the lead time by eliminating the wastes like overproduction, over processing, extra material handling, extra movement etc. and applying the principles like Just in time (JIT) and single minute exchange of dies (SMED). Lean manufacturing was introduced in the book "The Machine that Changed the World" (Womack *et al.*, 1990). The authors of the book brought into light the reasons why Japanese automobile manufactures are growing and attaining success at a faster pace than American and European manufactures. Lean manufacturing implements "Pull" rather than "Push system".

Lean manufacturing can be applied to any of the manufacturing strategies to make the system work better. But for a system demanding very high variety, lean itself is not suffice and has to be implemented in conjunction with other manufacturing systems to yield positive results.

2.2.3 Agile Manufacturing

One such manufacturing strategy is agile manufacturing that uses lean and JIT to quickly respond to changes. Agile manufacturing is "the ability to thrive and prosper in an environment of constant and unpredictable change to respond quickly to rapidly changing markets driven by customer based valuing of products (Maskell, 1996; Da Silveira *et al.*, 2001).

The difference between the agile manufacturing and flexible manufacturing is that in agile manufacturing, changes are brought much before than actually required. On the other hand in flexible manufacturing, changes are brought after encountering the requirement of the change. Agile manufacturer has a proactive behavior (Gutman *et al.*, 1995). But for the system to attain agility, flexible and automated manufacturing systems are required (Gunasekaran *et al.*, 2002; Huang, 2002).

Agile manufacturing is more organized way of the existing practices and helps in achieving better responsiveness. However, again for mass customization, incorporating agile manufacturing is helpful but not sufficient (Pine, 1993).

2.2.4 Cellular Manufacturing

Group technology is defined as “philosophy that exploits the proximities among attributes of given objects or situations for the purpose of performing a given task” (Choobineh, 1988). Based on this idea, different parts can be identified as groups on similarity basis and can be treated as part families and to process these part families, small cells are formed where the machines required for the processing of part families are put in sequence to provide flow shop type of environment for respective part families. This type of manufacturing systems is known as cellular manufacturing.

Different types of cells like virtual cells (logical grouping of cells) (Vakharia *et al.*, 1999; Prince *et al.*, 2003), dynamic cells (where machines can be physically rearranged) (Rheault *et al.*, 1996), Linked cells (composed of manufacturing cells and assembly cells linked to each other through pull system for material and information) (Black *et al.*, 1993; Black, 2003), Holographic cells (Monteruil *et al.*, 1996), Fractal cells (Venkatadri *et al.*, 1997; Montreuil *et al.*, 1999)**,** etc. are developed so far.

These cells help in providing flexibility but have some drawbacks and limitations also. Virtual cells are not suitable for very high variety products as it will lead to increased material handling and also a lot of information and communication between the machines is required because of the virtual existence of cells (McAuley, 1972).

Dynamic cells are also not easily applicable in a mass customized environment. They are suitable only up to the extent where it is possible to have modified and reconfigured layouts and cells by moving small movable equipment (Rheault *et al.*, 1996) but for a level, where very high variety is required and it is not easy to move equipment frequently (because of high costs and time constraints involved), Dynamic cell fail to perform well (Badurdeen, 2005).

Linked cells on the other hand are useful and are recommended if parts that are to be manufactured have very similar processing needs which require less changeovers and setup times. Otherwise changeover and setup times make use of linked cells less appropriate. In a mass customized environment, unless the parts to be manufactured have very similar processing needs, linked cells are not advisable. Practical implementation of holographic cells is also not widely seen and fractal cells can raise the problems of high in-process inventory, long lead times etc (Badurdeen, 2005).

Different types of mass customization manufacturing systems are discussed above. All of these have their own importance and have been implemented accordingly in various industries according to the needs and desires. On the other hand, at the same time when manufacturers are cultivating some benefits from various existing systems, they are also looking forward for better cellular manufacturing systems that can overcome various limitations or drawbacks of the existing techniques in mass customized manufacturing environment. Therefore, the desire of developing and designing new types of cells that can act more efficiently and effectively in mass customized environment has always remained a hot research topic for researchers.

2.3 Minicells

Recently, the challenges posed by highly mass customized environment led to an idea of minicells formation. Badurdeen, in her research work, came up with this idea of minicells in 2005. Minicells, when compared to traditional manufacturing cells, can provide better results and flexibility.

Empirical studies reveal that majority of the companies who offer customized products practice standardized customization. Examples are Dell computers, Bally engineered structures, Airborne bicycles and NBIC. In standardized Customization, Customers are given flexibility to choose from various options provided by the manufacturer for each product feature. For example, in computers industry, customers are allowed to choose the various options available for hard drives (60, 80, 100 GB), processors, mouse, keyboards etc. The reason why standardized customization is so common is because there are many options that are common to various product variants and due to this, demand for options is less fragmented than the product variants (Badurdeen, 2005). This led to the idea of creating cells by considering options rather than product variants (traditional cells) and are termed as "minicells"

Hence, Minicells can be defined as "small manufacturing cells, dedicated to produce option-families rather than product variants either partially or fully". Minicells are organized in a multi-stage configuration for mass customized manufacturing and provide more flexibility when compared to traditional cells. Figure 2-4 below explains the functional behavior of traditional cells and minicells.

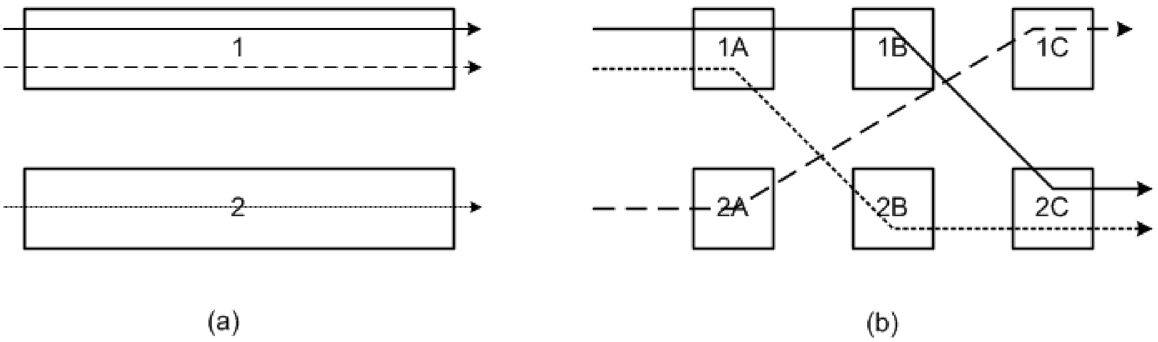


Figure 2-4: Functional behavior of (a) Traditional Cells (b) Minicells

(Badurdeen, 2005)

According to Badurdeen, "Each minicell is a grouping of machines and operators required to process a sub-set of operations for an option family". Table 2-1 describes the few differences between traditional cells and minicells.

Table 2-1: Differences between Traditional Cells and Minicells

Traditional Cells	Minicells
1. Product-machine matrix based	1. Option-machine matrix based
2. Less flexibility	2. More flexibility
3. Alternative routing rarely available	3. Alternative routing is a common practice
4. Larger in size	4. Smaller in comparison
5. Single-staged	5. Multi-staged

Two different methods have been developed to design minicell configuration. Though idea behind both methods is different, the initial step remains the same. Both methods use data in the form of option-machine matrix. Table 2-2 gives an example of option-machine matrix.

Table 2-2: Option-Machine Matrix

	Options/Machines	**M1**	**M2**	**M3**	**M4**
Feature 1	**Option 11**	**1**	**1**	**0**	**0**
	Option 12	**0**	**0**	**1**	**1**
Feature2	**Option 13**	**1**	**1**	**0**	**0**
	Option 14	**1**	**0**	**1**	**0**
Feature 3	**Option 15**	**1**	**0**	**1**	**0**

In Method A, stages were formed by dividing the matrix vertically (machine-wise) as opposed to Method B, where stages are formed by dividing the matrix horizontally based on the number of features (Badurdeen, 2005).

In Method A, minicells are designed in such a way that each option goes to multiple stages for its complete processing. Each option may or may not get fully processed in single minicells. Most of the time, It has to go through one minicell in each stage. In other words, minicells do not contain all the machines required for the complete processing of options. All options get partially processed in every stage and move to next stage and so on until they get fully processed. Also this method does not allow options to go to more than one minicell in the same stage. Figure 2-5 shows the schematic representation of minicells created using this method.

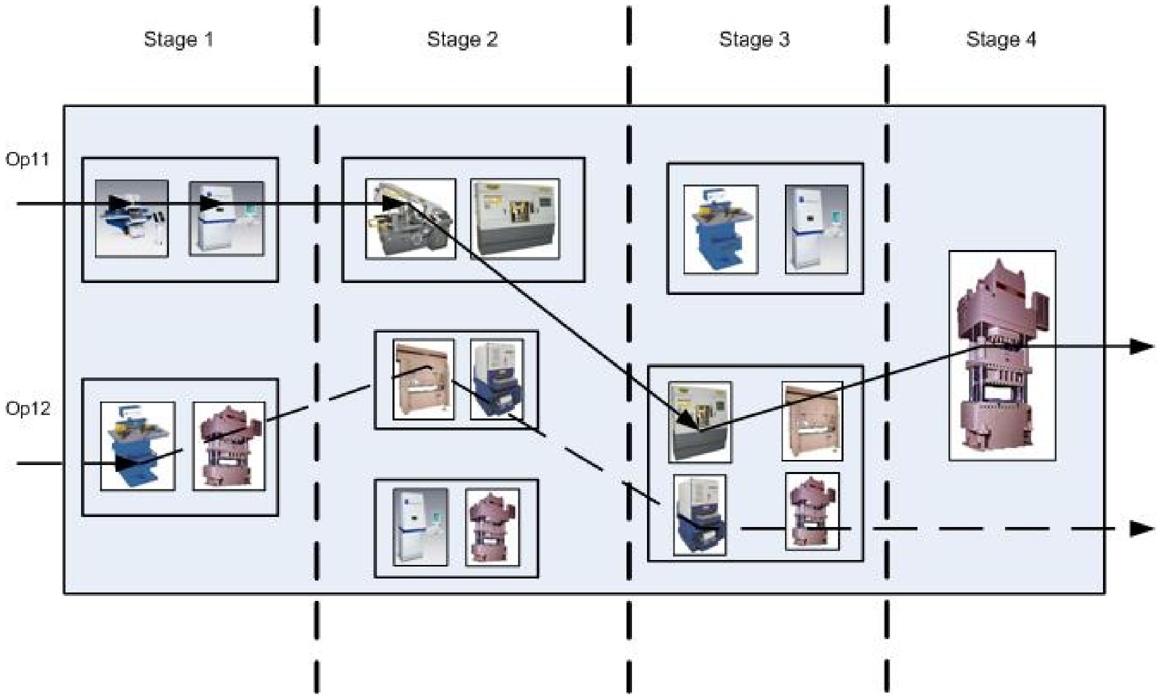


Figure 2-5: Minicell configuration generated with Method A

In Method B, options are not allowed to go to multiple minicells or multiple stages. Each option is assigned to a particular minicell in one of the stages and it has to get processed within that minicell. Minicells are designed in such a way that they consist of all machines required for the complete processing of options allotted to them. Compared to Method A, this method divides the option-machine matrix into stages based on features rather than machines (Method A).

In this method, every feature itself can be treated as separate stage or one can combine multiple features and their options and treat them as single stage. Hence, there can be n, n-1; n-2….2 stages possible when “n” is the number of customizable features. For example, if a product has three customizable features F1, F2 and F3 then one have 3 or 2 stages. 3 Stages: Each feature is a stage (F1, F2, and F3), 2 Stages: Combining two features in one stage and third feature as another stage (F1& F2, F3), (F1 & F3, F2) and (F2 & F3, F1).

Figure 2-6 indicates the type of minicell configuration generated using this method. In this figure, each feature is taken as one stage, therefore, for a product variant having all three customizable features, options get processed in their respective stages depending upon the features they belong to.

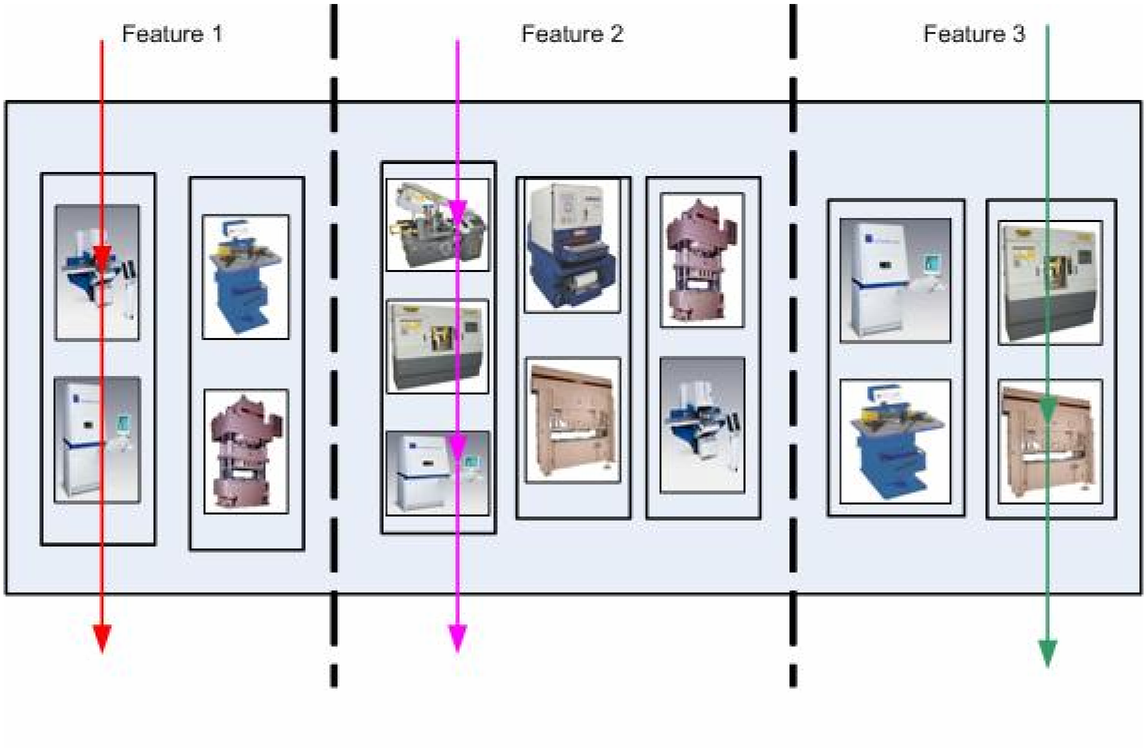


Figure 2-6: Minicell configuration generated with Method B

Badurdeen used Genetic-algorithm based method to design minicells with two objectives 1) minimizing machine count and 2) makespan. A large solution space of thousands of possible designs were developed based on the population size and number of generations. All these designs were then followed by scheduling of jobs, makespan and machine count calculations. Then, based on weights assigned to objectives, weighted objective is calculated for each design (Badurdeen, 2005). As, this method has multiple objectives, so there is a possibility that best minicell design could not get selected from a solution space.

To overcome the issue stated above, an alternate approach to this was established (Thuramalla, 2007). In this method, an attempt was made to identify best minicell designs without having to go through the time consuming process of developing a metaheuristic model (Thuramalla, 2007). Minicells with minimum machine count were first identified in design stage, followed by scheduling of jobs to selected minicells (identified from design stage) to determine average minimum flow time. The results achieved were then analyzed to select the best minicell design based on the desired objective. Statistical cluster analysis technique based similarity coefficient method (using Jaccard similarity coefficient) was used for the minicells design.

2.4 Benefits of Cellular Manufacturing

Despite having differences, both traditional cells as well as minicells are a part of cellular manufacturing. Hence, it has been seen that cellular manufacturing has a great potential for mass customization manufacturing environment and therefore always has an upper edge than other manufacturing systems. Some of the benefits offered by cellular manufacturing are listed below (Wemmerlov *et al.*, 1997)**:**

- Reduced throughput time
- Reduced WIP inventory
- Improved part/product quality
- Less response time to customer orders
- Reduced move distances/move time
- Increased manufacturing flexibility
- Reduced unit cost
- Easier production, planning and control

- Better employee involvement
- Reduced set-up times
- Reduced finished good inventory

Because of the benefits listed above, a lot of research has been done in this field and many different methods/techniques are suggested to design manufacturing cells. Comprehensive reviews of cell formation strategies are available (King *et al.*, 1982; Selim *et al.*, 1998; Shafer, 1998). Following section discusses in brief about the various cell formation techniques.

2.5 Cell Formation Techniques

CF techniques are classified into different categories. Researchers classified CF methods into three (Ballakur, 1987), four (King *et al.*, 1982; Wemmerlov *et al.*, 1986) , five (Selim *et al.*, 1998), six and eight categories (Singh, 1992).

Selim et al. classified CF methods into descriptive procedures, cluster analysis, graph partitioning, artificial intelligence and mathematical programming. Descriptive procedures are further classified into part families' identification (PFI) (Barker, 1970; Purcheck, 1975; Askin *et al.*, 1991), machine groups' identification (MGI) and part families/machine grouping (PF/MG) (Burbidge, 1963; Burbidge, 1975). Figure given below indicates the classification given by Selim et al.

In part families' identification procedures, part families are first identified based on similarity basis and then cells are developed by incorporating the machines required for each part family. On the other hand, in machine group' identification, machines are grouped together instead of parts. When machines and parts are both used simultaneously for designing manufacturing cells, then that procedure is termed as part families/machine grouping.

The main objective of cluster tool analysis is to identify those parts into a cluster that have high natural association. Clustering procedures are also further subdivided into array-based clustering techniques, hierarchical clustering techniques and non-hierarchical clustering techniques.

In array-based clustering, binary incidence matrix is used to represent the processing requirements of the components on the machines. Many algorithms based on array-based clustering are known such as Bond energy analysis, Rank order clustering (King *et al.*, 1982), modified rank order clustering etc (Selim *et al.*, 1998). In hierarchical clustering, matrix does not get divided into cells in the first step. Firstly, it gets separated into broader cells, then finer and so on (divisive methods). Similarly, it can do it other way round, starting with the finer clusters; it keeps on fusing finer clusters (agglomerative method) thus forming clusters of parts having similar processing sequence using same machines. Non-hierarchical techniques are iterative methods and in these techniques one has to decide the number of clusters in advance (Chandrasekharan *et al.*, 1987; Srinivasan *et al.*, 1990; Selim *et al.*, 1998).

Treating machines as nodes or vertices and processing of parts as arcs connecting these nodes forms the basis of graph partitioning method (Selim *et al.*, 1998). Main aim is to obtain disconnected sub graphs from a machine-part graph to form manufacturing cells. In artificial intelligence, patter recognition, artificial neural networks (Kaparthi *et al.*, 1992) etc are used for designing cells and finally, mathematical programming methods include linear programming, linear and quadratic programming (Ballakur, 1985; Kumar *et al.*, 1986; Vakharia *et al.*, 1993) dynamic programming and goal programming (Selim *et al.*, 1998).

Shafer, in his review classified cell formation into six broad categories namely, manual techniques, Statistical Cluster analysis, Sorting Machine part matrix, Mathematical and Al techniques. Shafer came up with these categories by taking into consideration the work done by all other researchers earlier. Following Figure 2-7: Classification Framework of Cell Formation Techniques gives the taxonomy of cell formation techniques given by Shafer (Shafer, 1998). For detailed review, one can explore the sources mentioned above.

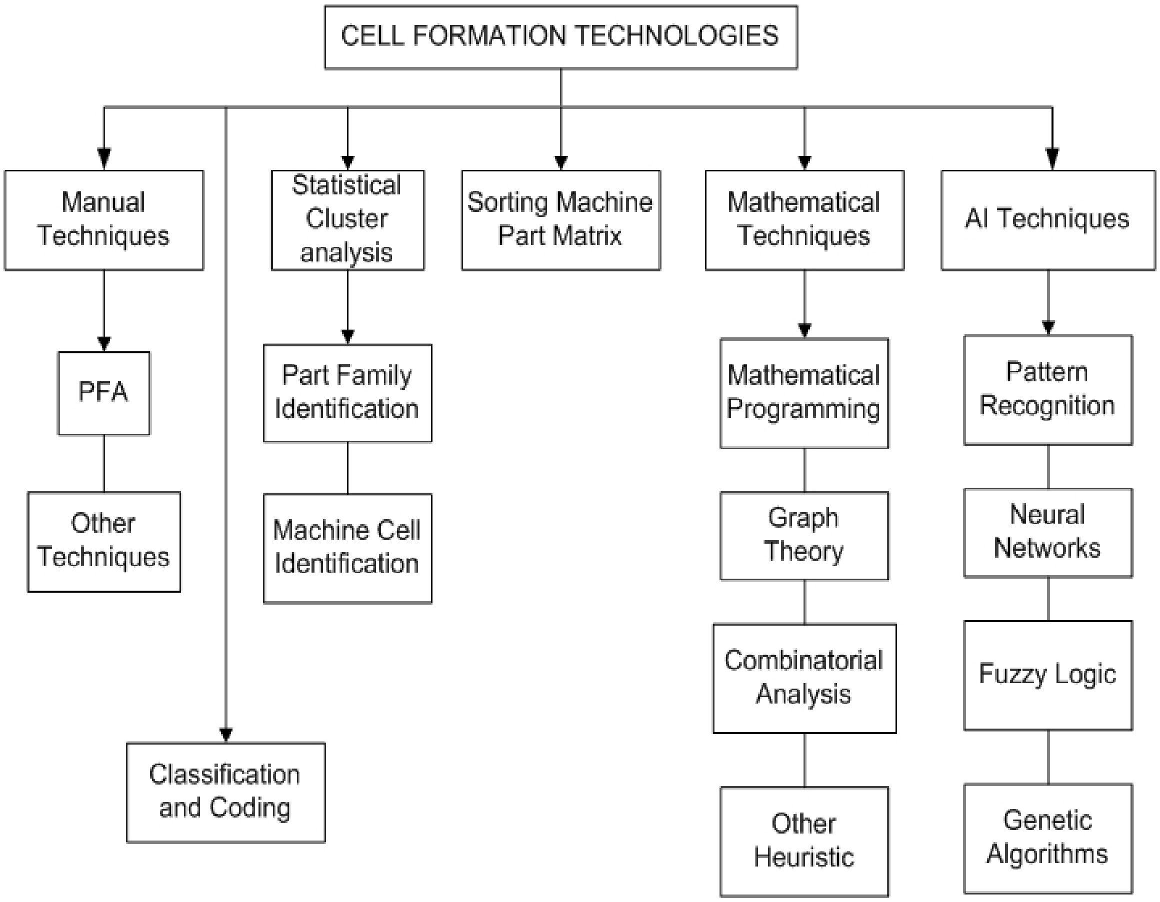


Figure 2-7: Classification Framework of Cell Formation Techniques
(Shafer, 1998)

Latest classifications of CF realized artificial neural networks, genetic algorithm, and fuzzy logic techniques of substantial importance and thus classified these techniques under a separate category named as "Artificial Intelligence" (Kaparthi *et al.*, 1992; Selim *et al.*, 1998; Shafer, 1998).

2.6 AI Techniques in Cellular Manufacturing

Besides various techniques such as manual techniques, statistical cluster analysis, mathematical techniques etc, artificial intelligence is also identified as a separate category for solving problems related to cellular manufacturing. The techniques that fall in this category are pattern recognition, neural networks, fuzzy logic, genetic algorithms and simulated annealing.

These techniques were introduced during 1990s to overcome the limitations of the conventional methods. In conventional methods, a given part or machine can be a part of one part-family or machine cell only. This limitation can be easily overcome by fuzzy models. Also, whenever a part or machine is introduced in the system, one has to redo the whole problem when using traditional methods but the non-conventional artificial intelligence techniques allow the new part or machine to enter the system without having the pain of redoing the problem. Neural networks have the ability to classify the new parts or machines to existing groups without considering the problem data set again (Venugopal, 1998).

Some other benefits of the neural networks over traditional approaches are listed below (Venugopal, 1998):

- Ability to learn complex patterns
- Ability to generalize the learned information faster
- Ability to work with incomplete information due to the parallelism present in neural networks.
- Ability to compute faster.

Genetic algorithms and simulated annealing follow natural phenomenon. These algorithms have ability to solve large problems which otherwise can give erroneous results due to local minima. “Simulated annealing” works on the principle of the process of cooling a physical system slowly in order to reach a state of globally minimum potential energy” (Venugopal *et al.*, 1992). The stochastic nature of the algorithm allows it to escape local minima, explore the state space and find optimal solutions.

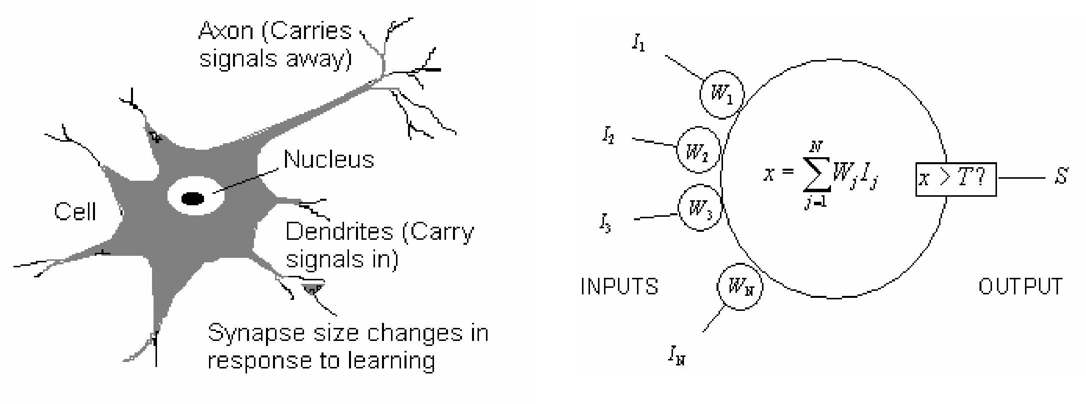
Genetic algorithm (GA) works on Darwin’s “survival of the fittest” strategy. They are capable of providing the optimal or near optimal solutions through mutation, cross-over, and selection operations (Suresh *et al.*, 1998).

2.6.1 Artificial Neural networks: An Overview

As described in Chapter 1, Artificial neural networks (ANN) “are parallel computational models comprised of densely interconnected adaptive processing units” (Hassoun, 1995). One of the best features that ANN has incorporated in it is the ability to “learn from examples” which replaces the “programming” needs in solving examples.

An artificial neural network is an attempt to simulate human brain. Human brain is comprised of ten to a hundred billion neurons. Artificial neural network is made up of artificial neurons similar to biological neurons but still a typical ANN is not likely to have more than 1000 artificial neurons (www.psych.utoronto.com). This field of ANN can go by different names such as connectionism, parallel distributed processing, neuro-computing, natural intelligent systems, machine learning algorithms, and artificial neural networks (http://www.makhfi.com/tutorial/introduction.htm).

Figure 2-8 explains clearly how the structure of the artificial neuron resembles biological neuron. Biological neuron has multiple dendrites that carry signal in and then one axon that carries signals away after inputs gets processed in the nucleus of the neuron. Similarly in an artificial neuron, there are multiple inputs that are attached with weights. All these inputs are processed in the nucleus and get transformed into single output.



Biological Neuron **Artificial Neuron**

Figure 2-8: Structures of biological neuron and artificial neuron

(http://ulcar.uml.edu; NIBS Pte Ltd)

McCulloch and Pitts introduced the first neural network computing model in early 1940's. Then in 1950's, Rosenblatt worked on neural network and developed two layered neural network called perceptron. This perceptron was capable of learning certain classification by adjusting connection weights. Initially this perceptron was successful in solving some of the problems but later on it was not able to solve XOR problem. Such limitations resulted in decline of neural network field. In 1980's, once again researchers showed great interest in ANN and since then, ANN has grown into a very vast field with lots of new additions such as Hopfield nets, competitive learning models and multilayer networks, self organizing maps and artificial resonance theory models.

2.6.2 Applications of artificial neural networks (ANN)

ANNs are used across a wide variety of industrial segments. Their versatility in solving different type of problems led almost every field to implement ANNs. Few examples of industries using ANNs and some of their applications are tabulated below in Table 2-3.

Table 2-3: Application of ANN in various fields

(http://www.palisade.com/neuraltools)

	Sample Application
Archaeology	Bone and artifact identification and dating
Banking	Loan underwriting, credit scoring
Credit Cards	Detection of fraudulent transactions
Defense	Target identification
Engineering	Structural fault detection
Environmental	Prediction of air and sea currents, air and water quality
Finance & Securities	Investment prediction, currency fluctuation
Flavors & fragrances	Beer& wine flavor prediction
Home and Security	Identification of potential terrorists
Insurance/reinsurance	Policy underwriting, loss reserves elimination
Manufacturing	Quality control, six sigma etc.
Marketing	Methods and campaigns, accurately measure targets
Medicine	Tumor and tissue diagnosis, heart attack diagnosis
Oil/Gas/Energy	Coal plant ash analysis, energy price prediction, oil reserves estimation
Pharmaceuticals	New drug effectiveness
Psychology	Criminal and psychotic behavior prediction
Real Estate	Real estate appraisal
Scientific research	Specimen identification, protein sequencing
Telecommunications	Network fault line detection
Transportation	Highway maintenance
Utilities	Power grid fault detection

Applications tabulated above are just few examples where ANNs are already in use and have provided very reliable results. Basically, ANNs are capable of solving four different categories of problems and most of the problems can come under one of these categories in way or the other. These four categories are: (a) Classification (b) Prediction (c) Function approximation and (d) Clustering.

Clustering problems are the problems where it is desired to extract information from the input data without the knowledge of desired output beforehand. An example is to cluster the people into groups based on their eating habits or buying habits or may be living styles etc. The basic difference between clustering problems and others is there is no desired output and because of this one cannot have an error and cannot train the network using back propagation. Such type of learning is termed as unsupervised learning.

2.7 ANN in Cellular Manufacturing

Wide range of neural network models is available for cellular manufacturing problems. In general, there are three types of neural network models namely, feedforward networks. feedback networks and competitive learning networks (Yang *et al.*, 2007). Many of the networks can be classified into these there general categories e.g., Multilayer perceptron fall into the category of feedforward networks, Hopfield network is feedback network and self-organizing map (SOM) and adaptive resonance theory (ART1) are categorized under competitive learning (Yang *et al.*, 2007).

Most of the Neural networks that are used for forming cells use unsupervised form of learning due to the fact that supervised learning always require some knowledge about the clusters that will be formed and a set of training data containing input elements with a known correct output value (El-Kebbe *et al.*) .This type of information is not available for cellular formation problems and therefore, a normal practice is to use unsupervised form of learning.

1n 1991, An attempt was made to use supervised learning for grouping similar parts into families and a three-layer forward network was proposed (Kao *et al.*, 1991). Some parts were arbitrarily selected to be the representatives of the part families and the network was trained using this data. All the remaining parts were classified by the network to belong to one of these part families. This method never yielded good results as the task of selecting the seed parts is left to human interaction and also a newly introduced part if cannot be assigned to existing part families causes the network to create a new part family and start the whole training process again (El-Kebbe *et al.*).

Adaptive resonance theory (ART), based on unsupervised learning, is widely used for machine and/or parts grouping problems. ART seeks to classify parts automatically and use output layer neurons directly to represent part families. It includes ART 1 (Carpenter *et al.*, 1988) ART 2 (Carpenter *et al.*, 1987) and fuzzy ART (Carpenter *et al.*, 1991; Suresh *et al.*, 1994; Peker *et al.*, 2004). ART 1 can handle only binary inputs patterns but ART 2 and Fuzzy Art can handle both binary as well as analogue. Some of the advantages of ART networks are fast computation and ability to handle large scale industrial problems. The disadvantage is that the grouping solution is highly dependent on the initial disposition of the machine-part incidence matrix.

Based on some similarity measure, ART neural networks use a threshold vigilance parameter that ensures that similarity between the parts within a part family is not less than threshold value assigned. Recently, a modified ART 1 algorithm (Yang *et al.*, 2007) has been developed and now, the vigilance parameter can be simply estimated by the data so that it is more efficient and reliable as compared to the Dagli and Hugahalli's method for selecting a vigilance value (Dagli *et al.*, 1995) and it is concluded that modified ART1 can yield better results when compared with the results of the former.

Graphical neural network (GNN) method is another approach used for cell formation (Mahadavi *et al.*, 2001). In this approach, the machine-machine matrix is used as compared to part-machine matrix and it is concluded that in GNN, because the initial machine-machine matrix keeps on reducing as one proceeds with the problem, it is fast and more reliable in presence of bottleneck machines and bottleneck parts.

One more approach other than ART, ART 1, ART II, fuzzy ART, is self-organizing neural network. Self-organizing maps have been used successfully for cell formation problems (Jang *et al.*, 1997; Guerrero, 2002; Venkumar *et al.*, 2006)**.** Results also show that SOFM have capability to solve any size problems with less computational times. Minicells as discussed above have never been designed so far using Self-organizing neural networks. Therefore, present research focuses on designing minicells using self-organizing neural networks. Neuro-solutions, an ANN based software has been used throughout the research for developing SONN models used for designing minicells. Chapter 3 discusses in detail about the methodology developed to design minicells using SONN model.

3 Methodology

This chapter focuses on the methodology used for designing minicells using self-organizing neural networks (SONN). To test the capabilities of SONN, three different methods were used. Two of these methods (Method A and B) are taken from previous research work (Badurdeen, 2005) and third (Method C) is developed by modifying the second method with an objective to get better results. A detailed explanation of all three methods is presented with an example, followed by a brief description of two performance measures: machine-count and material handling, used in the present research to analyze the results.

3.1 Framework

The first objective of this research is to design minicells using artificial neural networks. Neuro-solutions (NS) software based on artificial neural networks is used throughout this research to develop neural network models for designing minicells. NS is powerful software, capable of solving problems such as function approximation, classification, prediction and clustering problems. Since, minicell designs are based on combining similar options together; it can be categorized as a clustering problem for ANN. For such problems, Self-organizing neural network (SONN) models can be developed using NS and are used for designing minicells configurations in the present study.

Along with the objective of using ANN for designing minicells, two other objectives of the present research are to develop a new method for designing minicells and to use material handling as one of the performance measures for analyzing the results. Figure 3-1 provides the framework of the methodology followed.

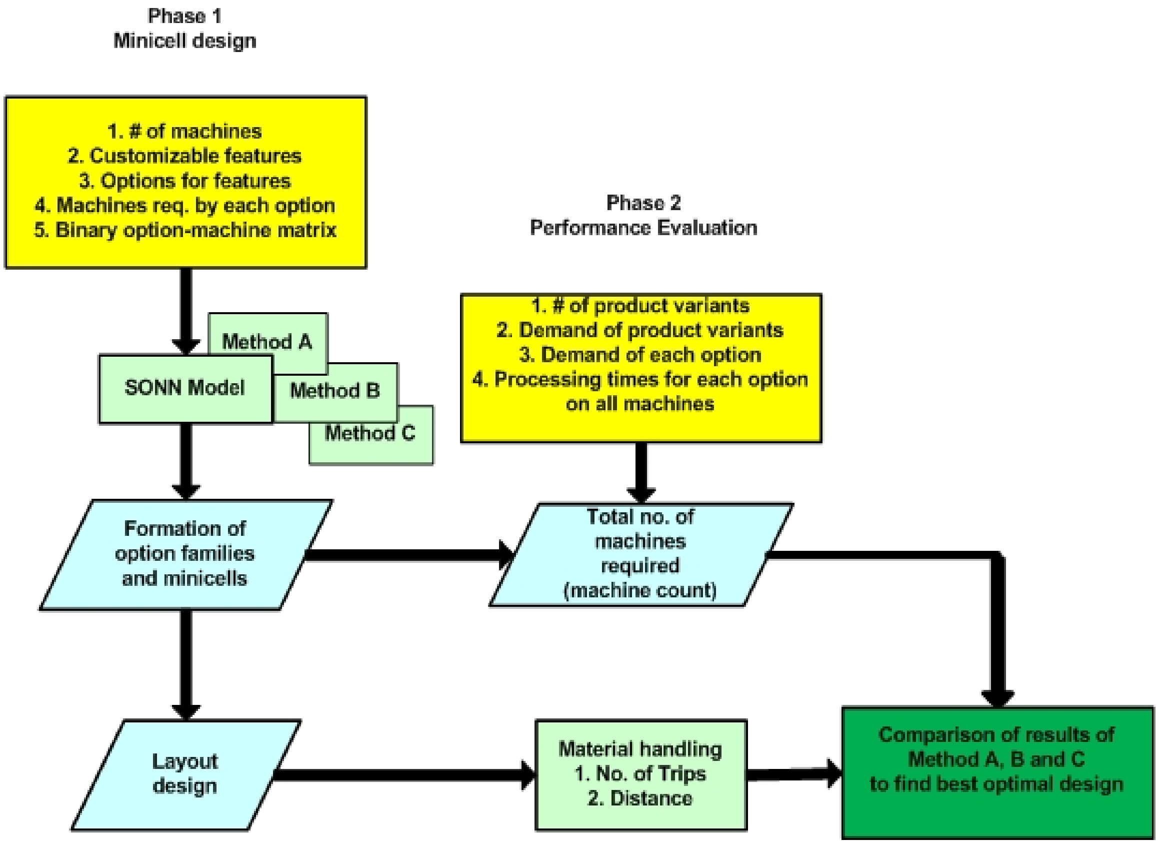


Figure 3-1: Framework of Methodology to design Minicells using ANN

The first phase of the research is the design phase where minicells are designed following two previous methods (Method A and B) (Badurdeen, 2005) and one newly developed method (Method C) using ANN. Second phase is the testing phase where minicells designed by different methods are analyzed and compared based on machine-count and material handling. Both phases are described in detail in the subsequent sections. A comparison of the three methods is tabulated in the Table 3-1.

Table 3-1: Comparison between Minicell Design Methods A, B and C

	Method		
	A	B	C
Stage Formation	User-defined	Feature-based	Clustering-based
Division/Cut-offs	Machine-based	Feature-based	Options-based
Minicells	Shared	Dedicated	Dedicated
Size of Minicells	Small	Large	Large
Option Routing	Inter-stage minicells	Intra-minicell	Intra-minicell
Preferred Material- Handling	Kitting	Individual	Individual/Kitting

3.2 Phase I: Minicell Design Approach

3.2.1 Minicell Design using ANN

As shown in framework above, the information required to design minicells using any method is,

- Total number of machines
- Total number of features
- Number of customizable features
- Number of options/customizable feature
- Machines required/option in sequence
- Processing time of each option on each machine.

Based on this information, an option-machine matrix can be generated in a binary form. Table 3-2 gives an example of an option-machine matrix for a problem with 3 customizable features, and 2, 2 and 1 option for each of them, respectively. If an option uses a particular machine, then it is indicated as 1 or else 0. For example, Option 11 (feature1) uses M1 and M2 but it does not require M3 or M4 for its processing.

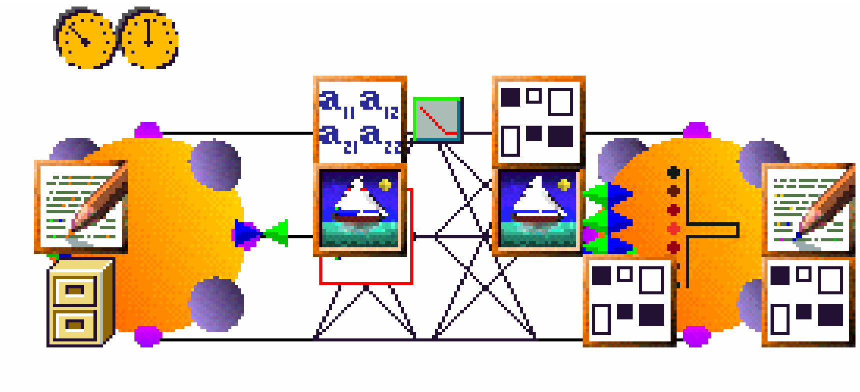
Table 3-2: Option Machine Matrix

	Options/Machines	M1	M2	M3	M4
Feature 1	**Option 11**	**1**	**1**	**0**	**0**
	Option 12	**0**	**0**	**1**	**1**
Feature2	**Option 13**	**1**	**1**	**0**	**0**
	Option 14	**1**	**0**	**1**	**0**
Feature 3	**Option 15**	**1**	**0**	**1**	**0**

The option-machine matrix is used as input to SONN model used for all methods to generate minicells. Following section describes in detail the SONN model used in this research.

3.2.2 Self-Organizing Neural Network (SONN)

There are various neural architectures available and the appropriate model must be chosen based on the problem to be solved. SONN follows unsupervised learning and is known for solving the problems of clustering. For designing minicells, there is no prior knowledge of the desired output therefore this problem cannot be solved by any of the neural architectures that use supervised learning to get trained. Also clustering is the basis to solve this problem and SONN is good at solving such problems. SONN is used whenever there is a need to project high dimensional data onto smaller dimension and to preserve neighborhoods at the same time. Therefore, in this research SONN models are used to design minicells. Figure 3-2 gives a screenshot of the SONN model in the NS software and a description of the icons represented.



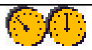
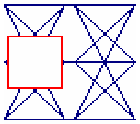
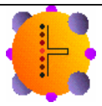
Icon							
Name	Axon	Static-Controller	File	Kohonen square	Winner-take-all	Datawriter	Matrix viewer

Figure 3-2: Description of the SONN model representation is NS software (NeuroSolutions 5)

As shown, in the Figure 3-2, the SONN model consists of various components which work in conjunction with each other to provide the desired results. The parameters of the network can be modified by changing the properties of these components.

Following steps are involved in running the simulation to develop a SONN model.

Step I

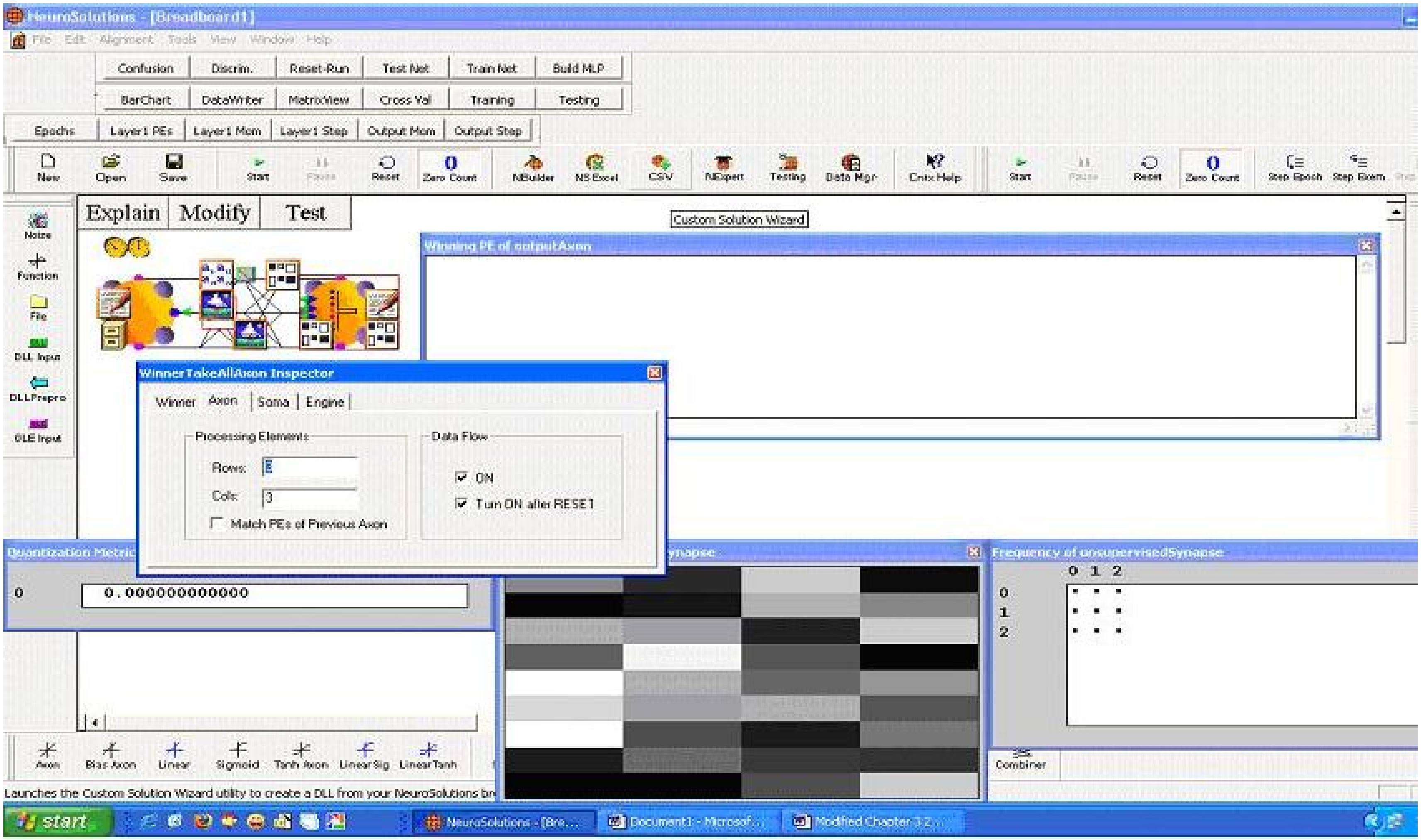
SONN accepts the data in ASCII format only. So, the Option-machine matrix is fed as a text file to the input file inspector. An example of such option-machine matrix is shown in Table 3-3 below. Here each row corresponds to machines needed for a separate option.

Table 3-3: Format of the input matrix to SONN

M1	M2	M3	M4
1	1	0	0
0	0	1	1
1	1	0	0
1	0	1	0
1	0	1	0

Step-II

Once the data is fed to SONN model, the next step is to set the parameters such as number of epochs and the number of processing elements desired. The number of epochs and processing elements can be changed by modifying the properties of static-controller and winner-take-all axon, respectively. Changing the number of processing elements affects the number of clusters SONN model is generating. Figure 3-3 gives a screenshot of the simulation while setting initial parameters.



WinnerTakeAllAxon Inspector

Winner | Axon | Soma | Engine

Processing Elements

Rows: 3

Cols: 3

☐ Match PEs of Previous Axon

Data Flow

☑ ON

☑ Turn ON after RESET

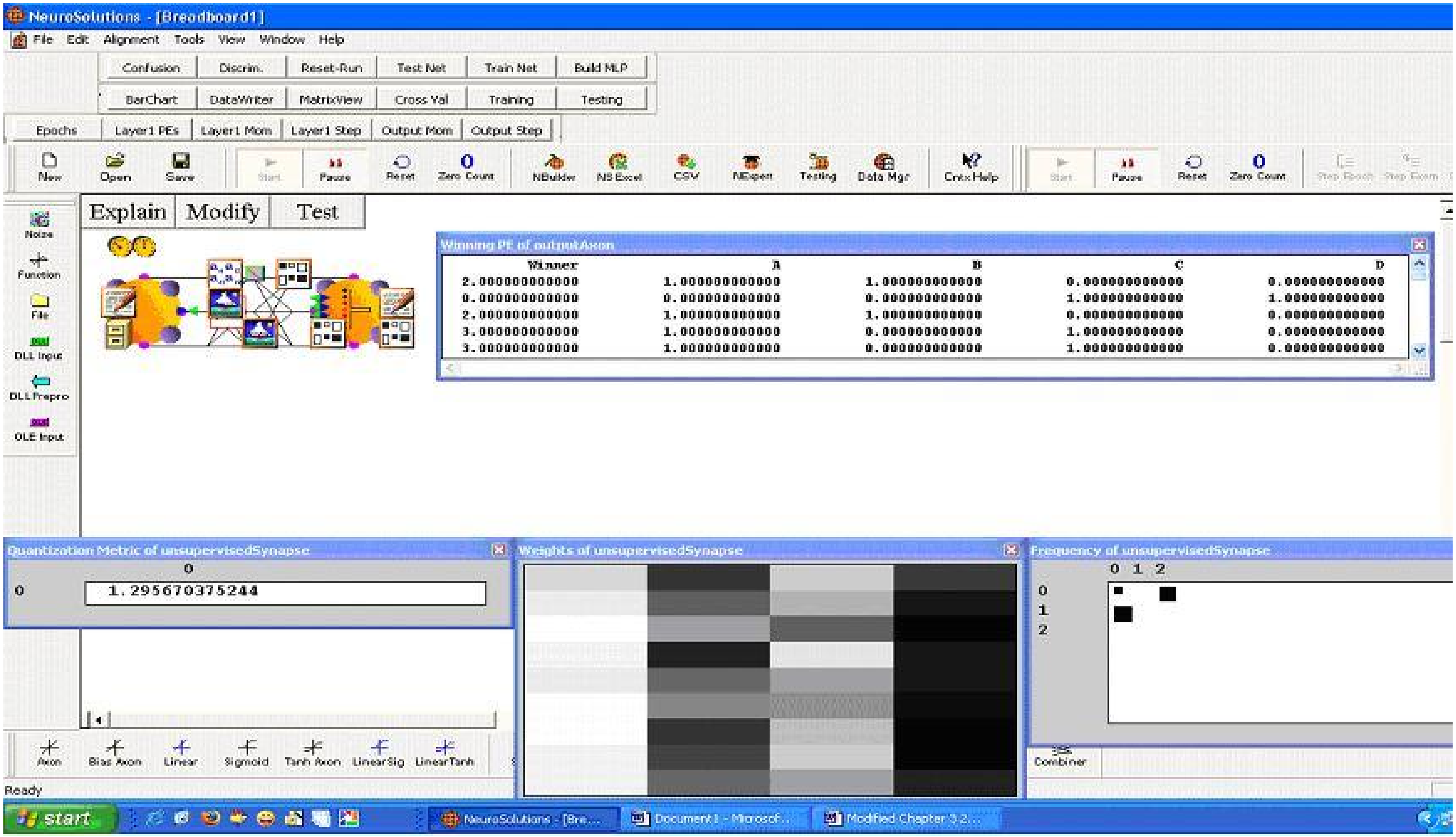
Launches the Custom Solution Wizard utility to create a DLL from your NeuroSolutions br

Figure 3-3: Setting up of initial parameters in SONN

As can be seen from winner-take-all axon inspector dialogue box in the Figure 3-3 the number of processing elements is set to 9 for this case.

Step-III

After the parameters are set initially, the next step is to run the simulation to assess the performance of the SONN model. The Figure 3-4 gives the screenshot of the simulation after initial run.



Winning PE of outputAxon

```
       Winner              A              B              C              D
2.000000000000 1.000000000000 1.000000000000 0.000000000000 0.000000000000
0.000000000000 0.000000000000 0.000000000000 1.000000000000 1.000000000000
2.000000000000 1.000000000000 1.000000000000 0.000000000000 0.000000000000
3.000000000000 1.000000000000 0.000000000000 1.000000000000 0.000000000000
3.000000000000 1.000000000000 0.000000000000 1.000000000000 0.000000000000
```

Quantization Metric of unsupervisedSynapse

```
        0
0   1.295670375244
```

Frequency of unsupervisedSynapse

```
  0 1 2
0
1
2
```

Figure 3-4: Screenshot after initial run of SONN

The winning processing elements are indicated by black square boxes (frequency of unsupervised synapse dialog box in Figure 3-4) and which also indicate the number of clusters thus formed. The density and size of the boxes is directly proportional to the number of options assigned to the respective cluster. For the present case, three processing elements 0, 2 and 3 are the winners. This indicates that all the options in option-machine matrix get assigned to these three winners resulting in three clusters.

Step IV

The process described above is repeated by varying the various process parameters which can help obtain a better SONN model. Subsequently, the winning PE's and the options assigned to them are used to generate clusters as shown in Table 3-4 below.

Table 3-4: Winning PE's for Options from SONN

Clusters	Options/Machines	M1	M2	M3	M4	Winning PE
Cluster 1	Option 11	1	1	0	0	2
	Option 13	1	1	0	0	2
Cluster 2	Option 14	1	0	1	0	3
	Option 15	1	0	1	0	3
Cluster 3	Option 12	0	0	1	1	0

As indicated above, three methods were used to generate minicell configurations. All these methods use the same type of SONN model as described above. Two of these methods (Method A and Method B) are taken from previous research (Badurdeen, 2005). Following two sections describe briefly the steps followed to design minicells along these methods using SONN model. A detailed description of newly developed method (Method C) is then discussed in the subsequent section.

3.2.3 Method A

In this method, minicell configuration can be obtained by dividing the problem into three different levels: Level 1 for clustering of initial option-machine matrix, level 2 for identifying vertical cut points (machine-wise) to form stages based on results of level 1 and finally level 3 for minicells formation and number of minicells/stage. This method was developed in previous research (Badurdeen, 2005) using genetic algorithms. Figure 3-5 shows the steps involved in forming minicells using SONN model based on method A.

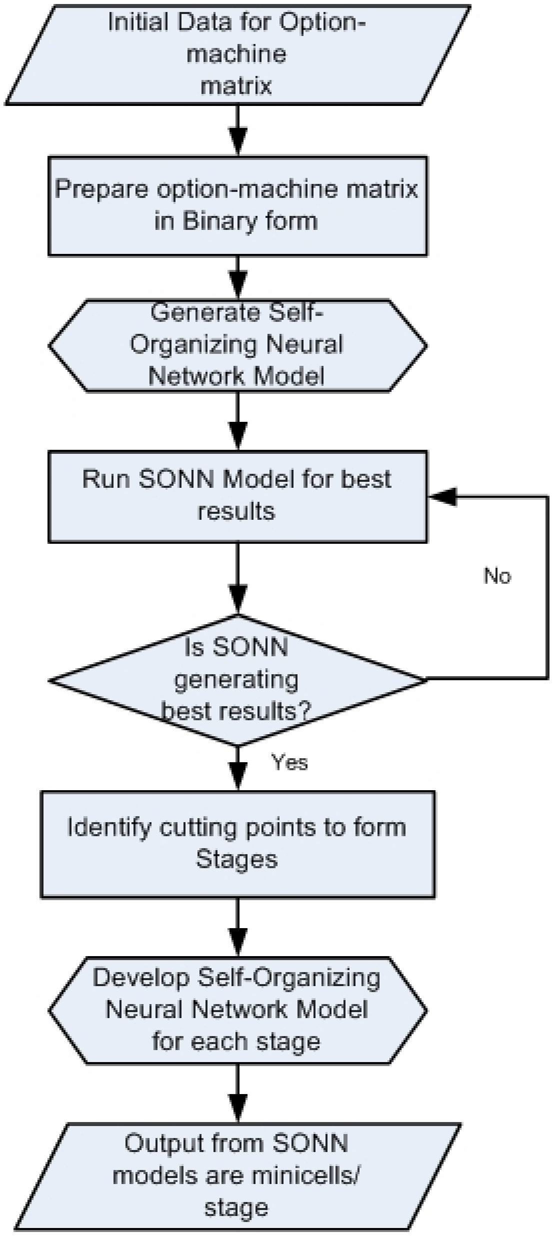


Figure 3-5: Steps involved in Method A to generate minicells

Following all the steps shown in flowchart above, minicells are generated. For example, consider the option-machine matrix given in Table 3-2 above. SONN gives following results for a two-stage case with machines M1 and M2 in first stage and M3 and M4 in second stage as in Figure 3-6.

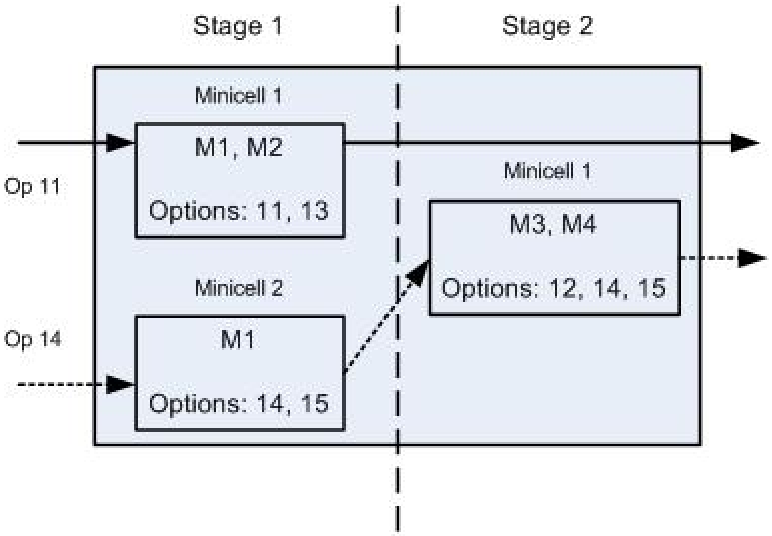


Figure 3-6: Results from Method A for a 2-Stage case

The results indicate 3 minicells in 2 stages with 2 minicells in stage 1 and 1 minicell in stage 2. It also shows all the options along with minicells to which each option has to go for its complete processing. Along with this it presents the machines allotted to different minicells. While Method A results in such type of minicell configuration, Method B and C are somewhat different and generate minicells and stages that work in a different manner when compared with former method. Following sections describe the step by step procedure followed in Method B and Method C.

3.2.4 Method B

In this method, the option-machine matrix is initially divided into stages based on the customizable features (Badurdeen, 2005) and then, information for each stage is fed to SONN model to generate minicells. Thus unlike in Method A, division into stages is pre-defined and the process reduces to only two levels. Figure 3-7 below indicates the step-by-step procedure followed in this method to get minicell configuration in mass customization manufacturing environment.

Also, division into stages in the case is option-based (horizontal) rather than machine-based (vertical cut-points) followed in Method A. This allows each minicell to have all machines required for the complete processing of option family dedicated to it eliminating the need to go to multiple stages and minicells. This finally helps in reducing the amount of material handling.

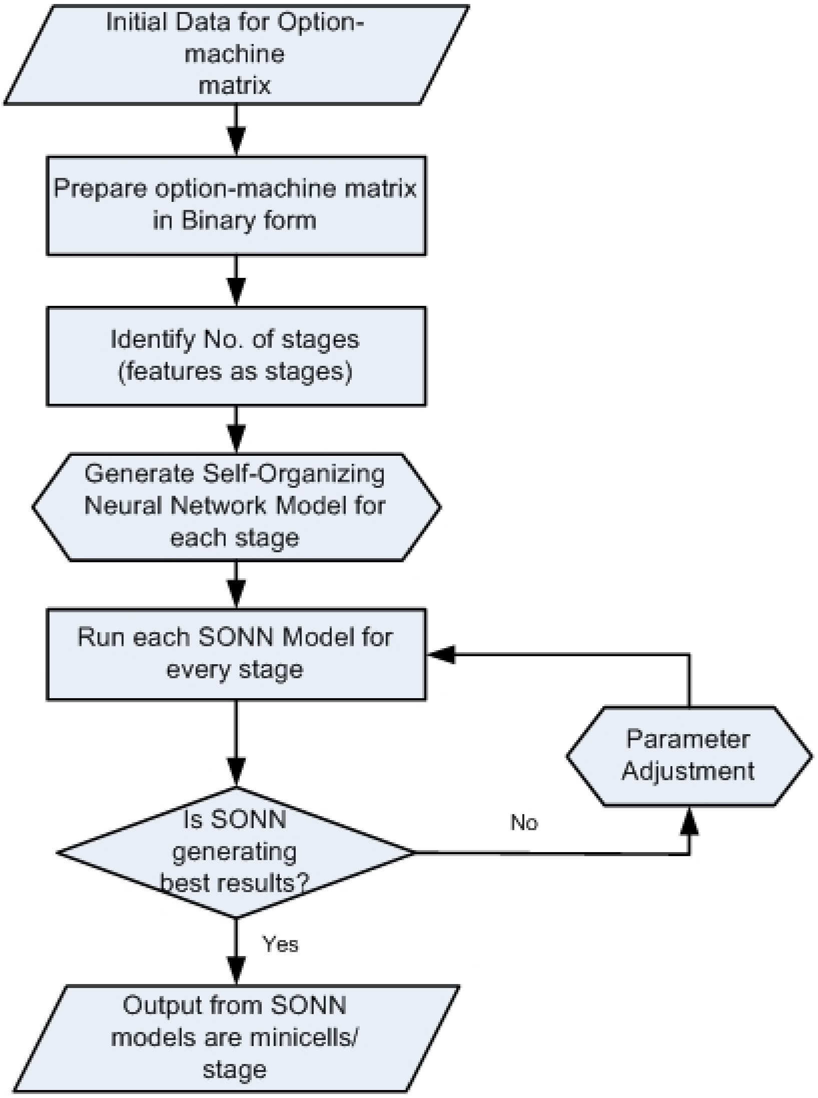


Figure 3-7: Steps involved in Method B to generate minicells

Following the same option-machine matrix as is given in Table 3-2, Figure 3-8 gives the results for a minicell design by Method B when feature 2 & 3 are in one stage and feature 1 is taken as another stage. The results indicate that minicell configuration designed using this method is very much different from Method A. Here, the options are fully processed within one minicell in any one of the stages only thus reducing the amount of material handling. However, this method increases the machine-count as there is more duplication.

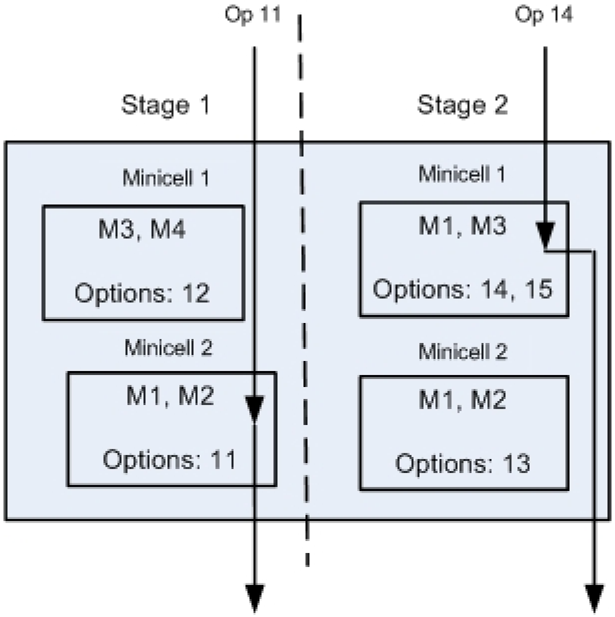


Figure 3-8: Results from Method B for a 2-Stage case

Minicell designs have been generated following Method A and B using genetic algorithm (Badurdeen, 2005). This research investigates the design of minicells by Method A and B using SONN. Examination of these two methods and the pattern of material flow indicate there may be opportunities to design modular minicell configuration following a different method to generate better performance. This new method- Method C- is discussed in the following sections.

3.2.5 Method C: Based on the modification of Method B

Analyzing the results closely, it evident that Method B results can be improved further by reducing the machine count and yet achieving all the benefits Method B provides. This improved methodology termed as Method C, could help provide better designs in fewer iterations of the SONN design simulation compared to Method B with less or equal number of machines.

Because Method C is an improved version of Method B, the final layout achieved using Method C is very much similar to that of Method B as shown in Figure 3-8 above.

In Method B, because features are treated as stages, a particular design could have either one or multiple features in a single stage. Analyzing the results of the example given by Method B in Figure 3-8, it is seen that sometimes, minicells consisting of the same machines are duplicated in different stages. This can lead to an unnecessary increase in the machine-count.

As seen in Figure 3-8, this indicates that it would be better if options 11 (feature 1) & 13 (feature 2) can be kept together in a single stage so that they can be processed in one minicell instead of two minicells. This will also reduce the machine-count by two. Considering this fact, one will come to next iteration where Feature 1 and Feature 2 will be kept together to get options 11 and 13 clustered as one option-family. This process is continued until a good solution is achieved. Also for very large data sets, where it is difficult to analyze the data visually, this problem can become more intense and difficult to solve.

For better (less number of machines) results in less number of iterations, Method C is developed by modifying Method B. Most of the steps in Method C are similar to Method B with few modifications as described below in flowchart as well as step-by-step procedure.

3.2.6 Method C: Step by Step Procedure

As shown in Figure 3-9 below, Steps I, II, III and IV of Method C are very similar to Method A. Based on the initial data (total number of machines, total number of features, number of customizable features, number of options/customizable feature, and machines required/option in sequence), generate option-machine matrix in binary form, develop SONN model using Neuro-solutions, feed option-machine matrix to SONN model, run the model multiple number of times by varying different parameters and get best clusters for given number of processing elements.

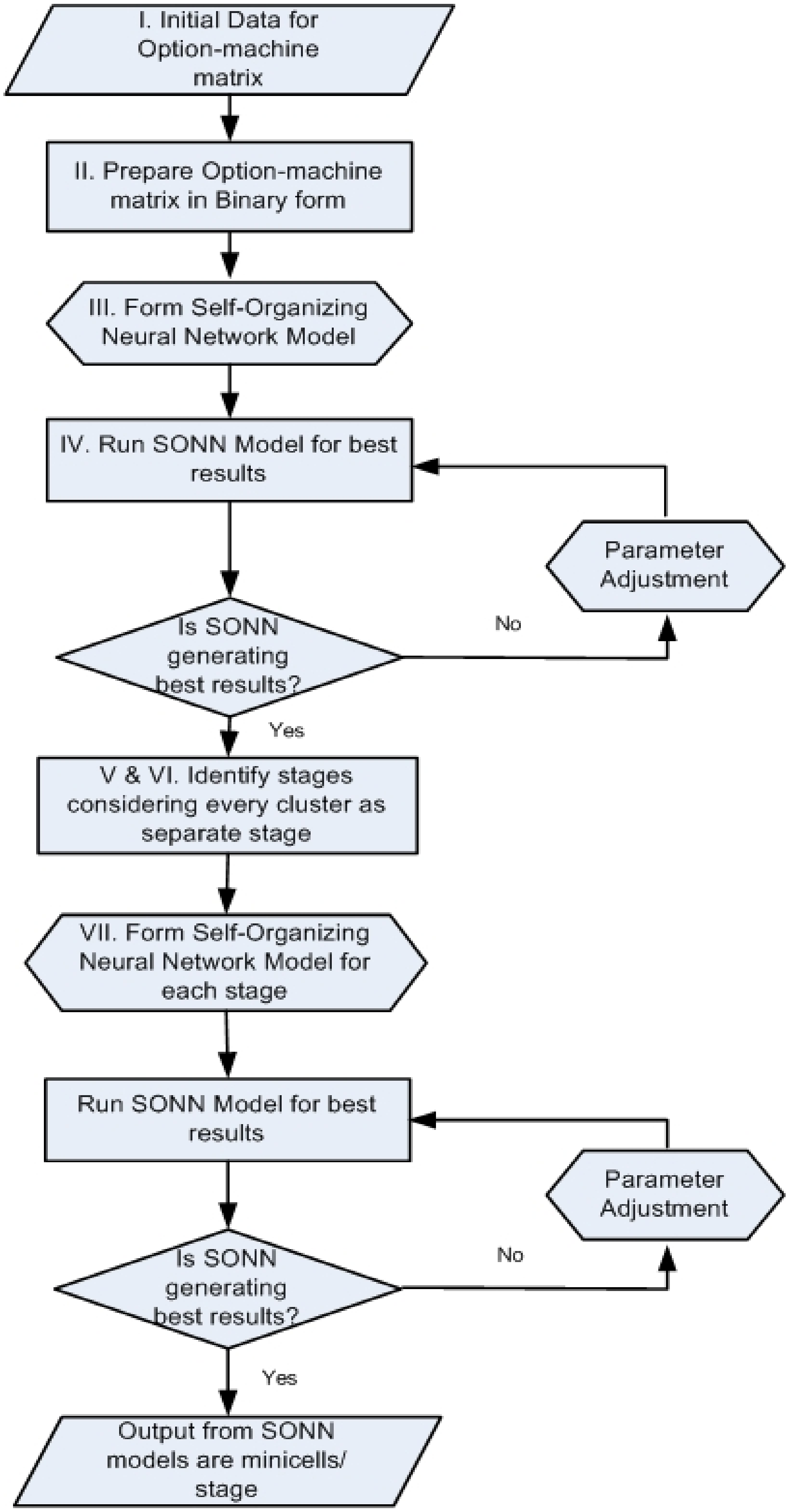


Figure 3-9: Steps involved in Method C to generate minicells

Step V

SONN model does clustering and thus, after step IV, all the options in the initial option-machine matrix get assigned to clusters thus yielding different option families. In Method C, the number of clusters thus achieved is very important because here each cluster thus generated is treated as one separate stage.

In other words, number of stages is equal to number of option-families or clusters. To consider various cases, one has to change the number of processing elements to get the option families or clusters in the desired range.

For example, considering the same example used in Method A and B, one can have different number of clusters/option families by varying the number of processing elements. Following Table 3-5 and Table 3-6 indicate the two cases generating different number of clusters from same the option-machine matrix by varying number of processing elements in a SONN model.

Table 3-5: Case 1: When number of processing elements is equal to 4.

(a) Option-machine matrix with Winning PE

	Options/Machines	**M1**	**M2**	**M3**	**M4**	**Winning PE**
Feature 1	**Option 11**	**1**	**1**	**0**	**0**	**0**
	Option 12	**0**	**0**	**1**	**1**	**2**
Feature2	**Option 13**	**1**	**1**	**0**	**0**	**0**
	Option 14	**1**	**0**	**1**	**0**	**2**
Feature 3	**Option 15**	**1**	**0**	**1**	**0**	**2**

(b) Formation of Clusters based on Winning PE

	Options/Machines	**M1**	**M2**	**M3**	**M4**
Cluster 1	**Option 11**	**1**	**1**	**0**	**0**
	Option 13	**1**	**1**	**0**	**0**
Cluster 2	**Option 12**	**0**	**0**	**1**	**1**
	Option 14	**1**	**0**	**1**	**0**
	Option 15	**1**	**0**	**1**	**0**

Table 3-6: Case 2: When number of processing elements is equal to 6.

(a) Option-machine matrix with Winning PE

	Options/Machines	M1	M2	M3	M4	Winning PE
Feature 1	**Option 11**	**1**	**1**	**0**	**0**	**0**
	Option 12	**0**	**0**	**1**	**1**	**4**
Feature2	**Option 13**	**1**	**1**	**0**	**0**	**0**
	Option 14	**1**	**0**	**1**	**0**	**1**
Feature 3	**Option 15**	**1**	**0**	**1**	**0**	**1**

(b) Formation of Clusters based on Winning PE

	Options/Machines	M1	M2	M3	M4
Cluster 1	**Option 11**	**1**	**1**	**0**	**0**
	Option 13	**1**	**1**	**0**	**0**
Cluster 2	**Option 15**	**1**	**0**	**1**	**0**
	Option 14	**1**	**0**	**1**	**0**
Cluster 3	**Option 12**	**0**	**0**	**1**	**1**

Step VI

After getting option-families based on clustering, the next step is to identify stages. The basis of dividing the option-machine matrix in this method is different from the first two methods. In this case, every option-family is considered a separate stage.

Consider the example shown in tables above, where there are two cases: one with 2 clusters and the other with 3 clusters. Thus, for the case in Table 3-5(b), clusters 1 and 2 will form stage 1 and stage 2, respectively. If the case in Table 3-6(b) is considered, clusters 1, 2 and 3 will form stages 1, 2 and 3, respectively.

Step VII

After identifying stages, each stage is treated as a separate option-machine matrix and fed to the SONN model. SONN model does clustering within the stage to generate minicells. For example, out of the two cases provided in step VI above, the minicells formed for the instance shown in Table 3-5(b) is graphically represented in Figure 3-10.

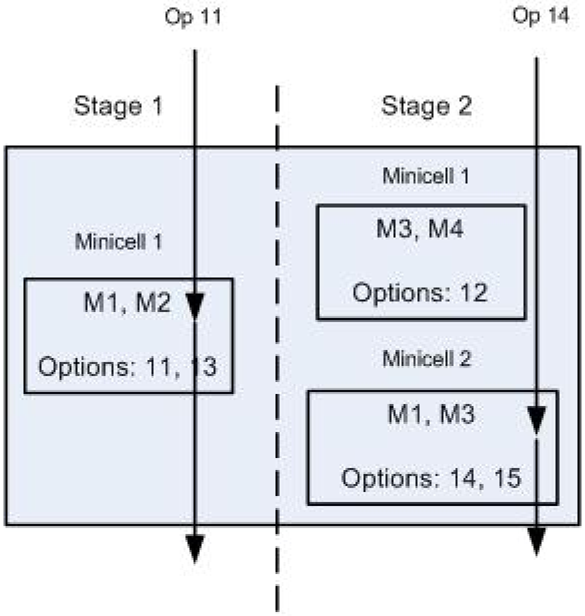


Figure 3-10: Minicell formation for case 1 in Table 3-5(b)

It can be seen that options from different features get assigned to same stage in Method C which makes it different from other two methods. Considering machine-count to analyze the results of Method B and Method C, it is evident that Method C generates better results than Method B. Different problems were solved using all three methods and a detailed discussion on all those problems, results and comparison of the three methods based on results achieved is explained in chapter 4.

3.3 Phase II: Evaluation Criteria

For each problem, there are various solutions possible. Therefore it is important to determine the best minicell design out of the various solutions generated. A number of criteria can be used to analyze and compare the various solutions such as:

- Total number of machines required (machine-count)
- Scheduling of Jobs and time-based performance criteria (makespan, flowtime, etc.)
- Amount of distance traveled by each option (material handling)
- No. of times the material is moved (frequency of material handling)
- Space required.

To analyze and compare different minicell configurations, machine-count, makespan and minimum flow time have already been used (Badurdeen, 2005; Thuramalla, 2007). However, when modular configurations are created by forming smaller cells such as minicells, the amount of material handling required can increase significantly. Therefore, it is also important to evaluate their designs in terms of the amount of material handling. To fill this void, present study takes into account the material handling issues along-with machine-count to analyze and compare the results generated by different methods. Thus, two important criteria (1) Machine-count and (2) Material handling form the basis of analyzing minicells configurations in the present work and are discussed in the following sections.

3.3.1 Machine-Count

The term “machine-count” means the total number of machines required to process the demand for all options going into various product variants. Depending on the processes involved, machines can be very costly and it is often desirable to design a configuration that involves least number of machines to meet the demand.

On the other hand, duplication of machines also means more flexibility and it can help in absorbing the demand variability without the need of re-designing the system. This can provide stability to the system which is of utmost importance in mass customization manufacturing environments. In evaluating minicell configurations designed using various methods; both these factors are taken into account. Hence machine-count is a very important criterion to analyze every minicell configuration generated by SONN model. To calculate number of machines required to meet the demand for each scenario, machine-count calculator (a C++ application) was developed.

3.3.2 Material handling

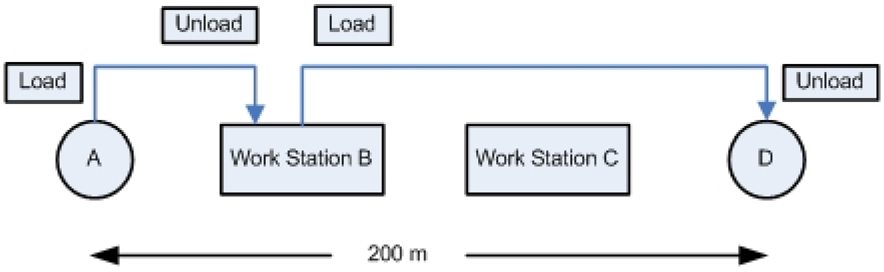
While designing any type of layout (functional layout, manufacturing cells or minicells), material handling must be considered. If not taken into account, it can lead to very high costs because it is directly related to

- Total distance traveled by options or product variants
- Total number of material handlers required
- Frequency of material transportation
- Number of material handling equipment.

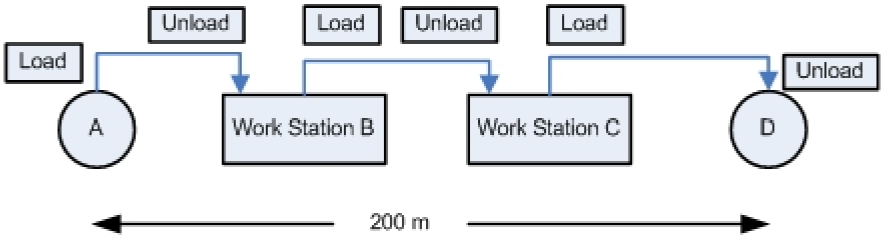
All these factors can lead to high costs and thus material handling must be evaluated at the design stage itself. A good layout can help in reducing a lot of wasted motion, transportation, labor and equipment thus providing better and cheaper products to the consumer.

Materials can be released to the shop-floor in two ways: (1) material for each option in the product variant released individually or (2) in kits. Therefore both these methods are considered in evaluating minicell designs.

Two other important aspects (1) total distance traveled by each product variant and (2) the number of times the material is moved (trips) are also taken into account for better understanding of the material handling issues in every design. It is important to mention here that sometimes the number of times material is handled, moved or transported from one location to another location provides a better understanding than the total distance traveled by the material. For example, consider the case where material handler has to move the material from one point (say A) to final point (say D). Suppose the distance between A and D is 200 m. Distance will remain the same whether material has to go to a single workstation between A and D or 2 work stations between A & D. But in the former case, the material handler has to handle the material twice compared to the latter where he has to load and unload it three times as shown in Figure 3-11.



(a) Same distance, processing at one station



(b) Same distance, processing at two stations

Figure 3-11: Differences in Material handling with loading-unloading

3.3.2.1 Material handling calculation procedure

The material handling (distance and number of times) are based on following information

- Total number of minicells and stages
- Number of minicells in each stage
- Number of machines in each minicell
- Number of options processed in each minicell.

All this information is available from the minicells generated by the SONN model as discussed above. This information collected is used to design a layout for the particular configuration. Based on available floor area restrictions, many different layouts are possible for any solution provided by SONN model. It is very difficult to analyze material handling for each and every possible layout. Therefore, some rules are established and layouts for all the solutions are designed following these rules. While this method avoids the assessing of all possible layouts, it ensures consistency in developing the layouts.

Following are the rules used to design layouts and compute material handling.

Rule 1

The space available for a layout is either square or rectangular. The space is divided into a square grid with squares of equal size. Each square represents the space allocated to one minicell.

Rule 2

First row/column is assigned to the warehouse. Based on the location of the warehouse, the final assembly line is either assigned to the last row or column (if the warehouse is in the first column, then the assembly shop is placed in the last column and if the warehouse is in the first row, then assembly shop will be in the last row).

Rule 3

Any one of the square blocks in the first row or column can be treated as the warehouse. Similarly, one of the blocks in the last row or column can be treated as the assembly shop.

Rule 4

Leaving the first column for warehouse and the last column for assembly shop, every column is treated as a separate stage. For example: if first column is assigned to warehouse, then the second column is stage 1, third column is stage 2 and so on with last column being the assembly shop. This is illustrated in Figure 3-12.

	Stage 1	Stage 2	
-			-
Warehouse			Assembly
-			-
-			-

Figure 3-12: Layout design with Assembly and Warehouse in columns

On the other hand as shown in Figure 3-13, if warehouse is placed in first row with assembly shop in the last row, then minicells can be assigned to stages starting from the second row because first row is assigned to warehouse already.

Stage 1	Stage 2	Stage 3	Stage 4
-	Warehouse	-	-
-	-	Assembly	-

Figure 3-13: Layout design with Warehouse and Assembly in rows

Rule 5

Minicells are assigned to each stage starting from the first block in the respective stage and so on. For example if warehouse and assembly line are assigned to columns, then first block of second column in the grid will be assigned to first minicell of that stage and so on. On the other hand, if warehouse and assembly shop are assigned to rows, then leaving the first row for warehouse, first minicell of stage 1 will be assigned to second block of first column and so on. Figure 3-14 below demonstrates this rule.

	Stage 1	Stage 2	
	Minicell 1	Minicell 1	
Warehouse	Minicell 2	Minicell 2	
		Minicell 3	Assembly

(a)

Stage 1	Stage 2	Stage 3	Stage 4
	Warehouse		
Minicell 1	Minicell 1	Minicell 1	
Minicell 2		Minicell 2	
		Assembly	

(b)

Figure 3-14: Demonstration of Rule 5

Rule 6

To minimize the material handling, minicells with maximum number of options are assigned first in every stage. For example, if stage 1 has two minicells with one minicell containing 6 options and other 4, then minicell with 6 options is assigned to first to the first block of that stage and then minicell with 4 options will be assigned to second block in the same stage. All the stages are filled following the same rule.

Rule 7

Warehouse and assembly shop are assigned to the blocks based on the minimum material handling criteria as shown in Figure 3-15 (they are placed close to the minicells having maximum number of options in order to reduce material handling).

	Stage 1	Stage 2	
	Minicell 1 (Op. 11, 12, 16, 19, 25)	Minicell 1 (Op. 11, 12, 16, 19, 25, 27)	
Warehouse	Minicell 2 (Op. 23, 28, 22, 42)	Minicell 2 (21, 35, 34, 33, 31, 39)	**Assembly Shop**
	Minicells 3 (Op, 21, 17)	Minicell 3 (13, 17)	

Figure 3-15: Rule 7: Placement of Warehouse and Assembly

Rule 8

Distance between adjoining blocks is always taken as unity. For example, considering Figure 3-15, distances between warehouse and minicell 2 of stage 1, minicell 2 of stage 1 and minicell 2of stage 2, minicell 2 of stage 2 and assembly line are always taken as unity.

Rule 9

Only rectilinear motion is permitted. For example, considering Figure 3-15 again, to move material from minicell 1 of stage 1 to minicell 2 of stage 2, total distance that one has to travel will be 2 units. Diagonal movements are not permitted.

Rule 10

Distance between the any two machines within the minicell is always taken as zero. Whether an option goes on one machine or multiple machines in the same minicell, the distance traveled between them is taken as zero.

After designing layouts and allotting the specific positions to stages, minicells, warehouse and assembly line, the next step is to calculate the material handling. The following situations are considered in computing material handling requirements;

a) Kitting: Material required for all options in a product variant is sent as a kit.

- Total amount of distance traveled.
- Total no. of trips required to meet daily demand.

b) Individual routing: Material for each individual option is sent separately.

- Total amount of distance traveled by all options.
- Total number of trips required to meet daily demand.

A software program (Material handling calculator) was developed to perform the computation based on both these methods. This program calculates the total distance traveled and total number of trips based on the shortest distance rule. While going from one stage to another, it goes to the nearest possible minicell following the shortest path rule. While considering kitting, all the options of a product variant start from warehouse and travel together to all the required minicells in first stage before moving to next stage. On the other hand, in the case of individual routing, options of the product variant are routed individually from one minicell to another in different stages (depending on the design) and are then brought together for the assembly. A detailed example on this is provided in Appendix I.

Based on the methodology and performance measures discussed in this chapter, problems of varied sizes were generated and solved. Results obtained are shown and discussed in the next chapter.

4 Results and Discussion

In order to analyze minicell designs developed using ANN discussed in the previous chapter, experimentations were conducted with the problems of varying size. The test problems were studied to evaluate minicell design using the performance measures: machine-count and material handling. The results obtained are compared with the results obtained from previously implemented statistical clustering technique to evaluate the use of ANN for minicell design. Minicells designed by the new method proposed (Method C) are compared with those with those designed by Methods A and B.

4.1 Test Problems

Four different problems were used for the experimentation to evaluate minicell design methods and are given in Table 4-1. The size of each problem is varied by changing the number of product variants and machine requirements (therefore the option-machine matrix size).

Table 4-1: Problems used for Experimentation

Problem No.	No. of Product Variants (PV)	No. of Machines (M)	Problem Size (PV*M)
1	27	7	189
2	12	10	120
3	18	8	144
4	10,000	25	250,000

The first test problem has three customizable features (F) and each of the features has three options. All these options can be processed using 7 machines. The product structure for this problem is given in Figure 4-1.

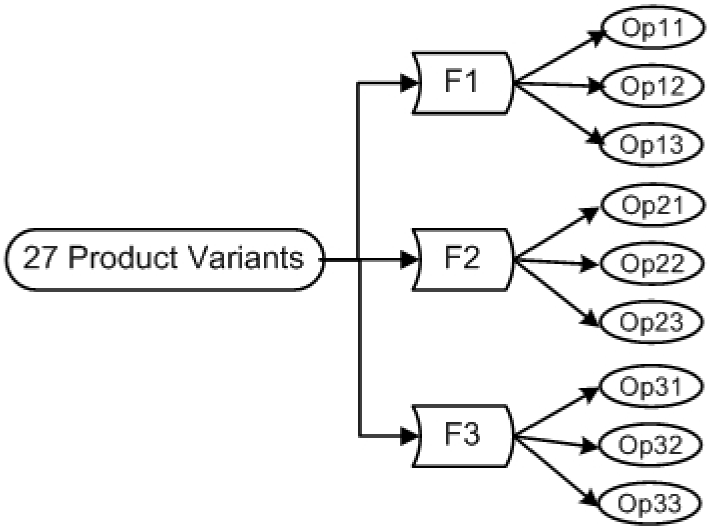


Figure 4-1: Product Structure for 27 PV

As shown in the Figure 4-1 above, each feature has three options. This results in 3*3*3 = 27 product variants. The option-machine matrix used for this problem is given the Table 4-2. This option-machine matrix indicates the machines each option is using for its processing and also the processing time (in minutes) of each option on a particular machine. This option-machine matrix is used for all the minicell designs to calculate the machine capacity required to meet the randomly generated demand for each product variant. The demand generated for this test problem is shown in Appendix II.

Table 4-2: Option-machine matrix of 27 PV

Options\Machines	M1	M2	M3	M4	M5	M6	M7
11	1.02	0	0.57	0.84	0	1.9	0
12	0	0.2	0	0.75	0	0	1.2
13	0	0	0.19	0.02	0	0	0
21	0.18	0	0	0	1.18	0	0.84
22	0	0	0	0.09	0	0.09	0
23	1.65	0.06	0.86	1.27	0	0.02	0
31	1.73	0.05	1.15	1	1.58	0	1.06
32	1.65	0	0	0.19	0	0.43	0.14
33	0	0.67	0.89	0	1.08	0	0

The second test problem also has three customizable features (F) with each of the first two features having two options and third feature having three options. All these options can be processed using 10 machines. The product structure for this problem is given in Figure 4-2. Product variant demand and Option-machine matrix is given in Appendix II.

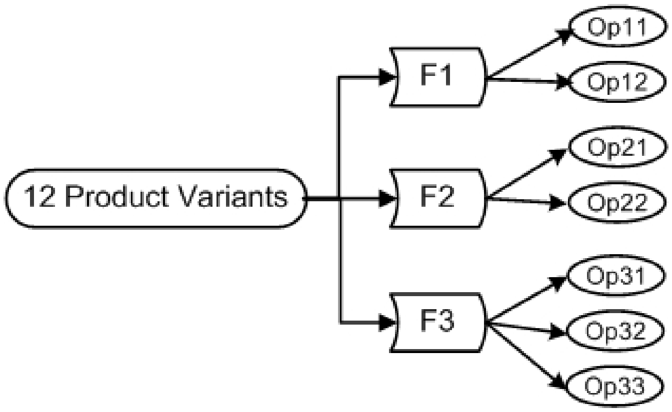


Figure 4-2: Product Structure for 12 PV

The problem # 3 consists of three customizable features. The product structure for this problem is shown in Figure 4-3 below.

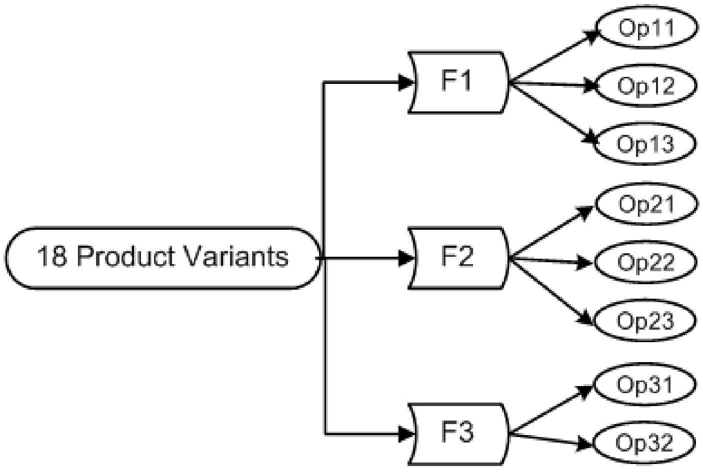


Figure 4-3: Product Structure for 18 PV

The option-machine matrix and demand for all the 18 product variants is provided in the Appendix II.

To test the capability of ANN in solving large problems, a test problem with 40 options and 25 machines is taken. For, this case, there are 4 customizable features, each feature has 10 options to offer thus providing product variety up to 10,000 PV. The product structure for this test problem is given below in Figure 4-4.

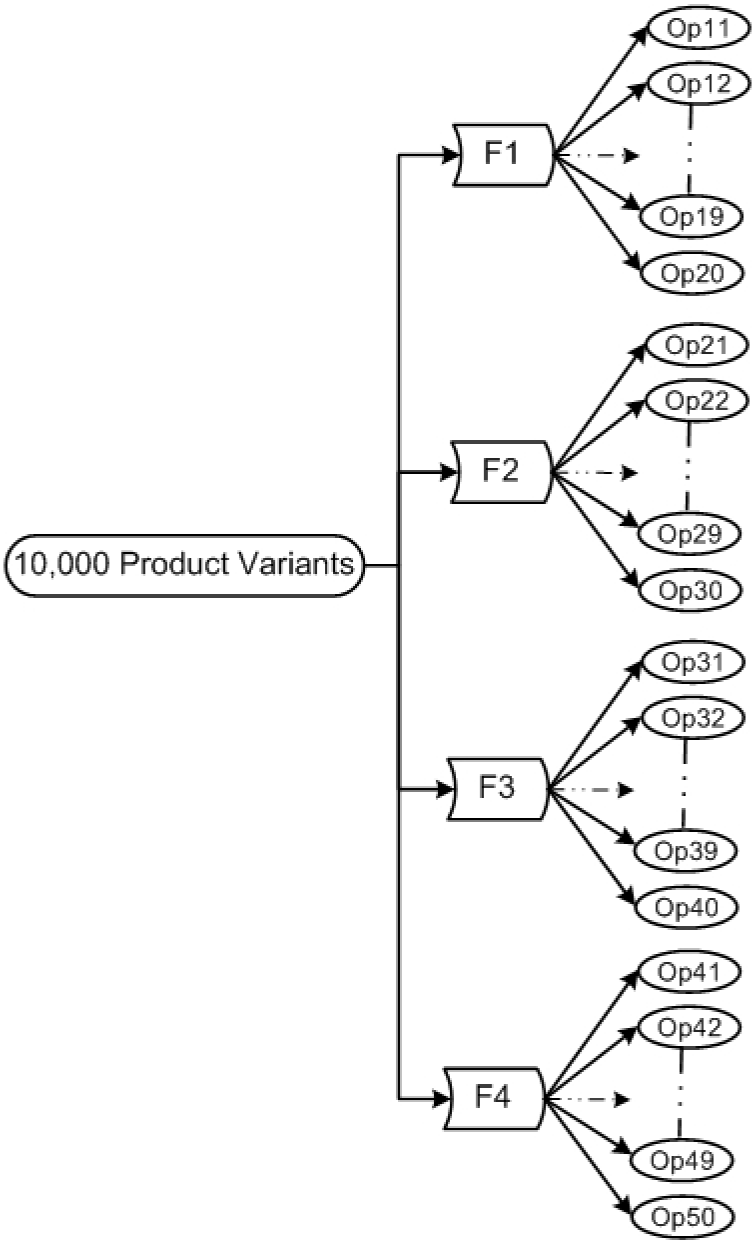


Figure 4-4: Product Structure for 10,000 PV

Option-machine matrix for this test problem is given in Appendix II. The values in the table indicate the processing time of each option on respective machine. Based on the set-up of this problem, the demand for all 10,000 PV is randomly generated and is shown in Appendix II.

To maintain the consistency, this problem was also solved using all three methods in the similar manner.

Data for first three problems is taken from previous research (Thuramalla, 2007) to compare the results. The fourth problem with 10,000 product variants (PV) was generated randomly by considering different demands for the product variants and processing times of options on machines. This problem was generated to test the capability of ANN with large data set problems.

4.2 Comparison with previous research

As discussed in chapter 2, Genetic Algorithms (Badurdeen, 2005) and Statistical Clustering Technique (Thuramalla, 2007) have previously been used to design minicells. To evaluate the performance of ANN, minicells are designed using the same method (Method A) as is followed in previous research work and are compared with the Statistical Clustering Technique results.

Results for Problem #1

Table 4-3 shows the comparison of the results obtained from ANN with results from Statistical Clustering Technique (SCT) for a 3-Stage design. First column in the table indicates the cut off points for the 3-stage design. For example: 1-1-5 means that stage 1, 2 and 3 has 1, 1 and 5 machines, respectively. It has already been found that SCT results are better than GA results (Thuramalla, 2007), therefore results given by ANN are compared with SCT results only.

Table 4-3: Comparison of ANN and SCT: 3 Stages, 27 PV

Division	# Minicells	# Machines		
		ANN	ALC	SLC
1—1—5	4	10	10	
1—2—4	7	13	12	11
1—2—4	6	11	11	
1—2—4	5	10	10	
1—3—3	8	13		12
1—3—3	7	11	12	
1—3—3	6	10	11	
1—5—1	4	10		8
2—1—4	6	12	11	
2—1—4	5	11	10	
3—1—3	8	13	12	
3—1—3	7	12	11	
3—2—2	8	13	12	
3—2—2	7	12	11	
5—1—1	6	14	14	12
5—1—1	5	12	12	
5—1—1	4	11		9

Note: Boxes left blank under SLC and ALC indicate that no results are available for the respective division and number of minicells.

As discussed in chapter 2, ALC and SLC had been used for minicell design with SCT. Comparing their results with ANN, it can be seen that for most of the cases, ANN gives results almost similar to ALC. For example, divisions such as 1-1-5, 1-2-4 and 5-1-1 require the same number of machines for same number of minicells.

In a few cases such as 3-2-2, 3-1-3 and 2-1-4 ALC generates better results based on machine-count while in a few others like 1-3-3, ANN is performing better than ALC. So, it can be concluded that both methods are yielding comparable results.

When compared with the results given by SLC, ANN results give more machines. For all cases such as divisions 1-2-4, 1-3-3, 1-5-1 etc., minicells designed by ANN require more number of machines than SLC. As explained in Chapter 2, clustering in SLC is based on the similarity existing for a single strongest link between two inputs. In other words, clustering is not well optimized in SLC. There may be cases when two clusters of options may join together merely because two of their members are similar while others members remain far apart in terms of similarity (Thuramalla, 2007). This is the reason why SLC, in terms of machine-count and minicells, performs better than ANN.

<u>Results for Problem #2 and #3</u>

To further verify the performance of ANN, two more problems with 12 and 18 product variants were tested and their results are also compared with SCT results. Table 4-4 and Table 4-5 show the comparison of results for all different stages of 18 and 12 product variants problems respectively.

In Problem #2, ALC and SLC performed better than ANN for most of the cases. But there are a few cases when results of ANN are comparable to ALC. For example, for 2 stages, 3 stages, ALC is giving less number of machines than ANN but as the number of stages increases, the difference between the performance of ALC and ANN reduces and both generate similar results.

Table 4-4: Comparison of ANN and SCT: 2, 3 and 6 Stages, 18 PV (Problem # 3)

# Stages	**Division**	**# Minicells**	**# Machines**		
			ANN	**ALC**	**SLC**
2	**1-7**	5	23		21
2	**4-4**	7	22		18
2	**6-2**	6	20		19
2	**6-2**	5	20	19	
3	**3-1-4**	6	20	18	
3	**5-1-2**	8	22	21	
6	**1-1-1-1-2-2**	8	16	16	15
6	**1-2-2-1-1-1**	8	18	17	

In Table 4-5, it can be seen that for 2 stages, ALC is performs better than ANN but as the number of stages increases, ANN starts giving better results than ALC. For example, in the case with 2 stages and 5-5 division, ANN is giving 17 machines as compared to 16. Similarly for 3 stage 5-2-3 division case, minicell configuration designed by ANN requires one extra machine as compared to ALC to meet the same demand.

Table 4-5: Comparison of ANN and SCT: 2, 3, 4, 5, 6 and 8 Stages, 12 PV

(Problem #2)

# Stages	Division	# Minicells	# Machines		
			ANN	ALC	SLC
2	**3—7**	6	16	16	
2	**5—5**	6	17	16	16
2	**5—5**	5	15		14
2	**8—2**	4	16	16	
3	**3--6--1**	7	17		15
3	**5--2--3**	6	14	13	
3	**7--2--1**	5	14	14	
4	**1-1-2-6**	6	14	13	13
4	**4-1-1-4**	6	15	13	
4	**7-1-1-1**	5	12	13	13
5	**1-1-1-1-6**	8	15	15	15
6	**1-1-1-1-1-5**	8	14		13
6	**1-2-2-3-1-1**	9	11	12	
8	**1-1-1-2-2-1-1-1**	10	10	11	11
8	**2-2-1-1-1-1-1-1**	10	10	12	

On the other hand, for 5 stage case, ANN is giving exactly similar results as are provided by ALC and SLC. Dividing further into more stages, ANN starts giving results better than ALC and SLC. For example, in Table 4-5, ANN is showing a requirement of 11 machines as compared to 12 machines required by ALC for 1-2-2-3-1-1 division, a 6 stage case. Following the same trend further, in 8-stage 1-1-1-2-2-1-1-1 division, ANN is performing better than both ALC and SLC methods.

Based on comparison, it can be concluded that ANN is providing comparable and in some cases better results than previously used techniques; therefore it can be used as an effective technique for designing minicell configurations for a mass customization environment. Having this basis, ANN is used to design minicell configurations for 4 different test problems of varying sizes. As discussed in the last chapter, three different methods (two old and one new) were used to design different types of minicells using ANN. Each test problem was tested using all the three methods. A detailed discussion of all the test problems to compare these methods is given in the subsequent sections of this chapter.

4.3 Analysis of Test Problems

Detailed discussion of the experimentation conducted for each problem and the analysis of the results is given below.

4.3.1 Problem No. 1 = 27 Product Variants

4.3.1.1 Method A

With Method A, the 27 product variants problem was tested for two and three stages. For every scenario, machines are distributed into stages in three different formats (Badurdeen, 2005): more number of machines in the earlier stages, more number of machines in the last stages, and even distribution of machines among all the stages.

For the same number of stages, many divisions are tested and analyzed. All these divisions result in minicell configurations having different machine requirements, number of minicells and material handling. Table 4-6 gives the number of minicells generated by ANN, total number of machines required, distance to be traveled if kitting is followed and total number of times the material is handled to meet the daily demand for a 2-Stage scenario. Some of the observations made are discussed below.

- Within the same division, an increase in number of minicells results in an increase in number of machines. For example, there are 18 machines in 8 minicells as opposed to 13 in 6 and 10 in 4 minicells for division 4-3. Same trend can be seen for division 5-2 also. The reason is the duplication of machines in the minicells as the number of clusters increases.
- For the same number of minicells, fewer machines are needed for when there is an equal distribution of machines among the stages as opposed to the cases with an uneven distribution.

Table 4-6: Method A: 2 Stages, 27 PV results

Division	Minicells	Machines	M/H Kitting [1]	Trips M/H Kitting[2]
1--6	4	14	890	579
4--3	8	18	1188	786
4--3	7	15	1032	700
4--3	6	13	948	629
4--3	6	13	972	674
4--3	6	12	972	658
4--3	5	11	792	621
4--3	4	10	690	582
5--2	7	19	1004	731
5--2	6	15	838	688
5--2	5	13	772	655
5--2	4	12	674	618
5--2	3	11	666	540

Within the same division, material handling distance traveled and frequency increases with increase in the number of minicells as one would expect. These observations are for the 2-stage scenario. To evaluate behavior of other scenarios, same test problem is tested for a 3-satge scenario results are tabulated in Table 4-7.

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[1] M/H Kitting indicates sum of the total distance traveled by all product variants to meet the demand.

[2] Trips M/H Kitting indicates the sum of total number of times product variants visited minicells to meet the demand

Table 4-7: Method A: 3 Stages, 27 PV results

Division	Minicells	Machines	M/H Kitting	Trips M/H Kitting
1--1--5	5	12	888	672
1--1--5	4	10	784	645
1--2--4	8	14	1150	853
1--2--4	7	13	1150	808
1--2--4	6	11	900	753
1--2--4	5	10	834	727
1--3--3	9	15	1104	873
1--3--3	8	14	1054	787
1--3--3	8	13	1054	831
1--3--3	7	11	1072	795
1--3--3	6	10	900	758
1--3--3	5	9	828	738
1--5--1	4	10	784	642
2--1--4	6	12	1226	812
2--1--4	5	11	1052	732
2--1--4	4	9	760	650
3--1--3	8	13	1330	817
3--1--3	7	12	1246	806
3--1--3	6	11	1078	786
3--1--3	5	10	996	749
3--2--2	8	13	1174	885
3--2--2	7	12	1090	874
3--2--2	6	11	964	837
5--1--1	6	14	1024	683
5--1--1	5	12	842	650
5--1--1	4	11	776	623

Results show that most of the observations made from 2-Stage scenario hold good for 3-Stage scenario too. The results indicate that within the same division, with an increase in the number of minicells there is an increase number of machines. For example, to meet the same demand, there are 15 machines required in 9 minicells as opposed to 9 machines in 5 minicells for 1-3-3 division. Also, for the same number of minicells, an even distribution of machines among stages gives less number of machines, for example, as seen in all the divisions with 5 and 6 minicells in Table 4-7 above. Material handling distance and number of trips are also following the same trend as is shown by 2-Stage scenario.

So far, observations are made for same stage scenarios. It is very important to compare the results of 2-Stage with 3-Stage division cases in terms of machine-count and material handling to see the impact of number of stages on minicells design. A brief discussion with some observations is made in the following section.

- When comparing the machine requirements, it has been observed that the same number of minicells in a 3-Stage division require less number of machines as compared to the requirement of a 2-Stage division. For example: considering the cases with 5 minicells, 3-Stage division gives machines in the range of 9-12 as opposed to 11-13 in 2 Stage. A similar trend is shown by cases having 4, 6, 7 or 8 minicells.
- For the cases having same number of minicells, material handling is more in 3-Stage divisions compared to 2-Stage divisions. For example, consider all the cases with 5 minicells. For 2-Stage divisions, distance traveled by product variants lie in the range of 772-792 units as opposed to 828-1052 units in 3-Stage divisions. The same trend is followed for total number of trips to minicells required to meet the demand. This observation holds good for any number of minicells.

The results obtained by ANN using Method A are shown and discussed above. Minicell configurations were also designed using Method B as discussed in last chapter. Following section is dedicated to the results and discussion of the minicell configurations obtained for 27 product variants problem using Method B.

4.3.1.2 Method B

As discussed in the previous chapter, in this method, the option-machine matrix is divided into stages based on the features. For the 27 product variant problem, there are three customizable features F1, F2 and F3.Thus, every feature or combination of features can be treated as one stage. Therefore in the present problem, only 3, 2 or 1 stage scenarios are possible out of which 3-Stage and 2-Stage scenarios were tested. The results given by ANN using this method are summarized in Table 4-8.

Table 4-8: Method B: 27 PV results

Stages	Minicells	Machines	M/H Individual [3]	Trips M/H Individual[4]
F1-F2-F3	6	25	1794	828
F1-F23	4	20	1518	828
F12-F3	4	19	1518	828
F13-F2	4	19	1518	828

Following observations are made based on the results above.

- With an increase in number of stages, the number of minicells increases and hence the number of machines also increases. For example, ANN gives 6 minicells and 25 machines for 3-stages as opposed to 19 or 20 machines and 4 minicells for a 2-Stage division.
- No. of machines required is dependent upon the features chosen to be placed in a single stage. For example, in 2-Stage divisions, F1-F23 requires more machines as compared to cases F12-F3 and F13-F2.
- As expected, material handling is more for the cases having more number of stages as compared to the ones having less number of stages. With the same

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[3] M/H Individual indicates the sum of the total distance traveled by each option of all product variants to meet the daily demand.

[4] Trips M/H Individual indicates sum of the number of times the options of all product variants visited minicells to meet the daily demand.

number of stages, cases with same number of minicells result in same amount of material handling in terms of total distance traveled.

- In this method material handling is calculated by considering each individual option separately. It is observed that the number of times each minicell is visited is same for each case. It is because in Method B, minicells are dedicated cells and therefore each option gets fully processed within one minicell. Therefore, irrespective of the number of stages or minicells, the number of trips remains same for specific demand.

As discussed, division of stages in Method B is based on either a single feature or a combination of features. It is observed that the machine requirement is dependent on the features chosen for each stage. Different combinations are possible and the number increases with an increase in the number of customizable features, thus, making it difficult and time consuming to design minicell configurations based on minimum machine requirement. To overcome such limitations, a new method extended from methodology applied in Method B is presented. This will be referred to as Method C. The approach to develop minicell configurations using this method was described in the previous chapter.

4.3.1.3 Method C

Table 4-9 indicates the results for 27 product variants problem when solved by Method C.

Table 4-9: Method C: 27 PV results

PE	Stages	Minicells	Machines	M/H Individual	Trips M/H Individual
2	**2**	4	19	1618	828
3	**3**	5	20	1884	828
4	**3**	6	23	1774	828
5	**4**	5	22	2512	828

In Method C, the number of stages is neither based on machine division not on the number of features. Here, it is based on the number of processing elements (PE) selected initially in ANN model. Changing the total number of processing elements results in a change in number of winning processing elements and hence the initial clustering yields different number of clusters. These clusters are then treated as individual stages. As indicated in Table 4-9 above, the problem is tested for 2, 3, 4 and 5 processing elements which lead to 2, 3, 3 and 4 stages respectively. Following are the observations based on the results obtained.

- As expected, for the same number of stages, an increase in minicells results in more machines. This can be seen for 3 stage case, where there is a requirement of 20 machines in 5 minicells as opposed to 23 in 6 minicells.
- Also increase in number of stages results in more material handling in terms distance traveled by each option.
- Increase in number of stages does not have any impact on total number of trips made to minicells. This is again for the reason as is explained in Method B. Like Method B, each option goes to only one minicell for its processing.
- For same number of stages, it is observed that material handling is less for the case where number of machines and minicells are more. This is because material handling does not only depend upon total number of minicells but also on number of minicells/stage. Irrespective of the total number of minicells or machines, the even distribution of minicells/stage may result in less material handling as compared to the ones having an uneven distribution of minicells/stage.

4.3.1.4 Comparison of Methods

As mentioned earlier, two performance measures: machine-count and material handling were used to compare minicell configuration designs generated by three methods using ANN. A detailed discussion and comparison of the results is given below.

Comparison based on Machine-Count

Table 4-10 given below compares the results of the three methods based on machine-count.

Table 4-10: Comparison of Methods based on Machine-count: 27 PV

Stages	**Minicells**	**Machine-Count**		
		M-A	**M-B**	**M-C**
2	4	10 12 14	19 20	19
3	5	9 10 11 12	-	20
	6	10 11 12 14	25	23
4	5	-	-	22

Number of machines required to meet the same demand is calculated for various cases for all the three methods. Table 4-10 indicates the machine-count and number of minicells for various stage divisions. It can be observed that for the same number of stages and minicells, Method A (M-A) gives minimum machine requirement compared with Method B (M-B) and Method C (M-C). For example, machine-count lies within the range of 10-14 for all 2-stage 4 minicell cases in M-A as compared to 19-20 and 19 in M-B and M-C respectively.

In Method A, options have to go to multiple minicells for complete processing. As options in this design are allowed to go to multiple stages in multiple minicells, there is less requirement of duplication of machine which results in fewer machines when compared to M-B and M-C.

Using M-B and M-C, the handling of options in minicells is similar because options are not allowed to go to multiple stages or minicells. Each option is completely processed in one minicell only. Therefore, there are chances for more duplication of machines compared to M-A.

When M-B and M-C are compared with each other, it is seen that M-C performs slightly better than M-B. Table 4-10 shows that for same number of stages and minicells, M-C gives either same or slightly less number of machines than M-B. So, it can be concluded M-C lies somewhere in-between M-A and M-B in terms of machine-count. Another very important performance measure, material handling is also calculated for all cases of three methods and is discussed below.

Comparison based on Material Handling

Based on the rules discussed in chapter 3, layouts for all cases were designed and material handling was calculated. Table 4-11 indicates the material handling for various configurations generated by three methods when kitting is taken into consideration.

Table 4-11: Comparison of Methods based on Kitting: 27 PV

Stages	Minicell	Machine-Count			Distance traveled: Kitting			No. of Trips: Kitting		
		M-A	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**
2	4	10 12 14	19 19 20	19	690 674 890	690 690 690	646	582 618 579	454 488 475	464
3	5	9 10 11 12 12	-	20	828 996 1052 842 888		862	738 749 732 650 672		481
	6	10 11 11 11 12 14	25	23	900 900 964 1078 1226 1024	966	844	758 753 837 786 812 683	552	493
4	5	-	-	22	-		1112			489

A few observations that are made from the comparison are listed below:

- In terms of total distance traveled, it can be seen that for same number of stages and minicells, M-C is providing best results overall when compared to M-A and M-B.
- Comparing M-A and M-B, considering cases with minimum number of machines for the former; material handling is almost similar to M-B. But with more machines, M-B is giving better material handling performance.
- Considering total number of trips, both M-B and M-C provide better results than M-A. For example, for 3-Stages and 6 minicells, total number of trips for M-A lie in the range of 683-837 as compared to 552 and 493 in M-B and M-C.

- Comparing M-B and M-C, minicells designs given by M-C gives less number of trips as compared to configuration given by M-B.

Observations made above indicate that minicell design configurations given by M-C are performing better than M-A and M-B in terms of material handling when kitting is followed.

There are cases when kitting is not followed and parts are routed individually. Results for those cases where material handling is calculated considering Individual-Routing for all the cases of all the three methods are tabulated below in Table 4-12.

Table 4-12: Comparison of Methods based on Individual-Routing: 27 PV

Stages	**Minicell**	**Machine-Count**			**Distance traveled: Individual**			**No. of Trips: Individual**		
		M-A	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**
2	4	10	19	19	1700	1518	1618	1200	828	828
		12	19		1748	1518		1164	828	
		14	20		2094	1518		1080	828	
3	5	9	-	20	2180		1884	1452		828
		10			2282			1505		
		11			2502			1416		
		12			2046			1205		
		12			2200			1293		
	6	10	25	23	2252	1794	1774	1452	828	828
		11			2218			1545		
		11			2278			1380		
		11			2364			1505		
		12			2674			1416		
		14			2286			1205		
4	5	-	-	22	-		2512			828

Observations based on the above comparison are listed below:

- For same number of stages and minicells, material handling is minimum for M-B and maximum for M-A. As the total distance traveled is very high for the minicell configuration designs given by M-A, it is very much clear that M-A is suitable for kitting only.
- Comparison of M-B and M-C shows that material handling in terms of distance traveled individually is more in case of M-C than in M-B.
- In terms of total trips, M-B and M-C perform equally well and better than M-A.

Results of 27 Product Variants problem are discussed and compared above. All three methods used in ANN for designing minicells are analyzed based on material handling and machine-count. Some significant observations are also made while comparing the methods. To verify these observations, more problems were tested and the results thus obtained are discussed in the following sections.

4.3.2 Problem No. 2 = 12 Product Variants

4.3.2.1 Method A

To get a better idea of the results and to better understand M-A, this problem has been tested for more stages as compared to 27 product variants test problem. Various cases for 2, 3, 4, 5, 6 and 8 stages were solved to analyze the behavior. Following Table 4-13 shows the results obtained for all the stages.

Table 4-13: Method A: 12 PV results

Stages	Division	Minicells	Machines	M/H Kitting	Trips M/H Kitting
2	1—9	3	14	455	356
	3--7	6	16	601	472
	5--5	6	17	637	467
	5--5	5	15	549	424
	8—2	4	16	455	433
3	3--6—1	7	17	884	571
	5--2--3	6	14	646	531
	7--2--1	5	14	546	497
4	1-1-2-6	6	14	637	515
	3-2-3-2	8	13	811	685
	4-1-1-4	6	15	761	537
	7-1-1-1	5	12	605	515
5	1-1-1-1-6	8	15	910	624
	1-2-4-2-1	9	13	908	798
	5-2-1-1-1	8	13	816	655
6	1-1-1-1-1-5	8	14	913	646
	1-2-2-3-1-1	9	11	839	738
	4-2-1-1-1-1	7	13	819	674
8	1-1-1-1-1-1-1-3	9	18	987	626
	1-1-1-2-2-1-1-1	10	10	943	821
	2-2-1-1-1-1-1-1	10	10	965	788

Observations made in the last problem also hold good for this problem. In this problem also, for the same number of minicells, as the number of stages increases, the number of machines decreases. For example, consider the case of 5, 6 and 7 minicells. But there are a few exceptions for example; there are 18 machines in 9 minicells in 8-stage case as compared to 11 machines in 6-stage case.

Regarding material handling, for same number of minicells, material handling increases with an increase in number of stages. Also, with an increase in number of stages, the number of trips keeps on increasing thus resulting in more material handling.

4.3.2.2 *Method B*

Table 4-14 represents the results of the minicell design configurations given by ANN using M-B. Same observations regarding machine-count can be made as were observed in 27 product variants problem.

Table 4-14: Method B: 12 PV results

Stages	Division	Minicells	Machines	M/H Individual	Trips M/H Individual
3	**F1-F2-F3**	7	30	1547	546
2	**F12-F3**	6	29	1274	546
	F1-F23	6	27	1547	546
	F13-F2	6	29	1547	546

In case of material handling, it has been observed that F12-F3 division is giving minimum material handling when compared to other divisions having same number of stages and minicells. This is because of the minicells/stage. For F12-F3, there are 2 minicells in first stage and 4 minicells in second stage as compared to 3 minicells in each stage for other cases. This shows that distribution of minicells over the stages also affects material handling.

4.3.2.3 *Method C*

Table 4-15 gives the results given by ANN using Method C. All the observations for 27 product variants problem hold good for this problem also.

Table 4-15: Method C: 12 PV results

PE	Stages	Minicells	Machines	M/H Individual	Trips M/H Individual
2PE	**2**	4	24	1099	546
3PE	**3**	5	27	1085	546
4PE	**4**	7	27	1390	546
5PE	**4**	5	27	1397	546

4.3.2.4 Comparison of Methods

Considering machine-count, for this problem, M-A gives minimum number of machines. Comparing M-B and M-C, M-C performs in a better way and requires less number of machines as compared to M-B. Table 4-16 shows the comparison of methods based on machine-count and material handling with kitting.

Table 4-16: Comparison of Methods based on Kitting: 12 PV

Stages	Minicell	Machine-Count			Distance traveled: Kitting			No. of Trips: Kitting		
		M-A	M-B	M-C	M-A	M-B	M-C	M-A	M-B	M-C
2	4	16		24	455		435	433		322
	6	16 17	27 29 29		601 637	637 546 637		472 467	351 364 364	
3	5	14		27	546		473	497		327
	7	17	30		884	725		571	364	
4	5	12		27	605		637	515		328

For all cases, it can be seen that for 2 and 3 stages, M-C provides minimum material handling in terms of both distance traveled as well as number of trips but for 4-stage division, M-A is giving less traveling distance than M-C.

Comparing M-A and M-B, for 2-stage division, both methods give almost same results for total distance traveled but as the number of stages increase, M-B gives better results than M-A. Regarding number of trips, M-B performs better than M-A for all cases.

As shown in Table 4-17 below, for Individual-Routing (No kitting), M-C gives minimum material handling in terms of distance traveled as compared to M-A and M-B. Number of trips remains same in M-B and M-C for all cases and is less than M-A cases.

For 2-Stage case, M-A provides less material handling than M-B but as number of stages increase, M-B provides better results than M-A

Table 4-17: Comparison of Methods based on Individual-Routing: 12 PV

Stages	**Minicell**	**Machine-Count**			**Distance traveled: Individual**			**No. of Trips: Individual**		
		M-A	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**
2	4	16		24	1187		1099	761		546
	6	16 17	27 29 29		1425 1427	1547 1274 1547		819 819	546 546 546	
3	5	14		27	1518		1085 1397	990		546 546
	7	17	30		1864	1547	1390	1034	546	546
4	5	12			1581			1021		

4.3.3 Problem No. 3 = 18 Product Variants

Following sections provide the results from all the three methods and their comparison.

4.3.3.1 <u>Method A</u>

2, 3 and 6 Stage cases were tested with this method and results thus obtained are tabulated below in Table 4-18.

Table 4-18: Method A: 18 PV results

(a) 2 Stages

Division	Minicells	Machines	M/H Kitting	Trips M/H Kitting
1—7	5	23	2748	1556
3—5	7	22	3104	1933
4—4	7	22	3000	1955
6—2	7	22	2870	1928

(b) 3 Stages

Division	Minicells	Machines	M/H Kitting	Trips M/H Kitting
3--1--4	9	22	4810	2427
3--3--2	11	22	4056	2750
5--1--2	8	22	4042	2281

(c) 6 Stages

Division	Minicells	Machines	M/H Kitting	Trips M/H Kitting
1-1-1-1-2-2	8	16	3078	2749
1-2-2-1-1-1	8	18	3078	2875
3-1-1-1-1-1	9	19	4020	2803

Observations made for previous problems hold good for this test problem also but one exception that can be seen is that material handling (Kitting) reduces as number of stages increases from 3 to 6. Regarding the number of trips, with an increase in number of stages, the number of trips also increases.

4.3.3.2 Method B

Table 4-19 summarizes the results given by Method B. The results show the same trend as is observed in previous problems.

Table 4-19: Method B: 18 PV results

Division	Minicells	Machines	M/H Individual	Trips M/H Individual
F1-F2-F3	6	30	4788	2052
F12-F3	4	26	3762	2052
F1-F23	4	24	4104	2052
F13-F2	6	30	5814	2052

4.3.3.3 Method C

Five different cases were tested using Method C and the results show that the same kind of behavior as was observed in previous problems with no exceptions. Table 4-20 gives a summary of results for Method C.

Table 4-20: Method C: 18 PV results

PE	Stages	Minicells	Machines	M/H Individual	Trips Individual
2	2	4	24	4104	2052
3	2	4	26	4104	2052
4	3	5	26	4470	2052
5	4	5	27	4688	2052
6	4	5	24	5508	2052

4.3.3.4 Comparison of Methods

To compare the three methods, Table 4-21 gives the results from the three methods.

Table 4-21: Comparison of Methods based on Kitting: 18 PV

Stages	Minicell	Machine-Count			Avg. Distance traveled: Kitting			Avg. No. of Trips: Kitting		
		M-A	M-B	M-C	M-A	M-B	M-C	M-A	M-B	M-C
2	4	18 19	24	24 26	2134 1774	1666	1664 1638	1403 1445	1149	1214 1189
	5	23	26		2738	2140		1556	1273	
	6	20 22	30 31		2694 2316	2394 2426		1869 1800	1368 1368	
	7	22			2870			1928		
3	5			26		2040				1243
	6	20	30		2570	2256		2030	1368	
	8	22			4042			2281		
	9	22			4810			2427		

It can be seen that for 2-Stage cases, M-C gives equal number of machines to M-B and both of these gives more machines than as compared to M-A. For 3-Stage cases, M-C performs better than M-B but still M-A give better machine-count than other methods. Regarding material handling (with Kitting), it is observed that M-C outperforms M-A and M-B in terms of total distance traveled as well as total number of trips.

All the three methods were also tested for the cases when the options are individually routed instead of using kitting and it has been observed that M-C gives less material handling than M-A and M-B for all stages in terms of total distance traveled. Regarding total number of individual trips, M-C and M-B performs equally well and better than M-A.

4.3.4 Problem No. 4 = 10,000 Product Variants

Following the same trend as above, test problem with 10,000 products variants was also tested. Results for Method A, B and C are provided in Appendix II. Following observations are made while comparing the three methods.

Comparison based on Machine-Count

For all stages, it can be seen that M-B gives designs with high machine-count. For a few cases, M-B gives less number of minicells than other methods but with a very high machine-count. M-C on the other hand gives very good results. For all stages, machine-count is very much similar to what is required for M-A minicell designs. Because M-C results in dedicated minicells as opposed to M-A where there are shared minicells, it can be concluded that M-C outperforms M-A and M-B for large problems.

Comparison based on Material Handling

For all stages, results from M-A gives more material handling as compared to M-B and M-C. Comparing M-B and M-C, for a 2-Stage scenario, M-B and M-C performs almost equally well but for 3-Stage and 4-Stage scenarios M-C outperforms M-B and also gives minimum material handling in terms of distance traveled by all product variants. In terms of total number of trips also, M-C performs better than M-A and M-B.

Considering the second case of material handling, when options are routed individually (no kitting), it has been observed that M-B and M-C gives exactly same results for all cases and outperform M-A completely in terms of number of trips.

For most of the cases comparing the total distance traveled (without kitting), M-C outperforms M-A and M-B completely. Comparing M-A and M-B, with the increase in number of stages, M-B provides better results than M-A.

Based on the results discussed in this chapter, some conclusions are made and discussed in next chapter.

5 Conclusions and Future Recommendations

In the previous chapter, results obtained following three methods are discussed in detail. The first section of this chapter reflects the conclusions made based on results achieved followed by the future work that can be done in the same field to further improve the methodology and results.

5.1 Conclusions

As defined earlier, the objectives of this research were to implement artificial neural networks for designing minicells, test the capability of ANNs for designing minicells using previously developed methods, developing a new effective and efficient method and suggesting the best method to be used for various cases based on machine-count and material handling. Based on the objectives and experimentation done, following conclusions are made:

- Comparing the SONN results with SCT, it has been found that for less number of stages, the results are comparable with the SLC results; however as the number of stages increases, SONN provides better results than ALC as well as SLC. Hence, it can be concluded that SONN can be used as an effective technique for designing minicell configuration for mass customization.
- Using Method A, for same number of minicells; increase in number of stages results in increased material handling but less duplication of machines.
- Using Method A, for same number of minicells, even distribution of Machines among stages provides better results.
- Using Method B, less number of stages results in less material handling and machines. Machine-count varies from case to case if number of stages is kept same. It depends upon the features that are combined together.
- Using Method B, if individual routing is done, the number of trips remains the same for every case.

- For small size problems, it has been observed that M-C gives less number of machines than M-B but more than M-A for same number of stages.
- For small size problems, it has been observed that M-C gives better material handling (Kitting) than both M-A and M-B for same number of stages.
- For small size problems, it is found that M-B gives better material handling (individual routing) than both M-A and M-C. M-A is not suitable at all for individual routing of options.
- For problems with large data-set, material handling does not only depends upon number of stages or number of total minicells but also on number of minicells/stage. Equal number of minicells/stage results in better material handling.
- For large-sized problems, it has been observed that M-C outperforms both M-A and M-B on the basis of both material handling (kitting) and machine-count. Considering individual routing, M-B performs better than M-C when number of stages and minicells are kept low. But as number of stages increases, M-C outperforms both M-A and M-B.
- It is also observed that M-C converges faster than both M-A and M-B. In other words, there is a possibility to get better results in less number of iterations as compared to M-A and M-B.

Finally, it can be concluded that for problems with large data-set, M-C must be used to get better and faster results. For small size-problems, M-A should be used when the objective is to get minimum machine-count only. On the other hand, if both performance measures: machine-count and material handling are to be considered, M-C will give best results. While considering individual routing rather than kitting, M-C will be appropriate choice when both performance measures are considered. If machine-count is not an issue, then one can use M-B.

This indicates that SONN can be used effectively to design minicells. It has capability to solve large data-set problems in less time. Based on the conclusions made above, the

Table 5-1 can be used as a source for method selection criteria for different problem sizes and objectives.

Table 5-1: Method Selection Criteria

Problem Size	**Machine-count**	**Material Handling**		**Machine-count and Material Handling**	
		Kitting	**Individual Option routing**	**Kitting**	**Individual Option routing**
Small	M-A< M-C < M-B	**Distance Traveled** M-C<M-A<M-B	**Distance Traveled** M-B ≤ M-C < M-A	M-A or M-C	M-C
		No. of Trips M-C ≤ M-B < M-A	**No. of Trips** M-C=M-B<< M-A		
Large	M-A ≤ M-C << M-B	**Distance Traveled** M-C< M-B << M-A	**Distance Traveled** M-B ≤ M-C << M-A (for less stages) M-C< M-B << M-A (for more stages)	M-C	M-C
		No. of Trips M-C< M-B << M-A	**No. of Trips** M-C=M-B << M-A		

There are still some improvements that can be made to get even better and faster results. The following sections discuss some of the drawbacks or limitations of the current study and recommend some of the steps that can be taken to further improve the method.

5.2 Limitations of the present Research

As discussed in Chapter 3, SONN model was used to design minicells. For single problem, SONN model was run multiple numbers of times to test the problem with different number of processing elements, number of epochs etc. Present study was not able to get rid of this repetitive laborious work. There is no method developed that can indicate the number of processing elements that must be set initially to get best clustering.

Secondly, present methodology is stepwise procedure. For Methods A, B and C, SONN model is used in multiple steps for getting clusters within each stage. Present study was not able to design minicells for all stages simultaneously.

Material handling, one of the performance measures in the present study is calculated based on theoretical rules established which sometimes do no hold good in reality.

5.3 Future Improvements

All these three limitations can serve as directions for future work. Each of these limitations is discussed in detail in subsequent sections.

5.3.1 Rules Extraction

As discussed above, SONN model was run multiple times to get good results by changing parameters such as number of processing elements, number of epochs etc. This requires some rules that need to be established for using SONN model. Some of the rules that may be of help are listed below:

- Number of processing elements for varying size test problems.
- Number of epochs to be set to get optimal results in first run.

These types of rules are sometimes hard to establish because every test problem is different from each other. One other alternative that can be a potential remedy is to build parallel working multiple SONN models that are capable of taking input data from single input file inspector, but have different number of processing elements so that data gets tested for different number of processing elements simultaneously and finally gives one single best output. Figure 5-1 gives the idea of how future research can be different from present study.

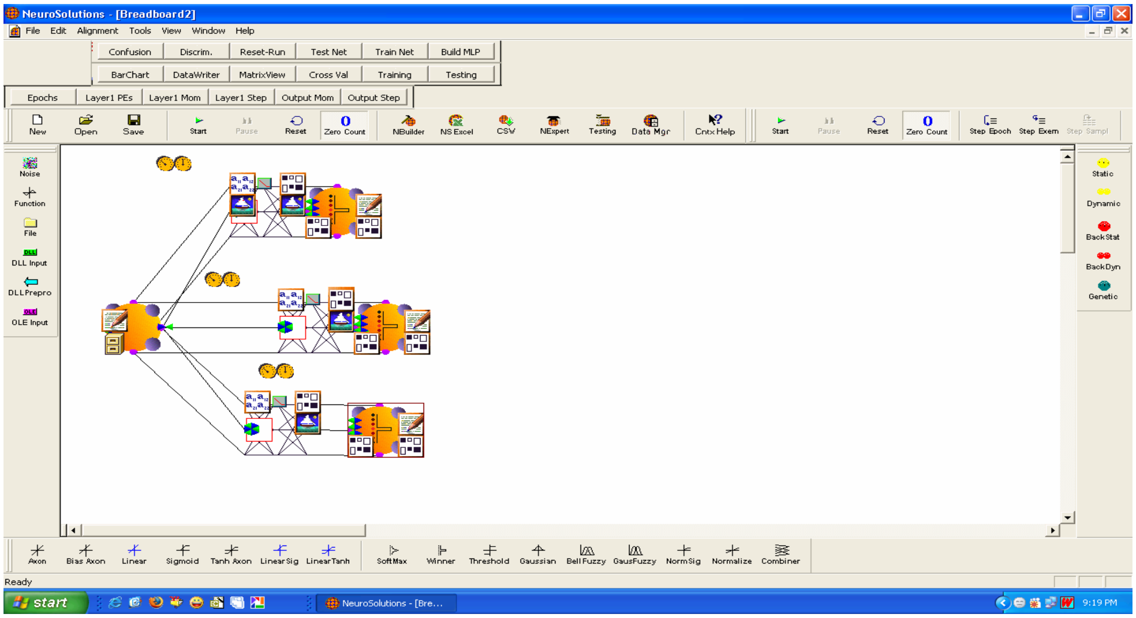

Figure 5-1: Parallel Processing with different Processing Elements

5.3.2 Reducing Manual Intervention

The current process is a stepwise procedure with lots of manual intervention after every step. For example, For Method A, during initial clustering stage, the output given by SONN model cannot be fed directly to next step in process. It has to be first converted into the form which is acceptable to next step. Also, for each stage, clustering is done separately to get minicells. This manual intervention makes the process time consuming and cumbersome.

A possible remedy to this is to put all steps in sequential order in such a way that manual intervention can get deleted thus making the process smooth and fast. It can be done if SONN models can get combined together in sequential order (in series) such that output from one can automatically become input for the next. In other words, an integrated automated system can be developed which needs just input data and provides the user with output thus generated. Figure 5-2 indicates the pictorial view of the proposed model that can developed in future.

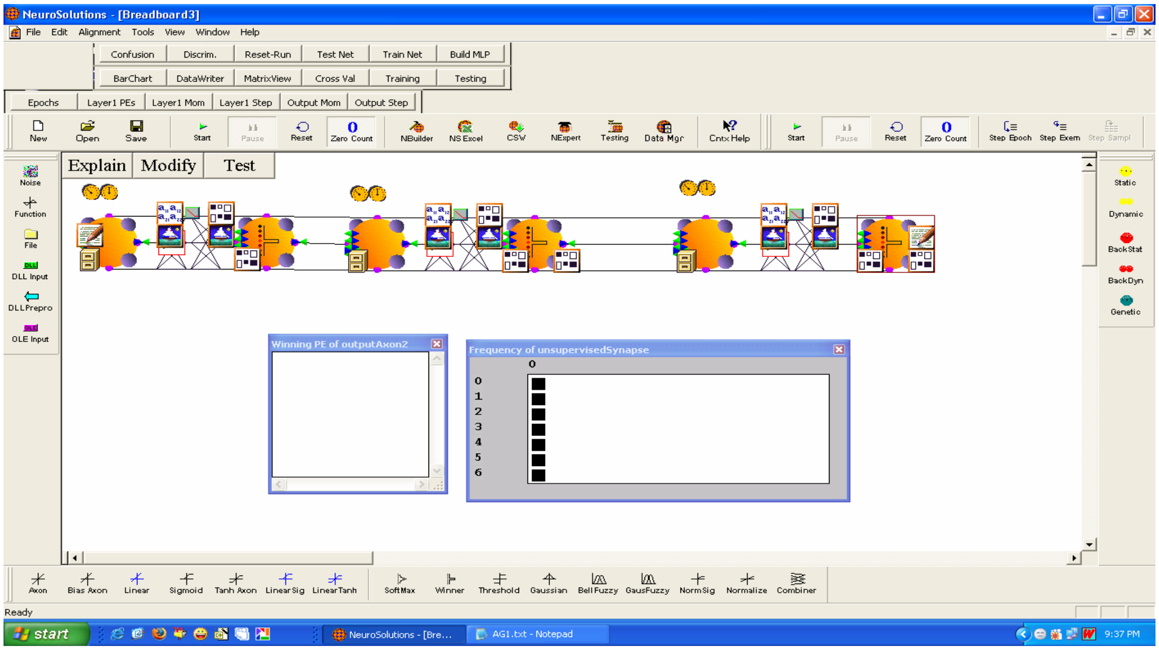

Figure 5-2: Pictorial View of Proposed Future Model

5.3.3 Reality based problems

Material handling is an important issue for any manufacturing industry. If not taken into account during design stage, it may lead to very high costs. In present research, material handling, in terms of total distance traveled is calculated for all layouts designs. All these layouts are designed based on the same rules. These rules hold good for comparison purposes but cannot reflect real environment. In reality layout of each facility is different from other because of varying sizes, shapes etc.

To calculate actual material handling, it is very important to test the reality based problems rather than theoretical problems. Data must be collected from the real world problem, layout should be designed keeping the size and shape of the facility in mind and then material handling should be calculated. Few reality based problems will help to compare the results given by three methods along with actual distance traveled in each case. This will help in validating the present research practically also.

5.4 Recommendation

The research shows that minicells can be successfully designed using ANN. It is also seen that results given by ANN are comparable to statistical clustering techniques used in previous research (Thuramalla, 2007). The new methodology developed is providing better results than the old methods in some cases. Still there is huge scope of improvement. The above mentioned limitations or drawbacks of present research can be removed by working on the proposed future work. If someone in future improves the methodology developed here and reduces or eliminates manual intervention, it can save a lot of time and makes the process of designing minicells much easier and faster. Minicell design as discussed in previous chapters has a potential to provide better flexibility than traditional cells therefore, it is highly recommended to further explore the possibilities and improvements to keep serving the competitive mass customized manufacturing environment.

APPENDIX I

Material Handling Illustration:

Consider the layout given below.

	Stage 1	Stage 2	
	Minicell 1 (Op. 11, 12, 16, 19, 25)	Minicell 1 (Op. 11, 12, 16, 19, 25, 27)	
Warehouse	Minicell 2 (Op. 23, 28, 22, 42)	Minicell 2 (21, 35, 34, 33, 31, 39)	**Assembly Shop**
	Minicells 3 (Op, 21, 17)	Minicell 3 (13, 17)	

Suppose options 23, 11 and 13 are required for a specific product variant, then “material handling calculator” will calculate the material handling as described below:

Case I: Kitting

Material required for all three options (23, 11 and 13) start from warehouse in a kit. Kit can either go to Minicell 1 or 2 in stage 1. Based on the shortest distance rule, Kit will go to minicell 2 first, and then to minicell1. After going through all the minicells required in that stage, it will go to the minicell in next stage following the closest minicell rule. For example, in this case it requires minicell 1 and 3 in stage 2. It will go to minicell 1 first and then minicell 3. Finally it will go to assembly line. Based on all the rules discussed above, total distance traveled by this kit is as given below:

From	To	Trips	Distance (in units)
Warehouse	M-2 Stage 1	1	1
M-2 Stage 1	M-1 Stage 1	1	1
M-1 Stage 1	M-1 Stage 2	1	1
M-1 Stage 2	M-3 Stage 2	1	2
M-3 Stage 2	Assembly line	1	2

Total distance traveled is 7 units and No. of times the material is handled (trips) is equal to 5. If demand of this product variant is say 100/day, then total distance traveled considering single-piece flow is 700 units and total number of trips required to manufacture this product variant is 500.

Case II: Individual routing

Following the same strategy and rules, "Material handling calculator" also calculates total distance traveled and total no. of trips for each option separately. The table below indicates the distance traveled and trips made to completely process the product variant which requires options 11, 13 and 23.

Option No.	Trips	Distance (in units)
11	3	5
13	2	5
23	2	3
Total	**7**	**13**

APPENDIX II

(a) Randomly Generated Daily Demand: 27, 18 and 12 Product Variants

	27 PV		18 PV		12 PV	
	Products	Demand	Products	Demand	Products	Demand
1	11.14.17	8	11.14.17	10	11.13.15	8
2	11.14.18	3	11.14.18	28	11.13.16	5
3	11.14.19	3	11.15.17	19	11.13.17	5
4	11.15.17	2	11.15.18	47	11.14.15	12
5	11.15.18	4	11.16.17	10	11.14.16	4
6	11.15.19	3	11.16.18	35	11.14.17	13
7	11.16.17	7	12.14.17	22	12.13.15	5
8	11.16.18	8	12.14.18	37	12.13.16	2
9	11.16.19	7	12.15.17	17	12.13.17	8
10	12.14.17	5	12.15.18	30	12.14.15	10
11	12.14.18	2	12.16.17	20	12.14.16	14
12	12.14.19	2	12.16.18	9	12.14.17	5
13	12.15.17	10	13.14.17	19		
14	12.15.18	4	13.14.18	8		
15	12.15.19	1	13.15.17	2		
16	12.16.17	10	13.15.18	8		
17	12.16.18	8	13.16.17	8		
18	12.16.19	9	13.16.18	13		
19	13.14.17	10				
20	13.14.18	2				
21	13.14.19	5				
22	13.15.17	3				
23	13.15.18	4				
24	13.15.19	2				
25	13.16.17	6				
26	13.16.18	6				
27	13.16.19	4				

(b) Problem No. 4 = 10,000 Product Variants

Option-Machine Matrix

Op.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
11	0	0	0	1.25	0	0	3.16	0	0	5.34	0	0	0	0	0	1.06	0	5.12	0	0	0	3.54	0	0	0
12	1.09	1.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.24	0	0	0	0	0	0	0	6.19
13	0	0	2.31	0	0	0	0	0	0	0	5.19	0	0	0	0	0	0	0	0	8.42	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	1.54	0	0	0	0	0	0	0	0	0	0	0.29	0	0
15	0	0	0	1.45	0	0	0	0	0	0	0	3.22	0	0	0	0	0	4.33	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	2.12	0	0	0	0.55	0	0	0	0	0	0	0.16	0	0
17	0	0	0	2.44	0	0	2.22	0	0	4.25	0	0	0	0	0	0.12	0	6.18	0	0	0	0	0	0	0
18	0	0	0	0	2.4	0	0	0	0	0	0	0	0	0	0	0.1	0	0	3.08	0	0	0	0	0	0
19	0	0	2.3	0	0	0	0	0	0	0	4.28	0	0	0	0	0	0	0	0	4.44	0	0	0	0	4.31
20	0	0	0	0	0	0	0	1.12	1.21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.15
21	0	0	0	0	0	0	0	2.31	0	0	0	0	4.2	0	0	0	0	0	0	0	2.45	0	0	0	0
22	1.35	0	2.26	0	0	0	0	0	0	0	0	0	0	0	0	0	8.21	0	0	0	0	0	0	6.2	4.35
23	0	0	0.3	0	0	0	0	0	0	0	2.12	0	0	0	0	0	0	0	0	2.14	0	0	0	0	0
24	0	0	1.22	0	3.12	0	0	0	0	0	3.31	0	0	0	0	0	0	0	0	2.16	0	0	0	0	0
25	0	2.05	0	0	1.21	0	0	0	0	3.5	0	0	0	0	0	4.21	0	0	4.22	0	0	0	0	0	0
26	0	0	0	1.22	0	0	1.34	0	0	0	0	0	0	0	0	4.05	0	6.09	0	0	0	0	0	0	0
27	0	0	0	0	0	0	1.14	0	0	3.21	0	0	0	0	0	0	0	5.27	0	0	0	0	0	0	0
28	0	0	0	2.15	0	0	2.21	0	0	0	0	0	0	0	0	0	0	5.34	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	3.22	1.11	2.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.44	0	0	0	0	0	0	6.12	0	0
31	0	0	0	0	0	0	0	2.11	2.17	3.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	1.32	0	0	0	0	1.23	2.12	0	0	0	0	0	0	0	8.32	0	0	0	0	0	0	0	0
33	0	0	0	0	2.5	0	0	0	0	0	0	0	0	0	0	3.01	0	0	5.33	0	0	0	0	0	0
34	0	0	0	0	1.24	0	0	0	0	0	0	0	0	0	0	4.25	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	2.16	0	0	0	0	0	0	0	0	3.24	0	0	0	0	0	2.42	0	0	0	0
36	0	0	0	1.22	0	0	0	0	0	0	0	5.08	0	0	4.18	0	0	0	0	0	0	0	4.24	0	0
37	0	0	0	0	0	0	0	0	0	0	0	3.15	0	0	0	0	0	0	0	0	2.1	4.32	0	0	0
38	0	0	0	0	0	0	0	2.12	2.43	2.23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	3.12	2.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.37	0	0	0	0
40	0	0	0	1.25	0	0	3.16	0	0	0	0	0	0	0	0	3.17	0	4.2	0	0	0	0	0	0	0
41	0	0	0	0	5.11	0	0	0	0	0	0	0	0	0	0	0	1.24	0	6.28	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.02	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	3.22	0	0	0	0	0	0	0	0	5.11	0	0	0	0	4.01
44	0	0	0	0	0	0	0	0	0	0	0	3.21	0	0	0	0	0	0	0	0	0	0	6.2	9.15	0
45	0	0	0	0	0	3.09	0	0	0	0	0	0	0	0	0.21	0	0	0	0	0	3.15	4.3	0	0	0
46	1.18	2.25	0	0	0	0	0	0	0	0	3.21	0	0	0	0	0	5.17	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	1.18	0	0	0	0	1.22	0	0	0	0	0	0	0	0	0	0	4.35	0	0
48	0	0	0	0	0	0	0	1.22	2.14	0	0	0	0	0	0	0	0	0	0	0	0	4.08	0	0	0
49	0	0	0	0	0	0	2.32	0	0	0	0	2.23	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	4.09	0	0	0	0	0	0	0	0	4.18	0	0	0	0	0	2.25	0	0	0	0

ANN Results: Method A

Method A: 10,000 PV results

(a) 2 Stages

Division	Minicells	Machines	Avg. M/H Kitting	Avg. Trips Kitting
6--19	8	105	8.773	5.583
12--13	8	102	9.086	6.087
15--10	8	100	9.043	6.036
20--5	7	102	8.321	5.237

(b) 3 Stages

Division	Minicells	Machines	Avg. M/H Kitting	Avg. Trips Kitting
5--5--15	10	103	10.206	6.723
5--10--10	11	102	11.284	7.34
6--8--11	12	102	11.719	7.481
6--10--9	11	101	11.736	7.498
8--8--9	12	103	12.892	8.465
10--10--5	11	103	10.795	7.151
15--5--5	11	101	10.855	6.983

(c) 4 Stages

Division	Minicells	Machines	Avg. M/H Kitting	Avg. Trips Kitting
5-10-5-5	14	102	13.061	8.287
7-8-5-5	15	101	13.49	8.503
10-5-5-5	15	102	13.207	8.118
12-4-5-4	11	101	12.088	7.641
15-3-3-4	13	105	12.981	7.827

ANN Results: Method B

Method B: 10,000 PV results

Division	Minicells	Machines	Avg. M/H Individual	Avg. Trips Individual
F12-F34	4	114	16	8
F14-F23	5	116	20	8
F13-F24	6	112	19.741	8
F123-F4	7	111	22	8
F124-F3	7	110	22	8
F1-F234	8	119	22	8
F12-F3-F4	8	117	22	8
F1-F2-F34	9	128	28	8
F1-F23-F4	9	125	26	8
F13-F2-F4	9	120	21.741	8
F14-F2-F3	9	122	22	8
F1-F24-F3	10	123	26	8
F1-F2-F3-F4	13	131	30	8

ANN Results: Method C

Method C: 10,000 PV results

PE	Stages	Minicells	Machines	Avg. M/H Individual	Avg. Trips Individual
4	4	10	106	23.028	8
5	5	10	102	20.487	8
6	4	8	104	19.718	8
7	6	12	110	24.549	8
9	5	10	112	22.19	8

Variation in Material Handling with Minicells/Stage: 10,000 PV

PE	Stages	Minicells/Stage	Minicells	Avg. M/H Individual
4	4	3--3--2—2	10	23.028
5	5	2--2--2--2—2	10	20.487
6	4	2--2--2—2	8	19.718
7	6	2--2--2--2--2—2	12	24.549
9	5	2--2--2--2—2	10	22.19

Comparison of Methods (Based on Machine-count and material handling)

Comparison of M-A, M-B and M-C based on Kitting: 10,000 PV

Stages	Minicell	Machine-Count			Avg. Distance traveled: Kitting			Avg. No. of Trips: Kitting		
		M-A	M-B	M-C	M-A	M-B	M-C	M-A	M-B	M-C
2	4		114			5.03			3.98	
	6		112	103		6.09	6.06		4.14	4.03
	7	102	110 111		8.33	7 7		5.24	4.28 4.26	
	8	100 102 105	119		9.05 9.08 8.77	7		6.04 6.09 5.58	4.35	
3	6			106			6.20			4.12
	8		117			8			4.50	
	10	103	123		10.21	8.92		6.72	4.62	
	11	101			10.86			6.98		
	12	102			11.72			7.48		
4	8			104			7.88			4.35
	10			106			8.64			4.41
	11	101			12.09			7.64		
	13	105	131		12.98	11.53		7.83	5	
	14	102			13.01			8.29		
	15 15	101 102			13.49 13.21			8.50 8.12		

Comparison of Methods based on Individual-Routing: 10,000 PV

Stages	**Minicell**	**Machine-Count**			**Avg. Distance traveled: Individual**			**Avg. No. of Trips: Individual**		
		M-A	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**	**M-A**	**M-B**	**M-C**
2	4		114			16			8	
	6		112	103		19.74	20		8	8
	7	102	110 111		20.45	22 22		9.90	8 8	
	8	100 102 105	119		23.40 22.28 21.47	22		11.69 11.69 10.30	8	
3	6			106			18.31			8
	8		117			22			8	
	10	103	123		24.82	26		11.74	8	
	11	101			29.28			13.24		
	12	102			27.33			12.67		
4	8			104			19.71			8
	10			106			23.03			8
	11	101			31.42			13.47		
	13	105	131		33.44	30		13.10	8	
	14	102			31.34			13.42		

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VITA

Arvind Goyal was born on June 1st, 1980 in Chandigarh, India. He received his bachelors' degree from Punjab Technical University, Jallandhar, Punjab, India in 2003. He joined the University of Kentucky in the Fall, 2005 to pursue his MS in Manufacturing Systems Engineering and is expecting his degree in May, 2008. As a Graduate student, he served as *Teaching Assistant* for MFS 512 (Manufacturing Systems), MFS 503 (Lean Principles and Practices) and also as *Research Assistant* for Lean Manufacturing Bootcamps I and III.

Scholastic Honors
Kentucky Graduate Scholarship, Fall 2005 – Spring 2007
University of Kentucky, Lexington, KY.