UNDERSTANDING OPERATOR PREFERENCES TOWARDS MANUFACTURING CELL TASK ASSIGNMENTS

by

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Abstract

Empirical research has shown that the majority of cellular manufacturing (CM) implementations do not consider in their design and operational phases socio-technical factors. However, in practice the performance and success of CM systems are directly linked to the degree in which these factors are considered. This research proposes the development of a quantitative model to describe and quantify operators' preferences and their impact on system performance. A modified multi-commodity transportation model using a network flow algorithm is proposed to assign operators among cells in specific operations across established periods. The linear programming model has the objective of minimizing the costs to assign, and operator's dissatisfaction. The model also considers capacity and demand constraints, and operator's skills. The suitability of this model for developing worker assignments is tested using data from an empirical study that reflects that socio-technical factors can be incorporated without impacting system performance.

Resumen

Investigaciones empíricas han demostrado que la mayoría de las implementaciones de celdas de manufactura no consideran en sus diseños y fases operacionales los factores socio-técnicos. Sin embargo, en la práctica el desempeño y éxito de las celdas está directamente relacionados con el grado en que estos factores sean considerados. Esta investigación propone el desarrollo de un modelo cuantitativo para describir y cuantificar las preferencias de los operadores y el impacto que esto tenga en el desempeño del sistema. Un modelo modificado de transportación multimodal es propuesto para asignar los operadores en periodos específicos. El modelo de programación lineal tiene el objetivo de minimizar los costos de asignar y la insatisfacción de los operadores. El modelo considera capacidad, las restricciones de demanda y la destreza de cada operador. La validez del modelo es probada usando datos reales y reflejos que estos factores pueden ser incorporados sin impactar el desempeño del sistema.

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1 Introduction

Cellular manufacturing based on group technology has become an important and significant part of the manufacturing strategy for many companies (Chan & Lam, Chee-Pui Lee, (1999)). One of the reasons has been the recent implementation of philosophies like lean manufacturing which pursues the elimination of waste (i.e. non value added activities). A cellular manufacturing (CM) system consists of a group of closely located workstations where multiple, sequential operations are performed on one or more families of parts and products. The majority of CM systems are designed as labor limited systems in which there are fewer operators than machines. From their beginnings cellular manufacturing has rely on labor flexibility, a system in which operators perform multiple tasks (i.e. multifunctionality) and can be allocated using different assignment rules. Labor flexibility is developed through cross-training operators in different tasks.

Most cellular manufacturing implementations do not consider in their design and operational phases social-technical factors. However, in practice the performance and success of a cell are directly linked to the degree in which human issues are considered. According to Bidanda et al. (2005) the lack of consideration of socio-technical factors has been because of the difficulty of measuring these parameters. Furthermore, it has been studied that operators who are not comfortable in their respective tasks tend to increase turnovers ratios Hyer and Wemmerlöv,(2002); therefore a complete breakdown of the training policy and performance will occur.

This research comprises quantitative evidence on cellular manufacturing labor assignment models taking into account both skills and preferences. After a vast literature review it was found a lack of research including human issues in worker assignment models. As a matter of fact, none of them incorporated this topic because of the complexity that some authors have identified in the literature once they tried to analyze them. This research developed a strategy to first consider human factors and then to incorporate them in a worker assignment model. The strategy used to successfully achieve the quantification and incorporation of those skills and preferences factors into a mathematical model was performed using a two phase methodology. The first phase, the qualitative phase, consisted of administering a work environmental survey and a cellular manufacturing questionnaire (interpreted using a multi criteria technique known as Analytical Hierarchy Process). This first step helps in the link between preferences and skills. The second phase, the quantitative phase, used a mathematical assignment problem approach known as the multicommodity assignment model to be able to incorporate skills and preferences in the cellular labor assignments. The challenges found in the literature are discussed in the literature review, where it is shown that for operators it is more important to take into account the preferences than the skills once they are going to be assigned. Finally, the integration in a two phase methodology of two phases of resulted on a feasible cellular manufacturing assignment that considers both preferences and skills making this one of the research major contributions.

The next sections of this chapter explained in details the objectives and scope of this research.

1.1 Problem Description

Several research studies including Askin & Y. Huang, (1997) and Warner, Kim Lascola Needy, & Bidanda, (1997) have investigated labor flexibility in CM and discussed the difficulty in measuring human issues quantitatively. This gap identified in previous works results in a lack of theory evidence of how to address this kind of issues. Because worker satisfaction is sometimes difficult to measure and validate previous, works have mainly focused on tangible performance (e.g. production rates, utilization, work in process levels, etc). The concern in recent literature however, is in the consideration of human issues. Therefore a model to quantify these aspects of work needs to be explored.

The aim of this work is to develop a quantitative model to describe and quantify operators' preferences and assess their impact on system performance.

1.1.1 Justification

Empirical research has shown that the majority of cellular manufacturing implementations do not consider in their design and operational phases socio-technical factors. However, in practice the performance and success of cells are directly linked to the degree in which these factors are considered.

1.1.2 Objective

The purpose of this work is two folded:

a) Identify and quantify the factors (characteristics) of the manufacturing environment that operators prefer (operators' preferences) and leads to worker satisfaction.

b) To develop a labor assignment model that considers both operational factors (demand, capacity, periods, and skills) and operators' preferences without impacting the system performance.

1.1.3 Scope

The quantitative part of this investigation was developed in a particular manufacturing area comprised of five cells and sixteen operators. The socio technical factors considered included skills and operators preferences limited to those identified in this particular manufacturing setting. Figure 1 shows the targets established in this research.

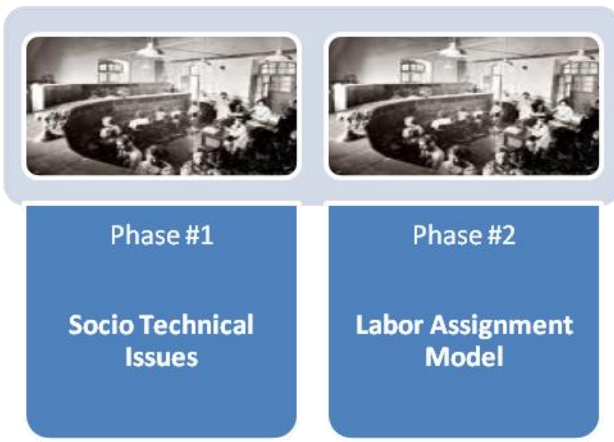

Figure 1. Phases

1.2 Approach

The approach to achieve the established objectives is divided in two phases: empirical study and mathematical modeling. The data collection for each phase relied on diverse sources of evidence including plant visits (to gather operational data), surveys, and focus groups. Phase I analyzes those factors that contribute to worker preferences and quantifies them. This phase includes the use of categorical analysis techniques such as questionnaires, focus groups and the application of the analytical hierarchy process. The results obtained in Phase I were used as inputs of Phase II.

Phase II consists in the development of a mathematical model that considers the costs of assigning an operator, operational factors and the established preferences. The mathematical model in which the preferences were taken into account focused on the multiperiod assignment problem. For this research the transportation multicommodity problem was proposed to solve the multiperiod assignment problem in cellular manufacturing.

1.3 Thesis Organization

The remaining of this document is organized in the following order; Literature Review is discussed in Chapter 2, Methodology in Chapter 3 and Results and Conclusions in Chapter 4 & 5 respectively.

2 Literature Review

The literature review for this research comprises several areas including: CM work design, labor assignment, human issues and skills, and cross-training. Figure 2 denotes a graphical representation of those areas by emphasizing the relationship of them with the satisfaction of employees according to various authors.

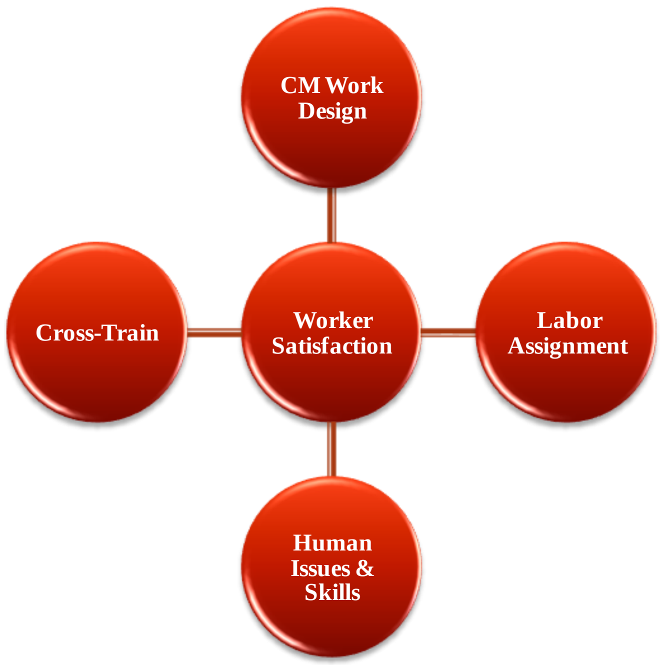

Figure 2. Worker Satisfaction (Source: **(Askin & Estrada, 2007)**, **(Norman, Tharmmaphornphilas, Kim Lascola Needy, Bidanda, & Warner, 2002)**)

The value added of labor cross-training in CM and the consideration of socio technical factors in their implementations are discussed extensively in the literature and reviewed in this section.

2.1 Cellular Manufacturing

CM has been described as a group of processes or machines, into specifics areas dedicated to the production of a family of parts. CM systems are typically designed a dual resource constraint systems where the numbers of operators' are less than the numbers of machines. As Cesaní & Steudel (2005) described DRC impacts the flexibility of the cell making the multifunctional workforce very critical to reduce the non-availability of a machine or a worker or both. Their cellular layouts improve the material flow which reduces the distance travelled by material, and therefore the cumulative lead times. However CM does not work with all kind of production environments as explained **Figure 3** success implementations are adequate for medium volume/medium variety environments.

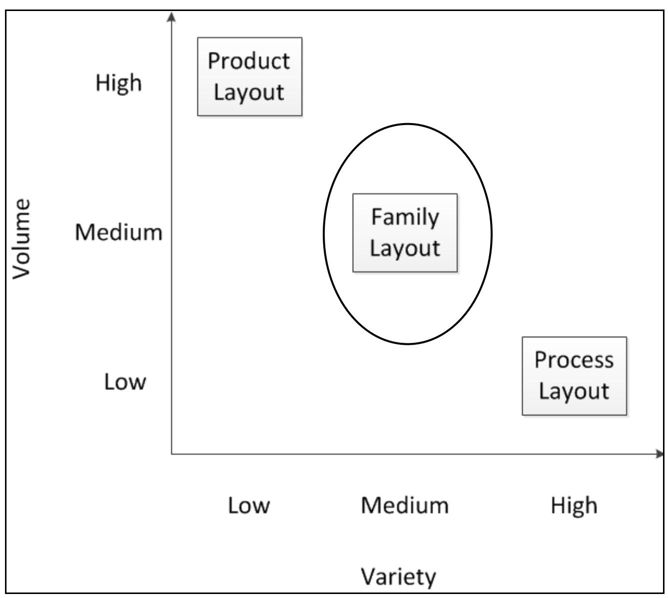

Figure 3. Cellular Environments, **(White, Bozer, & Tanchoco, 2002)**

Its implementation pursues the elimination of overflow among cells minimizing activities/times as bottleneck, waiting, and material handling (Pattanaik & Sharma, 2009).

Wemmerlov & Johnson, (1997), and Askin & Estrada (2007) using empirical evidence proved that companies have gained significant advantages such as lead time reductions, production space optimization, inventory reduction and quality improvements in their cellular manufacturing implementations. Results from their empirical study are summarized in **Table 1**.

Table 1: CM advantages

	Wemmerlöv & Johnson (1997)		
Performance Measure	MIN	AVG	MAX
Reduction of Move Distances or Move Times	15.00%	61.30%	99.00%
Reduction in Throughput Time	12.50%	61.20%	99.50%
Reduction in Response Time To Customers Orders	0.00%	50.10%	93.50%
Reduction in Work-in-Process Inventory	10.00%	48.20%	99.70%
Reduction in Setup Times	0.00%	44.20%	96.60%
Reduction in Finished Goods Inventory	0.00%	39.30%	100.00%
Improvement in Part/Product Quality	0.00%	28.40%	62.40%
Reduction in Unit Costs	0.00%	16.00%	60.00%

Some other benefits include improved productivity, communication, and quality. Communication is easier within each cell since every operator is relative close to the others thus improving quality and coordination and the sense of common mission enhances teamwork in the cell. In terms of worker productivity, the ability to deal with a product from start to finish creates a sense of responsibility and increased feeling of team achievement (Bidanda, Ariyawongrat, Kim Lascola Needy, Norman, & Tharmmaphornphilas, 2005).

The success of the cells has been clearly quantified in terms of business metrics such as production lead time, operators loading and throughput, among others (Norman et al., 2002). However, the structure design which includes labor assignment is very important

(Russell, P. Y. Huang, & Leu, 1991). Research work addressing models for CM labor assignments considering technical skills includes Cesaní & Steudel, (2005) Slomp, Bokhorst, & Molleman, (2005) Gürsel A., (1996) although the value of these models in significantly lack of considerations operators preferences (Norman et al., 2002), (K. E. Fraser, 2008). Why it is important to include them? Human skills were defined as follow; communication, conflict management, and teamwork needed in the transitions of job shops to cellular manufactures, researchers findings highlighted that these skills become as important as the technical skill (e.g. mathematics, machining, inspection, and data entry). (Bidanda et al., 2005).

2.2 Labor Assignment

This section reviewed and explained some labor assignment definitions, description and rules mentioned in the literature and how they are incorporated in CM.

Labor assignment for CM allows the allocation of operators into operations within cells, rules for those assignments are known in literature as Dual Resources Constraint, i.e. less or equal quantity of operators than machines. Bokhorst and Slomp, (2007) defined some important aspects for CM labor assignments that are; when (i.e. at what moment the labor become eligible to transfer), where (i.e. from which center or machine a worker need to be transfer) and who (i.e. when a worker becomes available to transfer) rule. Some when rules can also be explained as centralized (i.e. a worker is eligible to move once he/she has finished in a work center and decentralized (i.e. a worker is eligible to move if the work center is idle after he/she has finished). Planning control has also be taken into account by many researchers studying different labor assignments in cellular manufacturing, Pastor & Corominas, (2007) deals with an assignment of operators for each period of a planning horizon (i.e. multiperiod assignments). Some strategies of assignment have been defined in order to reduce the cost of assignment, Batta, Berman, & Wang, (2007) studied a problem of workloads by balancing and switching cost due to inflation in the demand services, and developed an assignment taking into account just the demand fluctuations. Aronson, (1986) tried to minimize the cost of assigning an operator in an environment where intra cell environment is allowed. To be able to successfully implement the dual resource constraint principle it's important to have the work force cross train, the concept is discussed in detail in the next section,

2.2.1 Labor Flexibility

Molleman and Slomp (1999) define labor flexibility with three basic concepts; total number of skills in a team, multifunctionality (i.e. the number of different machines a worker is able to operate) and redundancy (i.e. machine coverage). Those concepts allow the flexibility to take place in order to apply the dual resource constraint principle, therefore it will be important to cross-train operators in order to deal with capacity and demand fluctuations Balakrishnan & Cheng, (2007) and Aronson, (1986).

Labor flexibility has been modeled in many ways including models of labor utilization and skill improvement throughout SayIn & KarabatI, (2007) and Cesaní & Steudel, (2005) maximizing the worker utilization and skill considering the cross assignments. Hopp & Van Oyen (2004) developed a strategic assessment by a cross trained workforce supporting the organizational strategy; concluding that the flexibility may result in an improvement on labor productivity, responsiveness, and internal/external quality. Molleman and Slomp (1999) suggested as a general training policy that each task should be mastered by at least 2 operators in order to reduce the negative impact of absenteeism.

Mastered or remembered most of the task learned has been also a concerned for some researchers. Jaber & Kher (2002) studied the learning and forgetting phenomenon and developed a model to predict the time for a worker to learn a task taking into account the constant rotation. From this same article it can be derived the minimum period needed to transfer a worker in order to practice and not forget the tasks learned. The learning and forgetting phenomenon in labor flexibility is very important once the benefits of the training are studied. It is also important to create and developed a training policy in which the multifunctionality of the worker and the redundancy of the machine optimize the utilization of the resources and machines. Molleman and Slomp (1999) established that when the training of a task is too expensive it is appropriate to define a maximum of multifunctionality operators and to allow some maximum redundancy in the machines. Labor flexibility has also been analyzed taking into account system performance. (Cesaní & Steudel, 2005) studied a labor flexibility assignment model in which via simulation they analyze the utilization of the system changing the number of operators and assigning fixed and rotational operators.

The issues of labor flexibility also can be divided into levels Wemmerlov & Johnson, (1997) as shown in **Figure 4**.

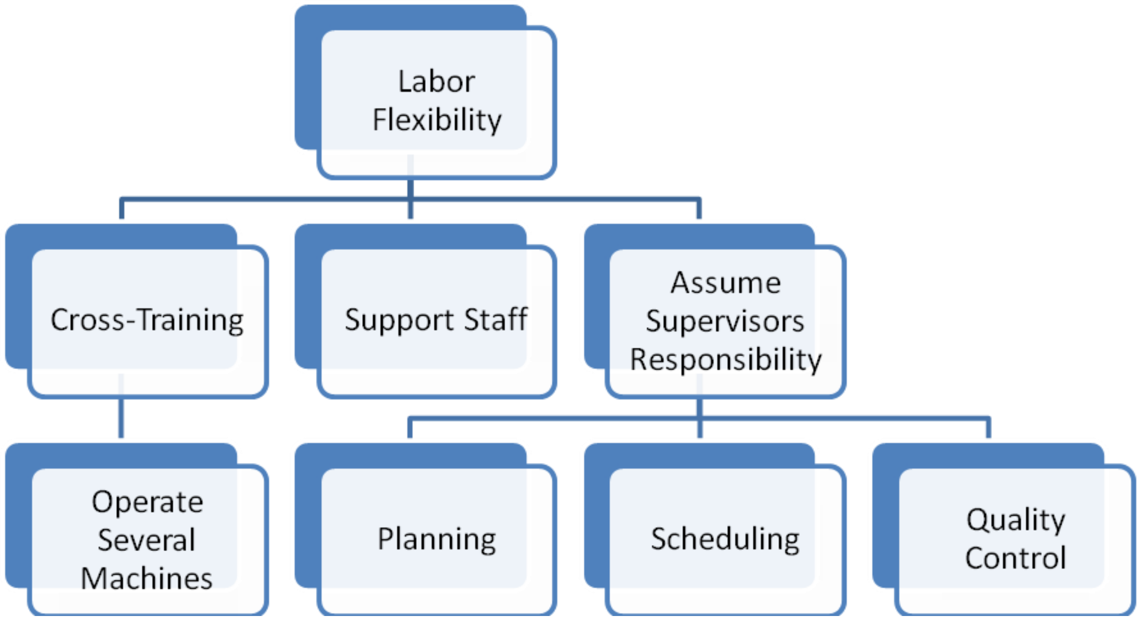

Figure 4. Flexibility Hierarchy (Source: **(Hyer & Wemmerlöv, 2002)**.

In summary labor flexibility is one of the drivers for the success of the CM implementation, therefore it will depend on operators' performance and this is directly influenced by the operator satisfaction.(Lee, 1988).

2.2.2 Skills

Research in cellular manufacturing specifically in human skills have been focused on the following characteristics; communication, conflict management, and teamwork needed in the transitions of job shops to cellular manufactures (Bidanda et al., 2005). These skills become as important as the technical skill such as mathematics, machining, inspection, and data entry (Cappelli & Rogovsky, 1994). **Figure 5** details each of the results that a skilled workforce contributed.

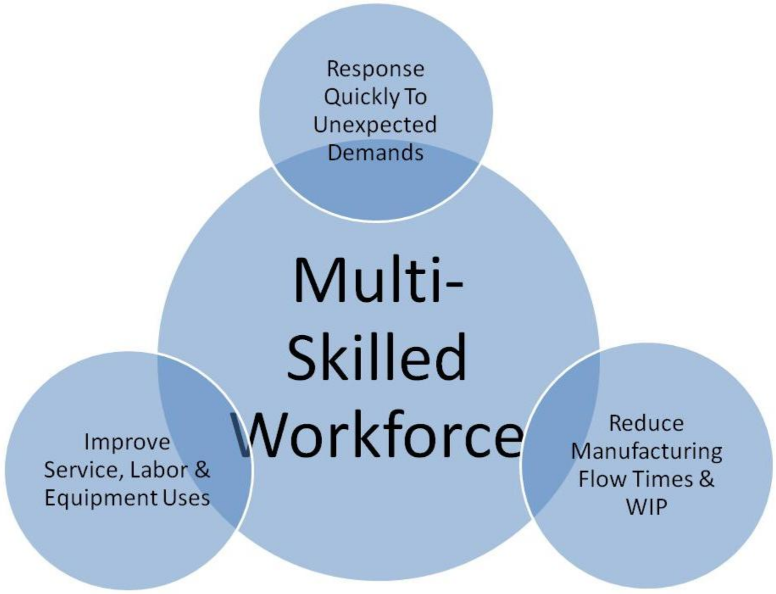

Figure 5. Skill workforce

Skills that an individual should have in CM will be less specialized and more flexible, (Bidanda et al., 2005). This will allow the organization to determine their training gaps and needs. A cross-training policy in this kind of environment is very common because of the flexibility emphasis.

There is a gap between the integration of skills in the workstations assignment and the consideration of human skills, (Bidanda et al., 2005) and (Fraser, 2008). Most of the work in the literature studies work team formation (Stevens & Campion, 1994), (Molleman and Slomp, 1999) and (Hackman, 1983) in isolation from the rest of planning and scheduling functions and also based mostly on skills. Few studies consider personal/human variables, beyond knowledge, experience and ability (Fitzpatrick & Askin, 2005) and (Stevens & Campion, 1994), however none of them has quantified those factors to incorporate them in their mathematical models. Table 2 shows a list of recent research work where factors such as human preferences were not included in their CM labor assignment mathematical models.

Table 2: Recent investigations of labor assignment including their main objectives

Paper	**Technical Skills**	**Human Issues**	**Model Considers Skills**	**Model Considers human issues**	**Objective Function Target**
(Cesaní & Steudel, 2005)	x		x		Maximize workload assignment
(Gürsel A., 1996)	x		x		Find the optimal manpower assignment and maximize cell loads
(Slomp et al., 2005)	x		x		Minimize the operating and training cost
(Satoglu & Suresh, 2009)	x		x		Minimize the labor assignment net capital cost
(Ertay & Ruan, 2005)	x		x		Maximize the operator's utilization
(John B, 2000)	x				Optimization of cellular layout and labor flexibility
(Süer, Cosner, & Patten, 2009)	x				Maximize production rate per products
(Mahdavi, Aalaei, Paydar, & Solimanpur, 2011)	x				Minimizes the total number of voids and elements in machine–part–worker
(Suer, Arikan, & Babayigit, 2009)	x		x		Maximize early jobs and minimize total man power

Note: An x means which type of skill (technical or human) is included in the research.

2.2.3 Socio-Technical Factors

The lack of studies in the socio-technical area is a result of the complexity in understanding human issues and their relationship to production performance. Literature in CM has intensively address technical problems such as

- workflow balancing
- machine-part groupings
- workforce scheduling
- material handling
- cell layout
- cell capacity

Therefore one of the biggest impacts of labor flexibility is how to align worker satisfaction which according to (Lee, 1988) is the organizational commitment to stay in the job with socio technical characteristics. More characteristics that affect the worker satisfaction have been identified by (Bidanda et al., 2005), (Burbidge, 1975) , (Fitzpatrick & Askin, 2005) and (K. E. Fraser, 2008) including:

1. Worker Assignment
2. Skill Identification
3. Training
4. Communication
5. Compensation
6. Conflict Management

Figure 6 shows some of the characteristics recognized in the literature review.

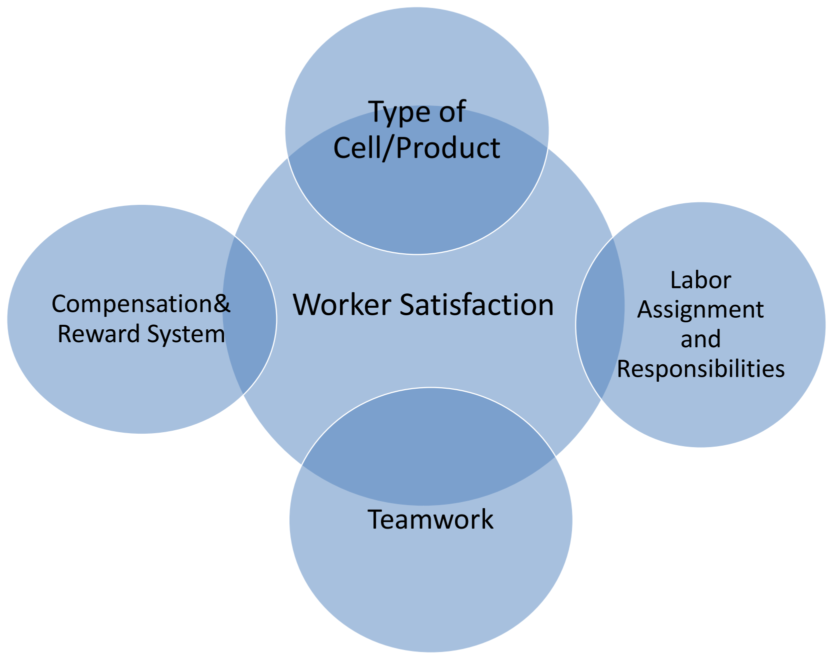

Figure 6. Worker Satisfaction Cycle

As described in section 2.2.2 it is important to consider both the technical and human skills. Wemmerlov & Johnson, (1997) "…the picture that emerges from this study is clear restructuring the factory to adopt cellular manufacturing should not be viewed merely as a technical, engineering-dominated problem but as a change process where the people element dominates". This concerned that Wemmerlov & Johnson had evolved in the following; (K. Fraser, 2008) "Where socio-technical systems such as cellular manufacturing are involved, both aspects need to be considered to maximize success. What is not addressed in the literature is the level of influence that either aspect has on CM systems. Are human factors important? ".

Furthermore, the absence of investigations related to human issues in CM is noticed;

there is a variety of this situation including the difficulty to quantify these needs, (Bidanda et al., 2005) and (Fraser, 2008). The lack of understanding of human issues in this kind of manufacturing environment can significantly reduce the benefits of group technology (Udo & Ebiefung, 1999). Table 3 show research studies from 1974 – 2005 that include human factors in their investigations however these models do not quantify and incorporate those factors in a labor assignment model.

Table 3: Research considering human factors (Source: **(K. E. Fraser, 2008)**)

Human factor studies	**Human Factors**										
	Supervision	**Worker assignment strategies**	**Skill identification**	**Training**	**Communication**	**Autonomy**	**Reward/compensation system**	**Teamwork**	**Conflict management**	**Top management support**	**Cell worker selection**
Bidanda et al. (2005)		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**		
Olorunniwo & Udo (2002)		**x**								**x**	**x**
Norman et al. (2002)	**x**		**x**		**x**				**x**		
Park & Han (2002)	**x**			**x**	**x**			**x**			
Small & Yasin (2000)				**x**				**x**			
Udo & Ebiefung (1999)				**x**			**x**			**x**	
Hyer et al. (1999)	**x**	**x**		**x**			**x**	**x**			
Wemmerlöv & Johnson (1997)		**x**		**x**			**x**			**x**	**x**
Badham & Couchman (1996)				**x**		**x**				**x**	
Afzulpurkar et al. (1993)				**x**				**x**			
Harvey (1993)							**x**				
Huq (1992)	**x**			**x**							**x**
Huber & Brown (1991)		**x**		**x**			**x**	**x**			**x**
Wemmerlöv & Hyer (1987)	**x**	**x**					**x**				
Huber & Hyer (1985)	**x**	**x**	**x**	**x**		**x**	**x**	**x**	**x**		
Fazakerley (1974)							**x**	**x**		**x**	
Totals	**6**	**7**	**3**	**11**	**3**	**3**	**9**	**8**	**3**	**5**	**4**

Bidanda et al (2005) agree that the socio-technical factors need to be explored and provide certain characteristics of human issues which may be equally important as technical skills. Furthermore, couple of authors K. E. Fraser, (2008) and Lee, (1988) have identified that there is a lack of empirical models considering those factors. Table 4 summarizes those research which incorporate people as variables without taking into account the human aspect in their models.

Table 4: Authors considerations in their CM investigations (Source: **(Nomden, 2011)**)

	Author(s)	**Resources**	**Implementation level**	**Layout**	**GT**	**Auto-mation**
Design	Altom, 1978	M/-/-	MPS/-/-	L	GT	
	Drolet et al., 1996	M/H/-	-/-/-	L		A
	Irani et al., 1993	M/H/-	MPS/-/-	L	GT	A
	Ko & Egbelu, 2003.	M/-/-	-/MRP/-		GT	
	Kühling, 1998	M/-/P	MPS/MRP/-		GT	
	Mak & Wang, 2002	M/H/-	-/MRP/SFC	L		A
	McLean et al., 1982	M/-/-	-/MRP/-			A
	Mertins et al., 1992	M/-/P	MPS/MRP/-			
	Montreuil et al., 1992	M/H/-	-/MRP/SFC	L		A
	Moodie et al., 1994	M/H/-	-/MRP/SFC	L		A
	Prince & Kay, 2003	M/-/P	MPS/-/-		GT	
	Ratchev, 2001	M/H/-	-/MRP/-	L	GT	A
	Rheault et al., 1995	M/-/-	-/MRP/SFC	L	GT	
	Saad et al., 2002	M/H/-	-/MRP/-	L	GT	A
	Sarker & Li, 2001	M/H/-	-/MRP/SFC			
	Slomp et al., 2004; 2005	M/-/P	-/MRP/SFC		GT	
	Subash Babu, et al., 2000	M/-/-	MPS/MRP/-		GT	
	Thomalla, 2000.	M/H/-	-/MRP/SFC			
	Vakharia et al., 1999	M/-/-	MPS/-/-		GT	
Operation	Flynn, 1987.	M/-/-	MPS/-/SFC	L	GT	
	Flynn & Jacobs, 1986; 1987	M/-/-	MPS/-/SFC	L	GT	
	Jacobs & Bragg, 1988	M/-/-	-/-/SFC			
	Jensen, et al., 1996, 1998	M/-/-	-/-/SFC	L	GT	
	Kannan, 1997	M/-/-	-/-/SFC		GT	
	Kannan, 1998	M/-/-	-/-/SFC	L	GT	
	Kannan & Ghosh, 1995.	M/-/-	-/-/SFC		GT	
	Kannan & Ghosh, 1996a, b	M/-/-	-/-/SFC	L	GT	
	Shambu & Suresh, 2000	M/H/-	-/-/SFC	L	GT	
	Suresh & Meredith, 1994	M/-/-	-/-/SFC	L	GT	
	Suresh & Slomp, 2005	M/-/P	-/-/SFC	L	GT	
Empirical	Hyer & Brown, 1999	M/-/P	MPS/-/-	L	GT	
	Wemmerlöv & Hyer, 1989	M/-/P	MPS/-/-	L	GT	
	Wemmerlöv & Johnson, 2000	M/-/P	MPS/-/-	L	GT	

Legend:
Resources: M (Machines), H (Material handling equipment), P (People)
Implementation level: MPS (Master Production Schedule), MRP (Material Requirements Planning), SFC (Shop Floor Control)
Layout consideration: L (Layout considered explicitly)
GT: Group Technology used explicitly
Automation: A (Automated manufacturing system assumed)

A couple of surveys have been made by CM authors to statistical find the needs of the operators or results of CM; Wemmerlov & Johnson (1997), Bidanda et al. (2005), K. Fraser, Harris, & Luong (2005), K. E. Fraser (2008) among others. However, although they mentioned how important it would be to consider those factors, none of them have incorporated the variables in their mathematical labor assignments. Further sections of this investigation show a method to translate the survey into empirical data to be able to incorporate them in the mathematical model.

Many researchers have investigated the importance of labor flexibility in cellular manufacturing and some of them have identified that socio-technical factors plays an important role in the success of labor assignments in CM. However there is a lack of models that incorporate technical factors in their mathematical formulations.

3 Methodology

This chapter contains the methods and activities developed in order to achieve the objectives of this investigation. In order to understand the importance of human factors in manufacturing and their relationship to system performance, the methodology for this research included both qualitative and quantitative studies. This two phase approach is described next:

a) Phase I: Qualitative Study

b) Phase II: Quantitative Study

3.1 Phase I: Qualitative Study

Many researchers have investigated the importance of labor flexibility in cellular manufacturing and some of them have identified that socio-technical factors play an important role in the success of labor assignments in CM. To empirically validate these claims two studies were conducted. The first study was an environmental survey applied as a research tool to explore issues related to job satisfaction and employee engagement. The purpose of this instrument was to gather information from the operator's point of view regarding the importance of human factors versus technical factors in cell systems. The instrument developed for this purpose was based on a previous study by Fraser (2008). The instrument is composed of twelve questions; eight questions with predefined answers and four open-ended questions. The instrument used is included in Appendix A. Questions 1 through 3 gathered information regarding the experience of the operators working in CM environments. Questions 4 and 5 were used to assess their opinions regarding the importance of technical versus human issues. Questions 6 and 7 focused specifically on technical issues. Whereas, questions 8 and 9 focused specifically on human issues.

Questions 10 and 11 referred specifically to issues related to operator's allocation on labor assignments within the cells. These questions were particularly important to the quantitative approach of the research. Question 12 was an open-ended question in which operators could comment about work in a CM system. In order to administer the survey the following protocol was followed:

a) The first step was the selection of the cellular manufacturing environment to conduct the study. A particular requirement was that the CM system needed to be characterized by a labor intensive nature and designed as a labor limited system. Furthermore, operators needed to be cross-trained and inter or intra cell labor mobility allowed. After contacting several companies, a major electronic manufacturing company was found suitable for the study and was willing to participate. It is worth mentioning, that identifying a company suitable for the study and obtaining the approval to conduct the study was very challenging. The majority of the companies' contacted did not allow students to conduct research studies in their facilities due to confidentiality issues.

b) Before conducting the study, the questionnaire form was submitted and approved by the UPRM Institutional Review Board for approval, (see Appendix J).

c) After a confidentiality agreement was signed, the questionnaire was finally administered to 27 operators. The questionnaire analysis and results are included in Chapter 4.

d) The work environmental survey was constructed from the manufacturing operator's perspective of whether or not these factors are important. (A copy of this questionnaire is included in Appendix A, this survey was validated among different countries and manufacturing companies).

In order to link the importance of human factors to system performance the following research question (RQ) was made:

- RQ: In the operation of cellular manufacturing systems, should technical issues and human factors be equally considered?
- The hypothesis for RQ:

  Ho: Technical issues and human factors are equally important.

  Ha: Technical issues and human factors are not equally important.

The results of both the questionnaire and research questions are presented in Chapter 4 and justified the importance of the research empirical work to be further integrated into the mathematical assignment problem.

3.1.1 Empirical Work

The empirical study relied on diverse sources of evidence including plant visits, questionnaire surveys and focus groups. For the purpose of this investigation, multiple plant visits were made in order to understand the manufacturing settings, assignment rules, operators' skills, workloads, and cellular layouts. The company selected for this study had the same characteristics as described previously; a labor limited system and labor intensive CM environment, where inter or intra cell mobility was allowed. **Figure 7** shows the relationship among the different sources of evidence in the qualitative phase. The first step in order to understand the manufacturing environment was to conduct a focus group with a group of operators.

Step 1:

A matrix was developed to classify the operator as skillful or not. Operators are classified as skillful if he / she has been trained in that operation. (i.e. certified in the task) and has developed proficiency (according to supervisor's input).

In order to measure the skills of a worker and to elaborate the skill matrix, operators and supervisor input were needed.

- In this study as in most companies, the assumption is that the manufacturing policy promotes, job cross-training in order to reduce operation hazards, boredom, and provide flexibility in the labor assignment process.

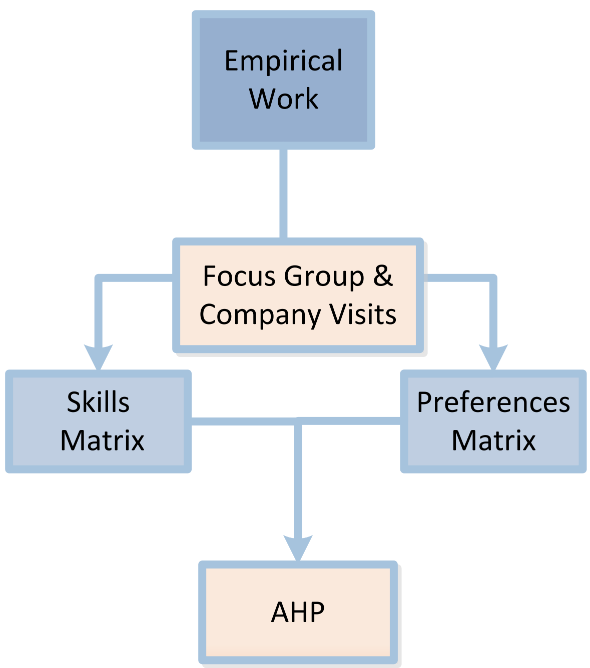

Figure 7: Empirical Work

The skills mentioned in this section include those related to cognitive and mechanics issues. Furthermore, those techniques require being agile and fast (i.e. excellent standard time). The skill matrix is presented in Chapter 4 and it was developed for 16 operators and 21 operations distributed among 5 cells.

To understand the skills and preferences of the operators, both a questionnaire and focus group were administered. A description is provided next.

Step 2:

An essential and critical part of this analysis was to identify and quantify those factors that contribute to worker preferences. In order to develop a practical model, this analysis relied on empirical evidence and categorical data analysis techniques.

a) Focus Group: This technique consists of a carefully planned discussion designed to obtain the perception of a group of members on a defined area of interest. Group methodologies are a great instrument to support conventional analysis, "*This is largely because the interactive and synergetic nature of groups discussions (one of the central themes of focus group research) allows deeper insights into how and why people think and behave the way they do*" (Langford & McDonagh, 2002) . The procedure by Langford & McDonagh, (2002) was used as guide for the focus group, the methodology and script used is presented in Appendix B. The questions used to guide the discussion in the focus group are included in Appendix B. The purpose of this exercise was to get familiar with the operators and to understand how they perceive their job. At the end of the session, a form (questionnaire) for the operator's to fill out was handed out.
b) Questionnaires: This tool was given to operators to measure their preference among operations, and team work. The questionnaire intends to gathered information about

the worker preference regarding the type of family parts, cell shape, working pace, working position that they like the most, it also captures whether they like to work as part of a team or alone. Details of the questionnaire surveys are shown in Appendix C. It is very important to understand the relationship between the operator's preferences and their manufacturing cells because the results of the questionnaire guide the strategies for the mathematical model (i.e. Phase II). The information gathered was totally confidential from the management perspective but not for the research point of view. However, the company received general feedback about the questionnaire and other relevant information. The activity required no more than thirty minutes to be executed; it means that the impact of lost production time was minimized as requested by management. This information was used to ranked operators' preferences.

c) Operator Preferences Matrix: The focus group and questionnaire were inputs for the construction of the preferences matrix of the operators.

The survey was translated into weights by using the Analytical Hierarchy Process.

3.1.2 Analytical Hierarchy Process

The Analytical hierarchy process (AHP) was developed by Saaty (1980) and this methodology has reported applications in the fields of transportation planning, portfolio selection, corporate planning, and marketing among others. The advantage of the AHP method lays in its ability to structure a multiperson, multiattribute problem hierarchically. It consisted of pairwise comparisons of the elements (usually, alternatives and attributes) that can be established using a scale indicating the strength with which one element dominates another with respect to a higher-level element. The pairwise comparisons aim to eliminate subjectivity and quantitatively represent qualitative data. To conduct the AHP methodology five stages are needed.

Stage 1: Construct a decision hierarchy by breaking down the decision problem into a tree of decision elements identifying decision alternatives. For this case, **Figure 8** presents the hierarchy process proposed for this research.

The attributes for worker preferences included issues related to work design such as:

1. Type of Task: working in team or alone
2. Velocity
3. Cell Shape/Space: working in a L-shape, U-shape or straight-shape design
4. Cell Family: working with different family parts
5. Type of Operation: assembling, packaging, screwing, etc
6. Administrative Task: doing schedules, quality or production reports

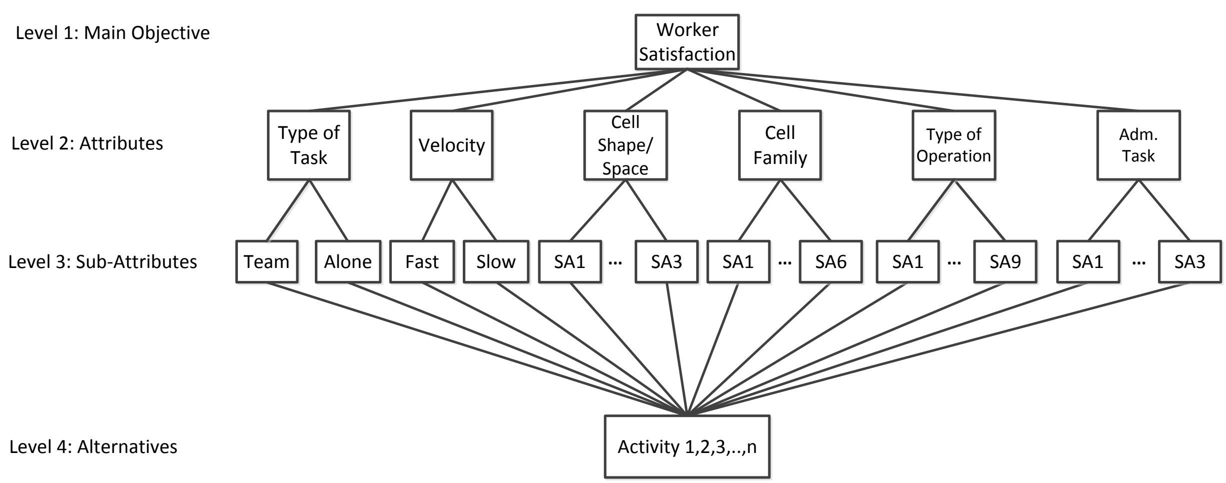

Figure 8. Hierarchy Diagram

Stage 2: Determination of the relative importance of attributes and sub attributes (if any).

To make the pairwise comparisons the scale presented in Table 5 was used:

Table 5: Saaty's scale for pairwise comparison

Equally Important	1
Weakly More Important	3
Strongly More Important	5
Very strongly More Important	7
Absolutely More Important	9

Stage 3: Determination of the relative standing (weight) of each alternative with respect to next higher level attributes or sub attributes. This stage is based on the scale of Table 5 and operators' input using the questionnaire.

Stage 4: Determination of indicators of consistency in making pairwise comparisons:

- There are two measures of consistency for the AHP method (the formulas for this measure are presented in Section 4.5.2)
  - Local – CR (consistency ratio)
  - Global – CRH (global consistency ratio)

Stage 5: Determination of the overall priority weight (score) of each alternative

The last stage of the AHP is to calculate the weight of each alternative. For this calculation the following formula is used.

$$Alternative_k = \sum_{j}^{n_2} \sum_{i}^{n_1} (principal.vector.weight) * (evaluation_{ijk}) \ \forall k \qquad (1)$$

3.2 Phase II: Quantitative Study

The mathematical model in which the preferences were taken into account focused on the multiperiod assignment problem. The transportation multicommodity problem was used to solve the multiperiod assignment problem in cellular manufacturing. Section 3.2.1 and 3.2.2 discusses this model.

In this phase the results from Phase 1 were incorporated into a mathematical model. The greatest challenge faced was to have enough skilled operators for a large number of tasks. The results of the model provide a contingency plan for unexpected situations, such as absenteeism, accidents and breakdowns in the process. **Figure 9** shows the operational and human issues were taken into account in the model.

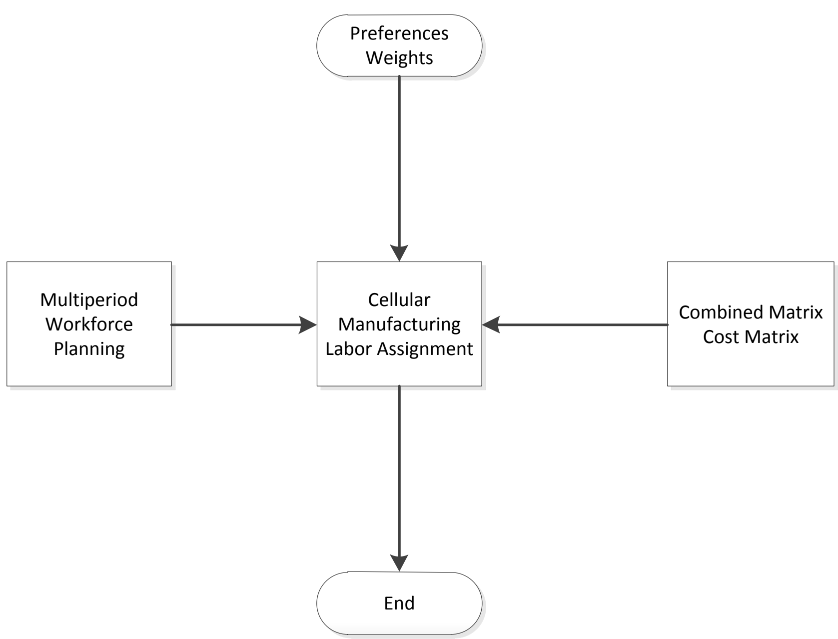

Figure 9. Phase Methodology

Phases I and II were combined by using the preference weights from the AHP model as input to the mathematical model. In order to accomplish the second objective of this research, additional data and analysis were needed:

a) Rough Cut Analysis to determine numbers of operators: The workforce planning model used (W. Hopp & Spearman, 2000) relates the profit generated by the product with the cost of inventory and labor costs. The model is shown in Appendix D and it was used to determine the expected operators demand per cell.
b) Cost Matrix: This matrix is based on the skill matrix previously explained and it basically assigns a cost (i.e. operator assignment) on each skill task of the worker.
c) Combined Matrix: The combined matrix is a combination of both the preference matrix and the skill matrix. **Figure 10** shows an example of the matrices.

Skills

Period 1	1		2		
Worker 1 / operation	1	2	3	4	5
Worker 1	X	X		X	X
Worker 2	X	X	X	X	
Worker 3	X			X	X

Preferences

Period 1	1		2		
Worker 1 / operation	1	2	3	4	5
Worker 1	X	X		X	X
Worker 2	X		X	X	
Worker 3	X		X	X	X

Combined

Period 1	1		2		
Worker 1 / operation	1	2	3	4	5
Worker 1	X	X		X	X
Worker 2	X		X	X	
Worker 3	X			X	X

Figure 10: Combined Matrix

Note: In the skills and preferences matrices an X means that the operator has the skill or preference in a particular operation, the combined matrix indicates those operators' that not only have the skill but also have the preference in a particular operation.

3.2.1 Network Description

The model used in this research was the multicommodity transportation problem (MCTP) also known as the multiperiod assignment problem (Aronson, 1986). For this case the commodity is defined as the worker in which *n* operators will be assigned *m* operations over a discrete time period with demand fluctuations. Furthermore, the model assigns operators taking into account the assignment costs of the next period and the preferences of each worker. **Figure 11** summarizes the idea of the multicommodity case, 3 operators must be assigned to 2 cells with different demands fluctuations among periods. Given that cells are designed as dual resource constrained systems a fraction worker can be assigned in any of the 5 operations. To guarantee that all operations are covered a couple of modifications were made in order to adopt the model to the actual problem (i.e. CM).

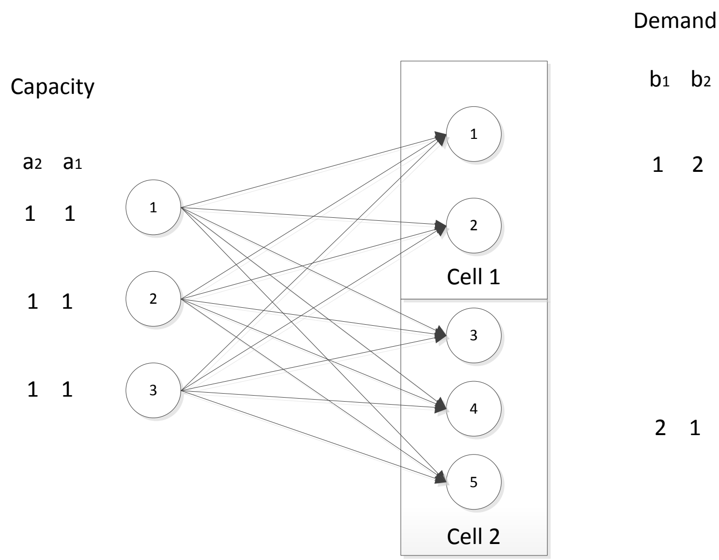

Figure 11: MCTP example

3.2.2 Model Discussion

The multicommodity network flow can be formulated as a linear program. The mathematical formulation for this problem is explained below:

Given:

p_{ijkl} = preference (weight) of a worker *i* assigned to cell *j* for operation *k* in period *l*, where $p_{ijkl} \leq 1$ (based on AHP).

c_{ijkl} = cost to assign a worker *i* in cell *j* to an operation *k* in a period *l*.

a_{il} = 1 for each period *l* the capacity of each worker *i* is equal to 1.

b_{jl} = demand for cell j in period l.

Decision variables

x_{ijkl} = Operators *i* assigned to cell *j* in operation *k* for period *l* (operators could be assigned in fractions due resource constraints).

$i = \{1,..,n_1\}$ where n_1 is the number of operators

j = $\{1,..,n_2\}$ where n_2 is the number of cells

k ={1,..,n_3} where n_3 is the number of operations

l ={1,..,n_4} where n_4 is the number of periods

Objective Function:

$$\text{Min } \sum_i \sum_j \sum_k \sum_l (1 - w_{ijkl}) * cx_{ijkl} \tag{2}$$

Subject to:

$$w_{ijkl} = p_{ijkl} * x_{ijkl} \quad \forall i, j, k, l \tag{3}$$

$$cx_{ijkl} = c_{ijkl} * x_{ijkl} \quad \forall i, j, k, l \tag{4}$$

$$\sum_k \sum_i x_{ijkl} = b_j^l \quad \forall j, l \tag{5}$$

$$\sum_k \sum_j x_{ijkl} = a_i^l \quad \forall i, l \tag{6}$$

$$\sum_i \sum_j x_{ijkl} \geq .10 \quad \forall k, l \tag{7}$$

$$\sum_i \sum_j x_{ijkl} \leq 1 \quad \forall k, l \tag{8}$$

$$\sum_j \sum_k a_l^i = \sum_i \sum_k b_j^l \tag{9}$$

For this model, the objective function (2) minimizes (3) and (4) which are the dissatisfaction and the sum of the cost to assign an operator, respectively. It is subject by (5) which is the cell demand that must be satisfied, (6) the capacity of operators that can be assigned in each period. Constraint (7) is to assure that operation k in period l will at least have a 10% of a worker assigned to it. Constraint (8) is to assure that no more than one worker will be assigned to an operation in any given period. Finally constraint (9) guarantee's that the supply is equal to the demand.

The results of the different phases are presented in the next chapter.

4 Analysis and Results

The findings of this research for both phases, qualitative and quantitative, are presented in this chapter. We provide insight to the CM literature and their implementations.

4.1 Phase I analysis

The analysis of Phase I provides an explanation of qualitative results regarding the empirical work (i.e., work environmental survey & questionnaire). As mentioned in section 3.1, an environmental survey was conducted to get the insight from operators' perspective regarding their preferences and skills once they are assigned to a task. The next sub-section explained in detail the results of this survey.

4.1.1 Work environmental survey

The survey described in section 3.1 was administered to 27 operators in a labor intensive manufacturing area. The instrument provided insight into whether or not operator's skills are equally important than preferences in the labor assignment process. The results for each of the questions are presented next:

A) Questions 1 and 3 gathered information regarding the experience of the operators working in CM environments. In general, this section of the survey provided a general background of each of the operators interviewed and provided a good insight of how experienced they were in this particular field.

- Are you or have you been involved in cellular manufacturing work?
    - 100% of the operators' interviewed have been involved with cells.

- How many years have you been involved with cellular manufacturing?
    - Table 6 shows the breakdown for the 27 operators in terms of work experience in CM systems. The results show that most operators have significant experience working in CM systems.

Table 6 Years of experience in CM systems

Years	Total Workers'
0-1 years	3
1-3 years	3
3-5 years	3
8-10 years	5
> 10 years	13

- What is the average number of people per cell you have been involved with?
    - Table 7 shows the breakdown for the 27 operators, these results show that the majority of the operators work or have worked in cells ranking from 1-4 operators per cell.

Table 7 Average cell sizes operators have experience working

Average per Cell	Total Workers'
1-4 per cell	23
5-7 per cell	1
8-10 per cell	1
>10 per cell	2

B) Questions 4 and 5 were used to assess operators' opinion regarding the importance of technical versus human issues. These two questions were integrated to address the formulated research question.

- Do you understand that most of the critical problems in cell operations come from:

a) Technical factors (e.g., missing materials, equipment downtimes, etc.)

b) Human factors (lack of communication, skills, lack of skills, lack of training, etc.)

c) Both (technical and human factors)

- Table 8 summarizes the results for question 4:

  Three percent (1/27) of the operators believe that the critical problems of the cells come from human factors. Fifty six percent (15/27) believe that technical factors are the main source. Finally, forty one percent (11/27) believe the source of critical problems is grounded on both technical and human issues. The fact that a significant number of operators agree that critical problems in CM systems are caused by technical factors is understandable since these problems include issues such as equipment breakdown, lack of material, etc. In other words, factors that when occurred make the CM system vulnerable in operation and thus critical in nature.

Table 8: Summary of results question 4

Question 4	Total
Human Factors	1
Technical Factors	15
Both	11
Grand Total	27

- Based on your experienced working in cellular manufacturing, please tell us which are more important for you.

- Technical Factors
- Human Factors
    - Question 5 addresses a type of question based on experience and as reflected in Table 9, 15/27 (56%) believe that human factors are more important, 9/27 (33%) believe that technical problems are more important, while 2//27 (7%) believe that both are important and 1/27 (4%) did not answer.

Table 9 Results of Question 5

Question 5	Total
Human Factors	15
Technical Factors	9
Both	2
Not Answer	1
Grand Total	27

The significantly high number of responses associated with the importance of human issues represents an important research result. After using empirical data this result validates our initial assumption about the importance of considering human issues in CM systems. It is important to highlight that human factors are associated with the social structure of the operators in the cell and in its daily work.

C) Questions 6 and 7 (refer to Appendix A for both questions) focused specifically on technical issues.

- Question 6 openly addresses operators' perspectives regarding common CM technical problems.
    - Figure 12: Principal Technical Problems. Using a Pareto diagram the principal technical problems from the operators' point of view in order of importance are: missing materials needed for production, equipment breakdown, material handling problems, scheduling problems, inappropriate cell layout, deficient or insufficient cross train, among others.

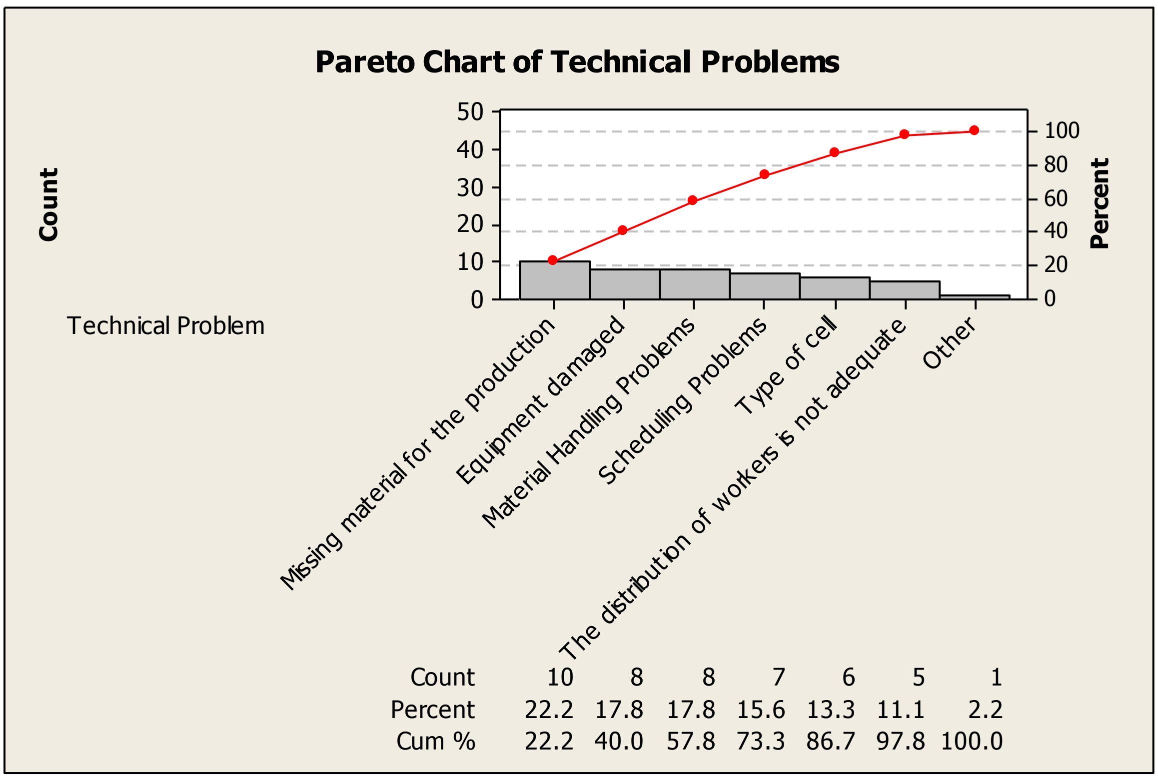

Figure 12: Principal Technical Problems

- Question 7: Using an opened question we gathered information regarding additional technical problems that were not listed in Question 6.
    - Operators' answers were diverse and included:
        - Obsolete Parts, less administrative tasks, more mechanic personnel in the manufacturing area, and managerial issues such as getting operators' opinions before a layout change.

D) Questions 8-9 focused specifically on human issues (refer to Appendix A for question 8)

- Question 8 captures the perspective of the operators in terms of the success of the cell if some human attributes are taken into account.
    - Figure 13 using a Pareto diagram shows the most important human issues. For this particular environment the most important factors in order of importance are communication (19%), training (15%), skills (12%) identification and, workers assignment (12%).

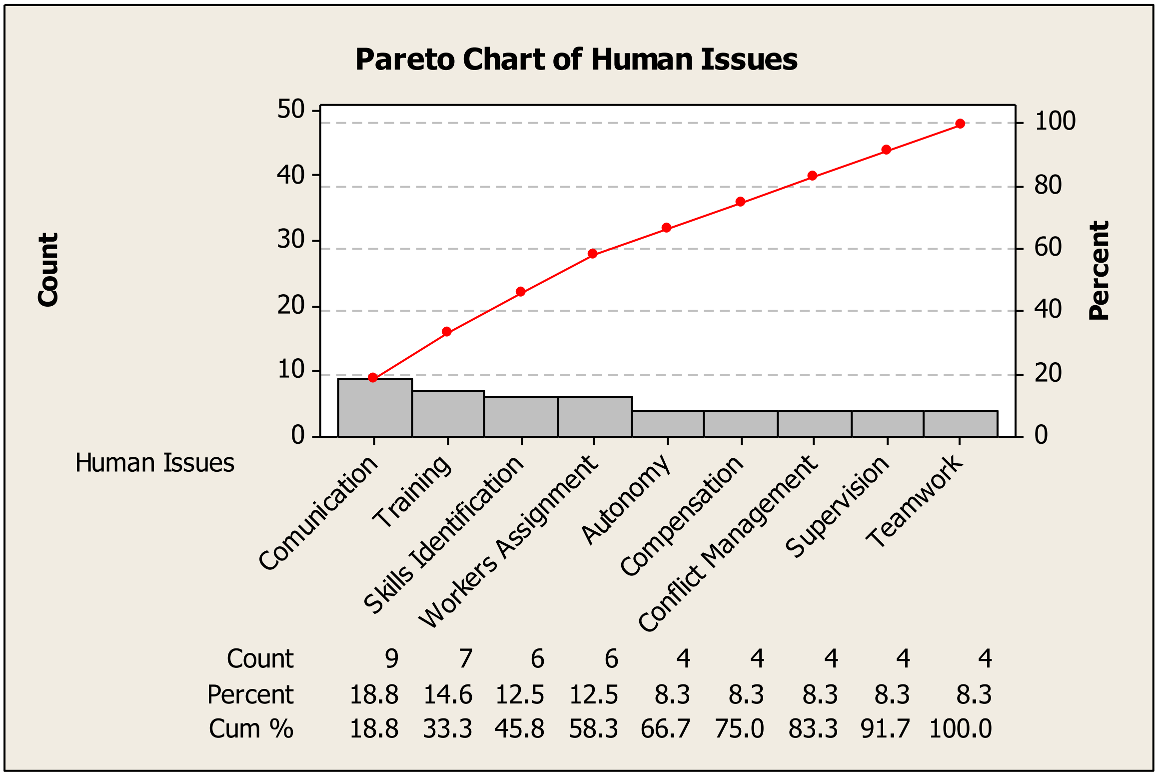

Figure 13 Principal Human Problems

- Question 9: In this question operators were asked to comment on any other human issue or operator related problem considered important in the manufacturing cells and that was not listed in Question 8.

  - Generally speaking answers were diverse and included:

    - Lack of leadership, lack of engagement, the employee need to be mentally prepared to execute the manufacturing tasks.

E) Questions 10 and 11 referred specifically to issues related to operator's allocation on labor assignments within cells.

- Question 10 (please refer to Appendix A) inquiries the most typical issues related to the labor assignment: Operators identified two main issues: uneven work (i.e. load is not level among operators') and lack of skills.
    - Furthermore, operators' lack of skills and absenteeism were mentioned as the most critical factors for failure in labor assignments. The term failure in this context refers to the inability in reaching the desired production rate.
- Question 11: If you had the opportunity to lead as the operators are assigned to manufacturing areas (cells) what would you take into account.
    - Generally speaking answers were diverse and included:
        - A diversity of answers were included in this section but the most highlighted answers pinpoint at skills & engagement, knowledge, and training.

4.1.2 Research Question

The statistical Research Question (RQ) are summarized and presented below:

- RQ: In the operation of cellular manufacturing systems, should technical issues and human factors be equally considered?
- The hypothesis for RQ:

Ho: Technical issues and human factors are equally important.

$$H_0 : P_{HF} = P_{TF}$$

Ha: Technical issues and human factors are not equally important.

$$H_{a:}\ P_{HF} \neq P_{TF}$$

For computational purposes Question 5 was used to analyze the hypothesis. Out of the 27 operators three observations were eliminated due to lack of response. A test for two proportions was used to statistically test the research hypothesis.

- The proportions P_{HF} (HF- human factors) and P_{TF} (TF- technical factors) were computed as:
  - $P_{HF} = \frac{15}{24}$
  - $P_{TF} = \frac{9}{24}$

Results for each scenario are presented below:

Test and Confidence Interval for Two Proportions

Sample	X	N	Sample p
1	15	24	0.625000
2	9	24	0.375000

Difference = p (1) - p alida(2)
Estimate for difference: 0.25
95% lower bound for difference: 0.0201247
Test for difference = 0 (vs > 0): Z = 1.73 P-Value = 0.042

From the Test Proportion (p<.05) therefore there is no evidence to accept Ho.

Therefore for both scenarios it can be concluded that the environmental survey reflects that human issues are more important than technical. Therefore, the conclusion from

Questions 4 & 5 and the statistical analysis is that human factors have the biggest impact from the operators' perspective.

4.2 Case Study Company Background

Part of this analysis is based on two companies; their names are not mentioned for confidential reasons. Generally speaking, the companies studied sell a wide variety of products for generation, transmission, distribution, control, and use of electricity for different types of business ranging from coffee shops to airplanes. Some characteristics of the plants include:

- Business- Manufacturing Industry
- Business Type -Fabrication, Molding, and Assembling
- Production Variety and Volumes-"High Mix, Low Volume"
- Workforce - 220 employees
- Lines- 48 production lines

Some of their line of products includes contactors, starters, lighting, push buttons, and overloads, among the others. These products are industrial equipment that protects other electrical equipments on subassembly parts.

4.3 Human Issues vs. Manufacturing Goals

This work has been divided into two phases and for each of the phases a target has been established. Phase 1 intended to distinguish the qualitative data (i.e. worker preferences) and translate into quantitative factors using categorical data analysis methods such as focus groups and AHP. To accomplish the target established this study focuses on a manufacturing area that is comprised of five cells. The cells are identified by the following numbers:

1. 101
2. 124
3. 105
4. 305
5. 1062

The detailed layout of each cell is presented in Appendix D. The manufacturing area can be classified as a labor limited system since there are 16 operators and 21 stations in this area. The skill matrix for each operator was provided by management and Figure 14 shows the operations each operator is trained as is proficient. This information was gathered throughout several visits to the plant.

	Cells																				
Skills	**101**			**305**						**105**			**124**					**1062**			
Workers\Operations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Worker 1			x		x	x				x	x	x	x	x	x	x	x				
Worker 2	x	x	x				x			x											
Worker 3	x		x						x	x											x
Worker 4	x	x		x	x	x	x	x		x	x	x						x			
Worker 5	x	x		x	x	x	x	x	x	x	x	x									
Worker 6	x						x			x	x	x									
Worker 7										x		x									
Worker 8	x		x	x	x	x	x	x		x		x						x	x	x	x
Worker 9	x	x	x		x	x	x			x	x	x						x	x	x	x
Worker 10	x			x	x	x	x			x	x	x						x	x	x	x
Worker 11	x	x	x	x		x	x	x		x		x						x			
Worker 12				x	x	x	x			x											
Worker 13	x	x	x	x		x	x	x			x	x	x	x	x	x	x				
Worker 14				x			x	x	x	x	x										
Worker 15	x						x	x		x	x	x									
Worker 16				x	x	x	x	x	x	x											

Figure 14. Skill matrix

Note: A x means operator is trained in that particular operation (1...21) within a cell (101...1062).

In terms of the operational policy, operators spent 8 hours in a hard subassembly environment with corresponding breaks for exercise and lunch. Operators are able to do ergonomic exercises for stretching their muscles. The production floor is a classic electronic assembly environment characterized by high noise from equipment such as drilling and welding machines. A big screen in each of the cellular layouts shows their takt time, throughput goals, and actual throughput. The assignment in which each worker will be more effective depends on the daily attendance which averages 80%.

Each of the activities are defined by a set of characteristics that can be described with seven attributes:

1. Type of task (individual or in team)
2. Operation’s Velocity (Slow or Fast)
3. Cell Shape/Space (U-shape, L-shape, Straight-shape)
4. Position (Stand or Seat)
5. Cell Family (101,124,105,305,1062,324)
6. Type of Operation (Assembly, Calibrate, Welding, Inspect, Screwing, Testing, Packaging, Drill, Precision.)
7. Administrative Task (Schedule Reports, Scrap Records, Production Reports)

4.4 Description of a typical assembly cell

The overload family is one of the high runners of the company. It has internal and external clients, most of them internal. Overload is a subassembly cell that is used on a product that is attached to the overload and then enclosed. Figure 15 shows that the Overload cell has a U-Shape, 5 stations and in special cases a sixth station is added. A Pareto diagram of the cell demand is depicted in Appendix F. Using production and demand data a workload analysis was performed and bottleneck identified.

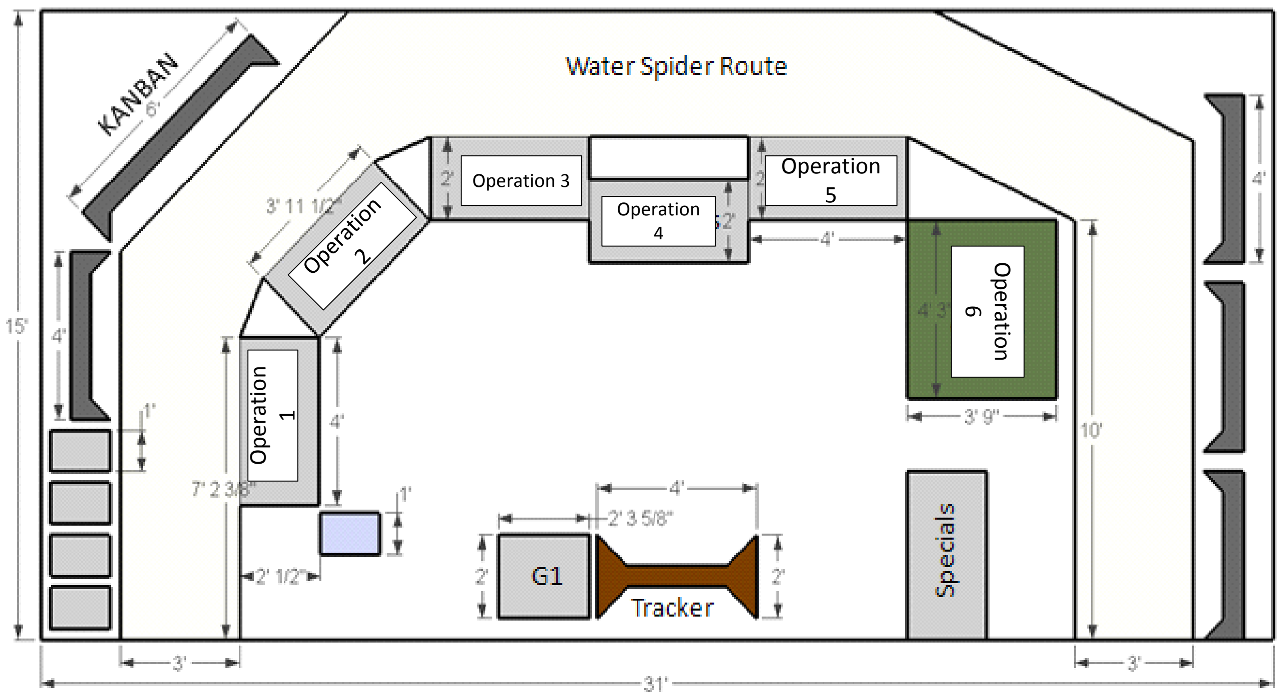

Figure 15: Overload layout

4.5 Qualitative tools used to analyze preferences

The tool used in this section includes the multicriteria decision making methodology known as Analytical Hierarchy Process explained in Section 3.2.1. It also presents the analysis of the questionnaires administered and the information in the questionnaires is integrated into the AHP model.

4.5.1 Questionnaires

As previously mentioned the questionnaire is presented in Appendix C and it was built to capture operator's preferences and to have a base to build the AHP model. AHP was chosen to analyze the questionnaire data because it eliminates subjectivity and allows the calculation of paired comparisons to establish operator's preferences.

Since AHP is a complex tool for the operators to understand, the questionnaires were used as the main data collection instrument. The data gathered was then converted to be used into the AHP model. The questionnaire is divided in three types of questions: introductory questions (to get worker's background), attributes questions (to make paired comparisons), and the sub-attributes questions (to understand what they like the most). Results of the questionnaire are discussed in Appendix I.

4.5.1.1 From the questionnaire to the AHP Model

After the questionnaires were administered the analytical hierarchy process was used to determine the weights of preferences for each activity for each operator. The hierarchical structure developed has as its goal operators' satisfaction followed by attributes and subattributes that are discussed later in this document. The weights obtained in the AHP for each worker for each activity are going to be used as inputs in Phase II. In order to convert the data from the questionnaires into the AHP model a particular procedure was followed, for example:

Question 6. Make a rank of the cell families from 1 to 6 (1 most preferred, 6 less preferred)

(5) 124 - Legacy	(6) 101 - Switches	(4) Interlock Small
(2) 1062	(1) Overload	(3) Interlock Big

To translate the questionnaire into AHP the following procedure was used:

Step 1: Make a list in order of preferences

1. Overload
2. 1062
3. Interlock Big
4. Interlock Small
5. 124
6. 101

Step 2: Compare the preference order by the worker with the list already established for the AHP. In this case the list that has been established in the AHP is the following:

	124	101	1062	105	305	OV
124	1.00					
101		1.00				
1062			1.00			
105				1.00		
305					1.00	
OV						1.00

Figure 16: Cell family matrix

Step 3: Using the ranked list each of the alternatives, thus were order as shown in Figure 18.

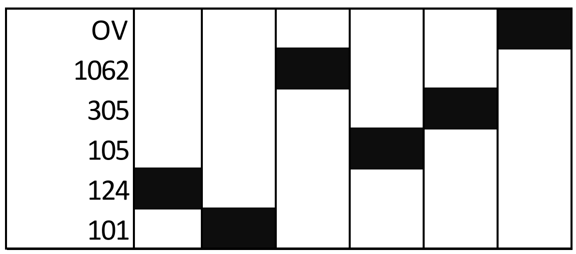

Figure 17: Anchored matrix

Step 4: Assign a scale from 3 to n (use odd numbers) for the alternatives below the marked box. For the alternatives above the marked box assign a scale from 1/3 to 1/n going upwards. Assign the scale in the AHP starting in to the first anchor position to the last one. To translate the questionnaire to be used in the AHP model modifications to the paired comparison scale were necessary.

OV	1/9	1/11	1/3	1/7	1/5	
1062	1/7	1/9		1/5	1/3	3
305	1/5	1/7	3	1/3		5
105	1/3	1/5	5		3	7
124		1/3	7	3	5	9
101	3		9	5	7	11

Figure 18: Scale matrix

4.5.2 AHP Model

To conduct the AHP methodology five stages are needed. Each stage is explained below.

Stage 1: Construct a decision hierarchy by breaking down the decision problem into a structure of decision elements identifying decision alternatives.

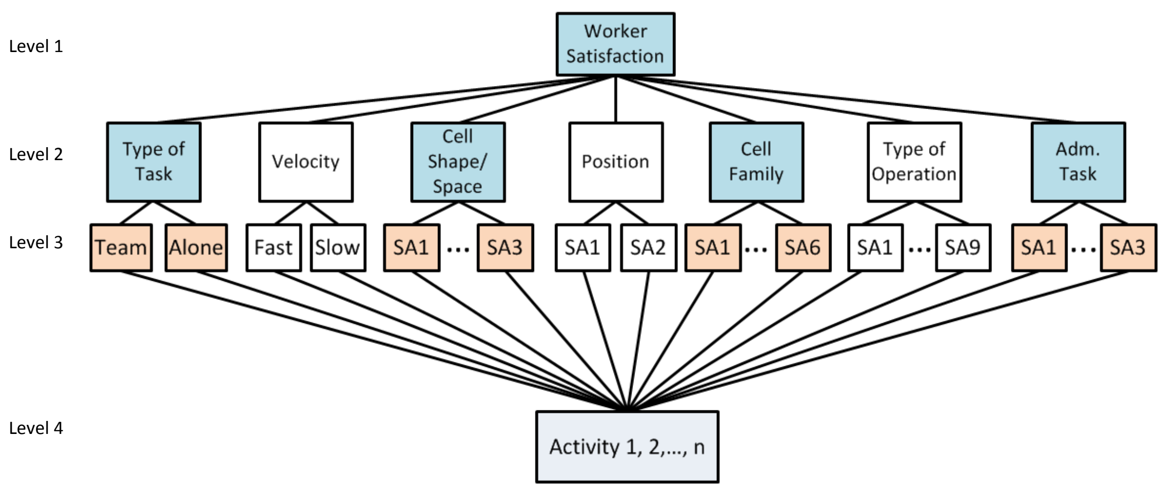

Figure 19: AHP into levels

As shown in **Figure 19** each decision was broken down into elements depending on the level of the tree. It is important to understand that this methodology divided each hierarchy in levels. Below the explanation for each of the levels:

Level 1: The focus, for this case the main objective is the operators' satisfaction (i.e., amount of satisfied preferences).

Level 2: Describe the attributes of the decision problem. It is important to mention that each attribute and sub attribute (if any) should be independent. The decision problem presented in this case has 6 attributes. Each attribute, in this case, was broken down into sub attributes in order to better quantify operators' preferences. One of the attributes that is of important relevance in this work is cell family (i.e., catalogs of products with the same characteristics) and it will be discussed among each stage of the AHP.

Level 3: In this level the subattributes for each attributes are established. A total of 6 attributes and 24 subattributes were weighted with respect to the activities sets in each of the stations by the company. The cell family attribute has 6 subattributes; 101, 124, 1062, 305, 105, OVERLOAD.

Level 4: A total of 16 different activities are considered. An activity is defined as the set of attributes and subattributes in which a worker is going to be assigned.

For example, Activity 1 (each activity needs to be linked to each operation to be able to use the weights in the mathematical assignments):

Type of task = team

Velocity = fast

Cell shape/space = straight/small

Cell space = small

Position = stand

Cell family = 101

Type of operation=screwing

The weights for each attribute and subattribute result in the weights of the alternative; furthermore, it will be the weighted rank of each worker for each activity.

In summary, the hierarchy decision tree was composed of level 1 which is the main goal, level 2 that corresponds to the attributes of the problem, the next lower level will depend if subattributes exist, if not, the next lower level will be the possible alternatives.

Stage 2: Determination of the relative importance of attributes and subattributes (if any).

In this stage pairwise comparisons are made of each attributes and subattributes to establish the relative importance of each one. The questionnaire was helpful to assign those priorities between attributes and subattributes. The responses then translated to numbers from 1-n (where n depends on the amount of attributes or subattributes). Table 5 is used to determine the scale. Even numbers (2, 4, 6, and 8) can be used to handle compromises among the preferences. As explained earlier, the scale used in this work was modified. The results of the pairwise comparison are placed in a matrix shown in **Figure 20**. This matrix shows the comparisons of the attributes to establish priorities among them.

Table 10: Legend for attributes

Attributes	
Type of Task	T
Velocity	V
Cell Shape	CSh
Cell Space	CS
Position	P
Cell Family	CF
Type of Operation	TO

	T	V	CSh/S	P	CF	TO	A
T	1.00	9.00	5.00	3.00	7.00	13.00	11.00
V	0.11	1.00	0.20	0.14	0.33	5.00	3.00
CSh/S	0.20	5.00	1.00	0.33	3.00	9.00	7.00
P	0.33	7.00	3.00	1.00	5.00	11.00	9.00
CF	0.14	3.00	0.33	0.20	1.00	7.00	5.00
TO	0.08	0.20	0.11	0.09	0.14	1.00	0.33
A	0.090909	0.33	1.00	0.11	0.20	3.00	1.00

Figure 20: Paired matrix for attributes

For example, a priority comparison of 3 for worker 1 means in this case that for the type of task (T) with respect of the Cell Family(CF), that is weakly important the cell family against the type of task. Observed that reciprocal comparisons are made for those paired interchangeable (e.g. From CF to T priority equals .33).

Same procedure was used to each subattribute, for example the cell family presented below:

	124	101	1062	105	305	OV
124	1.00	3.00	5.00	0.33	0.20	0.14
101	0.33	1.00	3.00	0.20	0.14	0.11
1062	0.20	0.33	1.00	0.14	0.11	0.09
105	3.00	5.00	7.00	1.00	0.33	0.20
305	5.00	7.00	9.00	3.00	1.00	0.33
OV	7.00	9.00	11.00	5.00	3.00	1.00

Figure 21: Paired comparisons of Cell Family sub attributes

As shown in **Figure 21** for worker 1 it is weakly more important to work with the cell family 1062 than with 105 families. A total of 1 paired matrix was developed for the attributes, and for those attributes, six matrices of paired comparison of each sub attributes within an attributes were made.

Stage 3: Determination of the relative standing (weight) of each alternative with respect to next higher level attributes or sub attributes.

As shown in **Figure 19** the next higher level for the activities are the sub attributes. Therefore a determination of relative standing of each sub attribute was made with respect to each activity. The same priority weight from 1 to n was used, reciprocal of interchangeable comparisons also applied for this step.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
2	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
3	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
4	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
5	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
6	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
7	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
8	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
9	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.1111
10	9	9	9	9	9	9	9	9	9	1	9	9	9	9	9	9
11	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.11
12	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.11
13	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.11
14	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.11
15	1	1	1	1	1	1	1	1	1	0.111111	1	1	1	1	1	0.11
16	9	9	9	9	9	9	9	9	9	1	9	9	9	9	9	0.11

Figure 22: Paired comparisons of alternatives with respect of a sub-attribute

To be able to calculate the consistency indexes the weights were transformed using the following methodology:

priority= importance weight from alternative i to alternative j

total= sum of the priority weight of each column j

i=1..16

j=1..16

$$Average(\sum_{j}^{n}\sum_{i}^{n}\frac{priority_{ij}}{total_{j}}) \qquad (10)$$

Weights
0.03
0.03
0.03
0.03
0.03
0.03
0.03
0.03
0.03
0.32
0.03
0.03
0.03
0.03
0.03
0.26

Figure 23: Priority Weights

Those weights are also known as the priority weights and it is a normalization of the paired comparison previous made. To obtain normalized matrix equation (10) was used. **Figure 22** suggested that for worker 2 the subattribute; cell family 101 with respect of the alternative 1 against alternative 2 is equally important. This analysis was made for a total of 24 subattributes in order to obtain the weights.

Stage 4: Determination of indicators consistency in making pairwise comparisons:

There are two measures of consistency for the AHP method

1. The local consistency for attributes and subattributes which is denoted by C.R. (i.e. consistency ratio) . The C.R. is a function of what is called the maximum eigenvalue

and it will be discuss further in this document how to calculate. A C.R. no greater than .10 it is useful for pragmatic purpose.

2. The global consistency for the entire problem can be applied to the entire decision hierarchy. The global consistency ratio is obtained calculating the M (i.e. aggregate consistency index) and $\bar{M}$ which is a random index value

For the local consistency values it is shown an example based on Figure 24.

	[a]						[b]	
	124	101	1062	105	305	OV	Sum	Average
124	0.03	0.01	0.01	0.05	0.01	0.02	0.14	0.02
101	0.14	0.06	0.12	0.08	0.03	0.04	0.47	0.08
1062	0.08	0.02	0.04	0.06	0.02	0.03	0.25	0.04
105	0.31	0.42	0.36	0.53	0.52	0.63	2.76	0.46
305	0.19	0.18	0.20	0.11	0.10	0.07	0.85	0.14
OV	0.25	0.30	0.28	0.18	0.31	0.21	1.53	0.25
	1.00	1.00	1.00	1.00	1.00	1.00		

Figure 24: Vectors

The normalized matrix presented above is obtained using the equation (10); a modification of the equation can be as follow:

$$position_{ij} = \frac{priority_{ij}}{total_j} \tag{11}$$

Generally the local consistency ratio can be obtained by the following equation

$$\text{C.R.} = \frac{CI}{RI} \qquad (12)$$

Where CI is a consistency index and RI is a random index. To calculate a consistency index CI it is needed a lambda which is obtained by multiplying the normalized matrix shown in **Figure 24** by their respective average [a] x [b]. An average of the product result of [a] times [b] is the lambda. After calculated the λ it can be computed the consistency index following the CI formula:

$$CI = \frac{\lambda - N}{N - 1} \qquad (13)$$

Where N is the number of attributes, subattributes or alternative in the matrix. The random index RI it is calculated by Saaty after large simulation numbers and it is presented in the **Table 11**.

Table 11: RI indexes

N	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51

After calculated the CI it can be obtained the CR using the equation 12. **Figure 25** presented a summary of all the local consistency parameters for the cell family attribute

Lambda	6.41
CI	0.08
RI	1.24
CR	0.07

Figure 25: CI

For those example the local consistency ratio it is acceptable because is less than .10.

The global consistency ratio for this problem was obtained using the following calculations:

$$M = \text{second level CI} + \left|vector - of - \text{sec}ond - level - weights\right| \text{x} \left|vector - of - third - level - CI\right| \quad (14)$$

$$\bar{M} = \text{second level RI} + \left|vector - of - \text{sec}ond - level - weights\right| \text{x} \left|vector - of - third - level - RI\right| \quad (15)$$

A summary of those calculations it is presented in **Figure 26**.

Aggregate M as CI for the second level
Now calculate M and M hat

CI second level	Vector of second level priority weights							CI Third level
0.12	0.25	0.09	0.03	0.05	0.02	0.14	0.42	0.00
								0.00
								0.00
								0.00
								0.08
								0.22
								0.00

M= 0.15

RI second level	Vector of second level priority weights							RI Third level
1.32	0.25	0.09	0.03	0.05	0.02	0.14	0.42	0
								0
								0.9
								0.0
								1.240
								1.450
								0.58

$\boxed{\bar{M}}$ = 1.82

CRH 0.08140129

Figure 26: Global Consistency

For this case the local and global consistency indexes are less than 10%, this was acceptable for the scale used.

Stage 5: Determination of the overall priority weight (score) of each alternative

The last stage of the AHP is to calculate the weight of each alternative. For this calculation it is establish the following formula:

$$Alternative_k = \sum_{j}^{n}\sum_{i}^{n}(principal.vector.weight)*(evaluation_{ijk})\ \forall k \qquad (16)$$

The **Figure 27** summary the ranks of each alternative with his respectively weight, mathematically the results as follows:

Alternative 1 Weight =.25*.10*.04+.25*.9*.06+……+.42*.09*.06+.42*.09*.06=.06

For the case shown in **Figure 27** the alternative prefer by the worker 2 is the alternative 4 which is equal to type of task = team, velocity=fast/slow, cell shape/space=all cell shape/spaces, position = seat, Cell family= 105, Type of operation=Packaging, Administrative Task=Scheduling.

This analysis was made for each of the 16 operators to establish the weights of the alternative base on their preferences. These weights are going to be used as inputs in the optimization model.

	Type of Task		Velocity		Cell Shape/Space			Position		Cell Family						Type of Task									Adm Task			
Attributes	0.25	0.25	0.09	0.09	0.03	0.03	0.03	0.05	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.42	0.42	0.42	
	A	T	F	S	R	L	U	S	Se	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	1	2	3	
Alternative/Subatt	0.10	0.90	0.50	0.50	0.33	0.33	0.33	0.10	0.90	0.02	0.08	0.04	0.46	0.14	0.25	0.04	0.10	0.06	0.25	0.16	0.01	0.33	0.02	0.03	0.82	0.09	0.09	Ranks Weights
1	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.059
2	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.02	0.06	0.02	0.06	0.06	0.05	0.06	0.06	0.054
3	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.02	0.06	0.02	0.06	0.06	0.05	0.06	0.06	0.054
4	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.02	0.06	0.02	0.06	0.06	0.05	0.06	0.06	0.054
5	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.059
6	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.02	0.06	0.02	0.06	0.06	0.47	0.06	0.06	0.197
7	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.02	0.06	0.02	0.06	0.06	0.05	0.06	0.06	0.054
8	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.02	0.06	0.02	0.06	0.06	0.05	0.06	0.06	0.054
9	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.05	0.06	0.06	0.062
10	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.32	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.05	0.06	0.06	0.063
11	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.05	0.06	0.06	0.062
12	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.05	0.06	0.06	0.062
13	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.47	0.06	0.06	0.205
14	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.23	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.47	0.06	0.06	0.206
15	0.04	0.07	0.06	0.06	0.06	0.06	0.06	0.23	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.05	0.06	0.06	0.064
16	0.38	0.01	0.06	0.06	0.06	0.06	0.06	0.23	0.06	0.06	0.06	0.26	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.06	0.10	0.06	0.06	0.05	0.06	0.06	0.059

Figure 27: Alternatives Weights

Green Zone: Satisfaction is accomplished

Yellow Zone: Average Satisfaction

Red Zone: Unsatisfaction

4.6 Mathematical Modeling

Phases I and II were combined by using the preference weights from the AHP model as input to the mathematical model. Appendix G shows the combined (skills & preferences) and cost matrices in order to solve the mathematical problem. The mathematical model (section 3.3.2) was programmed in LINGO (see code in Appendix H) which is a software designed to solve linear, nonlinear and integer optimization models.

The numeric illustration is based on the case study in an electronics' industry previously described. The following assumptions were made in constructing the model:

- The assignment of the operators could be in fractions but need to sum 1 to guarantee that the operator's capacity is used.
- All stations need to be covered (i.e., the demand requirements in each station need to be satisfied.)
    - In order for an operator to be assigned to a particular operation, he/she must possess at least the minimum skill required.
    - The model uses the combined (skills and preferences) and cost matrices
- In order to avoid operation assignments using unskilled operators the cost for this particular assignment was set to infinity.
- The total assignment of operators for each cell must be equal to the demand.
- The model was developed for a time horizon of 1 period.

The network representation for this problem is summarizes in Figure 28 and consists of 16 operators, 5 cells, 21 operations and 1 period.

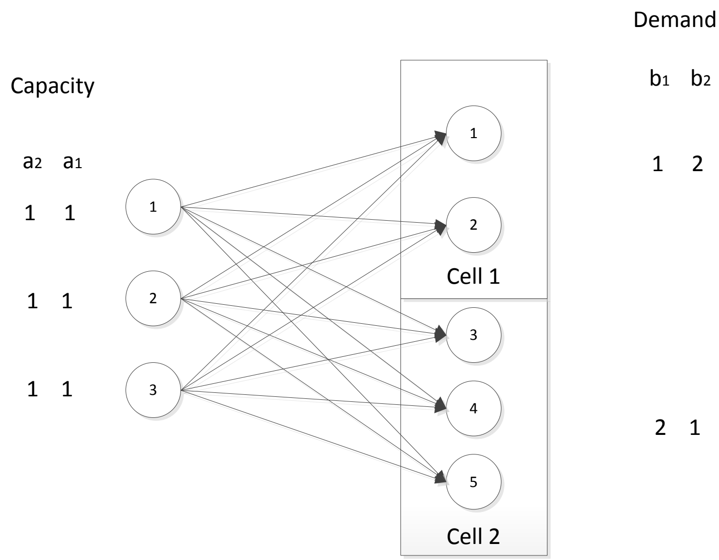

Figure 28 Network Representation

Results from Lingo shows a total iterations of 472 with an estimated run time of 2 seconds for a total of 2369 variables with an objective function equals to 564.43 [$\frac{\$ * preferences}{assignments^2}$], which means that for each preference that do not satisfy a big M cost was used as penalty. The summary of the results for the MCTP are shown in **Table 12**. These results are feasible in terms of skills and preferences thus satisfying the operators' demand per cell. However, this model contains limitations because random assignments are made to operations taking into account the demand per cell but not the particular demand for each operation. This may result in excessive or understaffed assignments in operations.

Table 12: Operators assignments

	Cells																				
	1			2						3			4					5			
Operators' \Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1						x															
2		x																			
3																					x
4					x																
5	x																				
6											x										
7										x											
8			x																		
9																			x		
10																				x	
11																		x			
12							x														
13													x	x	x	x	x				
14				x				x													
15												x									
16									x												
Operators' Demand	3			5						3			1					4			

Note: An x means an operator's assignment into an operation.

In this model each operator could be assigned to one or more tasks. Since assignments were made to cells instead of to operations we cannot conclude that the results are feasible, see Table 12. It is worth mentioning that this result might be feasible in the model but not in a practical scenario. Thus, this solution represents a lower bound for operators' dissatisfaction. However, the set of operators' assignments that is feasible in a practical sense is a subset of the aforementioned model. For this reason, a comprehensive model was proposed and it is discussed in the next section.

4.6.1 Mathematical Model Modification

A comprehensive model was proposed in order to assign operators considering the demand per operation. In order to modify the model, assignments were made considering the demand of the particular operations instead of cell demand. Therefore, for this model subscript j was no longer needed. The model is presented next.

Given:

p_{ikl} = preference (weight) of worker *i* assigned to operation *k* in period *l*, where $p_{ikl} \leq 1$ (based on AHP).

c_{ikl} = cost to assign worker *i* in operation *k* in a period *l*.

b_{kl} = demand for operation k in period l.

Decision variables

x_{ikl} = Operators *i* assigned to operation *k* for period *l* (operators could be assigned in fractions due resource constraints).

$i = \{1,..,n_1\}$ where n_1 is the number of operators

k = $\{1,.., n_2\}$ where n_2 is the number of operations

l = $\{1,..,n_3\}$ where n_3 is the number of periods

Objective Function:

$$\text{Min} \sum_i \sum_k \sum_l (1 - w_{ikl}) * cx_{ikl} \tag{17}$$

Subject to:

$$w_{ikl} = p_{ikl} * x_{ikl} \qquad \forall i, k, l \tag{18}$$

$$cx_{ikl} = c_{ikl} * x_{ikl} \qquad \forall i, k, l \tag{19}$$

$$\sum_k \sum_i x_{ikl} = b_k^l \qquad \forall k, l \tag{20}$$

$$\sum_k x_{ikl} \leq 1 \qquad \forall i, l \tag{21}$$

For the modified model, the objective function (17) minimizes (18) and (19) which are the operators' dissatisfaction and the sum of the cost to assign an operator, respectively. The objective function is subject by (20) which is the operations demand that must be satisfied and (21) the capacity of operators that can be assigned in each period. This model eliminated constraint (7) and (8) of the original model because constraint (20) is now subject to operations instead of cells ensuring assignments to operations. An example of the modified model was run in order to validate the assignments. Figure 29 summarizes the example and Table 13 the results.

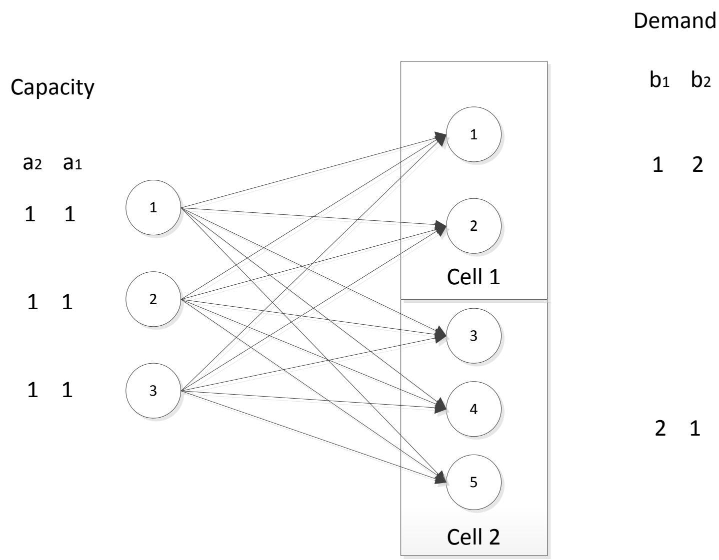

Figure 29: Labor Assignment Example

Figure 29 represents a network with two cells and five operations. In period one, Cell 1 have a demand for one operator and Cell 2 a demand for two operators. For illustration purposes, a hypothetical demand was assumed as presented in Table 13.

Table 13: Operators' Demand per Operation

Cell	1		2		
Operations	1	2	3	4	5
demand per operation (% of operator)	0.5	0.5	0.4	0.6	1
demand per cell (operator)	1		2		

The results of the comprehensive mathematical model are presented in Table 14.

Table 14: Example Results

Cell	1		2		
Operations	1	2	3	4	5
Operator 1	0.40				0.6
Operator 2	0.1	0.5	0.4		
Operator 3				0.6	0.4
assigned operators	**0.5**	**0.5**	**0.4**	**0.6**	**1**
demand per operation (% of operator)	**0.5**	**0.5**	**0.4**	**0.6**	**1**
assigned demand per cell	**1**		**2**		
demand per cell (operator)	**1**		**2**		

For this particular example, all operators were assigned with full or less capacity to a particular operation, thus satisfying the demand in each operation and cell. Using this comprehensive model the previous case study problem was run.

Table 15: Final Network Modified Results

	Cells																				
	1			2						3			4					5			
Operators' \Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1						1															
2			1																		
3																					1
4		1																			
5								0.5	0.5												
6							1														
7										0.5		0.5									
8																				1	
9																			1		
10											1										
11																		1			
12					1																
13													0.2	0.2	0.2	0.2	0.2				
14										0.5	0.5										
15	1																				
16				1																	
assigned operators	1	1	1	1	1	1	1	0.5	0.5	1	1.5	0.5	0.2	0.2	0.2	0.2	0.2	1	1	1	1
demand per operation	1	1	1	1	1	1	1	0.5	0.5	1	1.5	0.5	0.2	0.2	0.2	0.2	0.2	1	1	1	1
assigned demand per cell	3			5						3			1					4			
demand per cell	3			5						3			1					4			

The results using Lingo were obtained after a total of 319 iterations with an estimated run time of 5 seconds and a total of 316 variables with an objective function equals to

$$2113.4[\frac{\$ * preferences}{assignments^2}].$$

As in the previous model run (**Table 12**) these results are feasible in terms of skills and preferences. Moreover, the results are also feasible from the practical point of view since the operators demand per operation in every cell is satisfied. The following statements were concluded based on the comprehensive model:

- It minimizes the assignment cost and the cost of dissatisfaction per assignment.
    - The model satisfies both skills and preferences.

- Feasible and optimal results are reached when assignments are made to operations instead of cells.
    - The demand of every cell will be satisfied once each particular operation demand is covered.

5 Conclusion

This research developed a strategy to identify and quantify the factors (characteristics) of the manufacturing environment that operators prefer (operators' preferences) and lead to operators' satisfaction. The methodology included the use of both qualitative and quantitative methods. Using a combined methodology that relied on focus groups, environmental survey, company visits and the AHP model (the feasibility of this methodology was proven and its suitability verified), researchers were able to identify and quantify the factors that operators prefer and lead to workers satisfaction. Among those factors it is worth mentioning operators' preference for certain operations, teamwork, part family, and cell layout among others. Furthermore, a CM work environmental survey was conducted to assess the importance of human factors versus technical factors. The statistical analysis showed that from the operators' perspective human issues are more significant than technical issues and thus empirically validating the need for this research.

Using the AHP model, researchers were able to quantity operators' preferences and use them as input to the mathematical model. Thus, leading to the research second objective; to develop a labor assignment model that considers both operational factors (demand, capacity, periods, and skills) and operators' preferences. The mathematical model used was the MCTP mentioned in Chapter 3 and the results show that was a feasible fit to optimize the maximization of the preferences and to minimize the operator assignment cost in a CM implementation. Furthermore, it also helps to reduce the cost of assignments among tasks and periods. After exploring several scenarios it was concluded that the model could be also incorporated into others manufacturing environments taking into account those human factors that may apply. Finally, this research shows that human socio-technical issues can be incorporated in mathematical assignment models in CM systems to improve operators' satisfaction among tasks by using qualitative techniques such as AHP.

The following considerations and factors could be incorporated as future research:

- Assign operators considering the distance within cells and operations. In the case that an operators' walk time exceeds the appropriate walk time to complete the operator cycle time, this constraint must be taken into account. This will add an alert indicating excessive walking time.
- Calculate a trade-off between the cost of training and transfer and the skill matrix.
- Calculate a profitable proportion between training operators vs. cost of been trained.
- Based on the numbers of periods of the model determine how the model expanded and changed depending on the preferences changes among periods.

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Appendix A
Source: (K. Fraser, 2008)

University of Puerto Rico
Mayaguez Campus
Department of Industrial Engineering

This survey is designed to be filled out by shop-floor operators (operators) who have experience in cellular manufacturing. The purpose of this survey is to determine your opinion on technical and human problems encountered in cellular manufacturing and to rank the importance of different human issues in cellular manufacturing.

Supervisor Name______________________________

1. Are you or have you been involved in cellular manufacturing?

Yes No

2. How many years have you been involved in cellular manufacturing?

0-1 years / 1-3 years / 3-5 years / 5-10 years / >10 years

3. What is the average number of people per cell you have been involved with?

2-4 per cell / 5-7 per cell / 8-10 per cell / >10 per cell

4. Do you understand that most of the critical problems come because of:

a) Technical factors (missing materials, equipment downtimes, etc.)

b) Human factors (lack of communication, skills, lack of skills, lack of training, etc.)

c) both

5. Based on your experienced working in cellular manufacturing, please tell us which are more important for you.

    a) Technical Factors

    b) Human Factors

6. Mark in order of importance the technical problems encountered.

Technical Problems	Ranking (1-7) 1=more important 7=least important
Equipment damaged	
Missing material for the production	
The distribution of operators is not adequate	
The type of cell (L-shaped, U, C) hinders agility (movement)	
Problems in set up time increase the batch change	
Problems in production schedules	
Problems in the hauling of material	

7. Please comment on some other technical problem that you think is important in manufacturing cells and is not listed in question 6.

____

____

8. The successful operation of manufacturing cells involves a number of human factors. Please rank the following 9 major areas in human issues from the one you think is the most important (rank=1) to the one you think is the least important (rank=9), ensuring each numbers between 1 to 9 is allocated.

Human Issues in Cellular Manufacturing	Ranking (1-9)
a) Worker Assignment Strategies: Methods that help in assigning specific people to tasks within a cell or between cells.	
b) Skill Identification: Identifying skills needed for a task and identifying the skill levels of cell workers.	
c) Training: Developing training strategies and policies for increased productivity.	
d) Communication: Methods to enhance inter-cell communication (between cells), intra-cell communication (within cells) and "manager-cell" communication (between management and workers).	
e) Autonomy: Degree of self-government within a cell.	
f) Supervision: Role and activities of team leaders	
g) Reward/Compensation System: Designing reward systems to enhance productivity improvement.	
h) Teamwork: Methods to enhance team dynamics and interaction.	
i) Conflict Management: Tools and techniques for resolving conflicts.	

9. Please comment on any other human problem or problem with the people you consider important in manufacturing cells and is not listed in Question 8.

10. Mark in order of most frequent problems in the allocation of operators. Describe the problems of 1-9 with 1 being the most important and 9 the least, please be sure to include the numbers located between 1-9.

    a) _____Lack of skills

    b) _____ Absenteeism

    c) _____No preferences are considered operators

    d) _____Load not level (some work more than others)

    What do you think of the following is considered when are assigning to a cell (task)? (You may choose more than one)

    a) _____The team who will work

    b) _____The shift they will work

    c) _____ The tasks carried out

    d) _____ Type of product that will work

    e) _____ The shape of the cell

    f) _____ The type of monitoring

    g) _____ All of the above

    h) _____ None of the above

11. If you had the opportunity to lead as the operators are assigned manufacturing areas (cells) that would take into account for this.

____

12. Please add any other comments you want to do with respect to manufacturing cells.

(What would you do to make your life better?)

____

Thanks for your time and knowledge!

Appendix B

The procedure by (Langford & McDonagh, 2002) was used as guide for the preliminary focus group:

2) Get management agreement and establish the study protocol.
3) Select the operators to participate in the group session. Group session must not exceed 10 operators and were divided into clusters.
4) Prepare session
    (a) Have training on how to conduct focus groups.
    (b) Developed a script to get information from operators addressing issues such as: worker supervision, knowledge about the product, and opinion about the operational and cultural changes.

A. Welcome

Everybody will present themselves with their name, production line, and how they feel towards their work.

B. Focus Group Rules

The speaker will describe the terms of privacy.

C. Guide Questions

The collaborators will prepare a few guide questions to be delivered.

1. Do you like your work?
2. How do you feel about the supervision?
3. How do you feel about the manufacturing changes?
4. What do you think about your teammates?
5. Do you know use of the product?
6. If you were supervisor, what changes will you make?

(c) Ask permission to use a voice or camera recorder.

5) The time must not exceed 1 hour

Appendix C

1. How do you like to work?

- [ ] Team
- [ ] Alone

2. Do you feel comfortable doing a task?

- [ ] In fast speed
- [ ] In slow speed

3. Which type of cell do you prefer?

- [ ] U-shape
- [ ] Line
- [ ] L-shape

4. I feel comfortable in a cellular layout relative:

- [ ] Large
- [ ] Small

5. I feel comfortable working in a:

- [ ] Stand Position
- [ ] Seat Position

6. Mark the cells in which you are skillful (Enumerate the cells in order of ranking of pre

- [ ] 124 - Legacy
- [ ] 101 - Switches
- [ ] Interlock S
- [ ] 1062
- [ ] Overload
- [ ] Interlock I

7. In which type of operation do you prefer to work?

- [ ] Assembly
- [ ] Calibrate
- [ ] Welding
- [ ] Inspect
- [ ] Screwing
- [ ] Testing
- [ ] Packaging
- [ ] Drill
- [ ] Precision

Appendix D

The variables included in the model are:

r=net profit per unit of product sold

h=cost to hold one unit of product for one period

l=cost of regular time in dollar per worker-hour

l´=cost of overtime in dollar per worker-hour

e=cost to increase workforce by one worker-hour per period

e´= cost to decrease workforce by one worker-hour per period

x_t=amount produced in period t

s_t=amount sold in period t

I_t=inventory at end of t (I_0 is given as data)

W_t=workforce in period t in worker-hour of regular time(W_0 is given as data)

H_t=increase (hires) in workforce from period t-1 to t in worker-hours

F_t=increase (fires) in workforce from period t-1 to t in worker-hours

O_t=overtime in period t in hours

Objective Function

Maximize $\sum_{t=1}^{\bar{t}} \{rS_t - hI_t - lW_t - l'O_t - eH_t - e'F_t\}$ (D1)

Subject to:

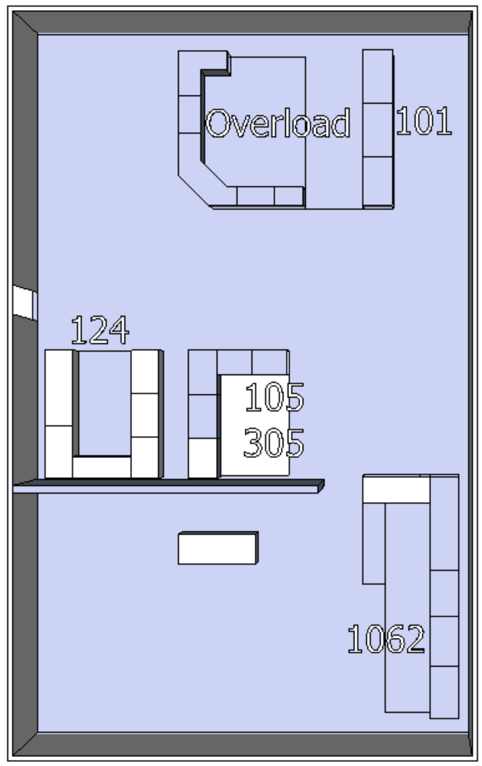
$I_t = I_{t-1} + x_t - S_t$ for all t (D2)

$W_{t=} W_{t-1} + H_t - F_t$ for all t (D3)

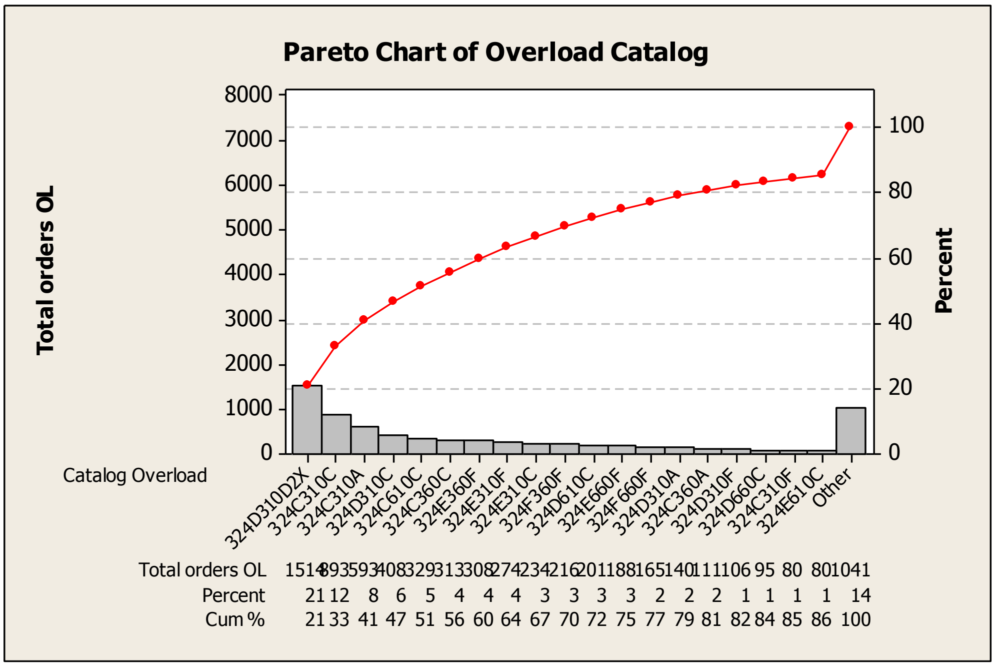
$x_{t,} S_{t,} I_{t,} O_{t,} W_{t,} H_{t,} F_t \geq 0$ for all t (D4)

For this mathematical model (D1) computes the profit between the difference of the revenue and holding cost. It is restricted by (D2) an inventory balanced, workforce restricted by time t (D3) which constraint the worker required to produce x_t to be less or equal to the workforce plus the overtime, (D4) all variables must be greater or equal to 0.

Appendix E



Appendix F



Pareto Chart of Overload Catalog
Total orders OL
Percent
Catalog Overload
324D310D2X
324C310C
324C310A
324D310C
324C610C
324C360C
324E360F
324E310F
324E310C
324F360F
324D610C
324E660F
324F660F
324D310A
324C360A
324D310F
324D660C
324C310F
324E610C
Other
Total orders OL 1514 893 593 408 329 313 308 274 234 216 201 188 165 140 111 106 95 80 80 1041
Percent 21 12 8 6 5 4 4 4 3 3 3 3 2 2 2 1 1 1 1 14
Cum % 21 33 41 47 51 56 60 64 67 70 72 75 77 79 81 82 84 85 86 100

Appendix G

	Cells																				
Skills	**1**			**2**						**3**			**4**					**5**			
Workers\Operations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Worker 1			x		x	x				x	x	x	x	x	x	x	x				
Worker 2	x	x	x				x			x											
Worker 3	x		x						x	x											x
Worker 4	x	x		x	x	x	x	x		x	x	x						x			
Worker 5	x	x		x	x	x	x	x	x	x	x	x									
Worker 6	x						x			x	x	x									
Worker 7										x		x									
Worker 8	x		x	x	x	x	x	x		x		x						x	x	x	x
Worker 9	x	x	x		x	x	x			x	x	x						x	x	x	x
Worker 10	x			x	x	x	x			x	x	x						x	x	x	x
Worker 11	x	x	x	x		x	x	x		x		x						x			
Worker 12				x	x	x	x			x											
Worker 13	x	x	x	x		x	x	x			x	x	x	x	x	x	x				
Worker 14				x			x	x	x	x	x										
Worker 15	x						x	x		x	x	x									
Worker 16				x	x	x	x	x	x	x											

Preferences	Cells																				
	1			2						3			4					5			
Workers\Operations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Worker 1				x	x	x			x	x	x	x									
Worker 2	x		x							x								x	x		
Worker 3				x	x	x	x	x	x	x								x			
Worker 4				x	x		x	x			x	x									
Worker 5	x		x	x	x		x		x	x	x										
Worker 6	x		x	x	x	x	x	x	x									x		x	
Worker 7				x		x	x	x	x		x	x									
Worker 8	x	x	x							x	x							x		x	x
Worker 9							x	x	x			x						x	x		
Worker 10	x	x	x							x	x							x			
Worker 11	x	x	x								x							x			
Worker 12				x	x	x	x	x										x	x	x	x
Worker 13				x	x	x				x	x		x				x				
Worker 14	x	x	x							x	x		x			x	x				
Worker 15	x	x	x									x	x	x							
Worker 16	x	x	x	x					x	x	x										

Combined	Cells																				
	1			2						3			4					5			
Workers\Operations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Worker 1					x	x				x	x	x									
Worker 2	x		x							x											
Worker 3									x	x											
Worker 4				x	x		x	x			x	x									
Worker 5	x			x	x		x		x	x	x										
Worker 6	x						x														
Worker 7												x									
Worker 8	x		x							x								x		x	x
Worker 9							x					x						x	x		
Worker 10	x									x	x							x			
Worker 11	x	x	x															x			
Worker 12				x	x	x	x														
Worker 13				x		x					x		x				x				
Worker 14										x	x										
Worker 15	x											x									
Worker 16				x					x	x											

	Cells																				
Preferences Weight	1			2						3			4					5			
Operators' \Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	0	0	0	0.27	0.21	0	0	0	0.173	0.173	0.173	0	0	0	0	0	0	0	0	0
2	0.357	0	0.286	0	0	0	0	0	0	0.357	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0.182	0.182	0	0.182	0.152	0	0	0.152	0.152	0	0	0	0	0	0	0	0	0
5	0.139	0	0	0.139	0.139	0	0.168	0	0.139	0.139	0.139	0	0	0	0	0	0	0	0	0	0
6	0.508	0	0	0	0	0	0.492	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0.504	0	0	0	0	0	0	0	0	0
8	0.148	0	0.234	0	0	0	0	0	0	0.129	0	0	0	0	0	0	0	0.143	0.121	0.098	0.127
9	0	0	0	0	0	0	0	0	0.409	0	0	0	0	0	0	0	0	0.321	0.27	0	0
10	0.278	0	0	0	0	0	0	0	0	0.222	0.222	0	0	0	0	0	0	0.278	0	0	0
11	0.208	0.292	0.333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.167	0	0	0
12	0	0	0	0.345	0.276	0.172	0.207	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0.345	0	0.172	0	0	0	0	0.138	0	0.172	0	0	0	0.172	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0.444	0.556	0	0	0	0	0	0	0	0	0	0
15	0.556	0	0	0	0	0	0	0	0	0	0	0.444	0	0	0	0	0	0	0	0	0
16	0	0	0	0.476	0	0	0	0	0.333	0.19	0	0	0	0	0	0	0	0	0	0	0

	Cells																				
costs	1			2						3			4					5			
Operators' \Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	100000	100000	1.5	100000	2.38	2.38	100000	100000	100000	8.63	8.63	59.11	19.53	19.53	20.87	19.53	19.53	100000	100000	100000	100000
2	1.5	1.5	1.5	100000	100000	100000	2.38	100000	100000	8.63	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
3	1.5	100000	1.5	100000	100000	100000	100000	100000	2.38	8.63	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000	8.63
4	1.5	1.5	100000	2.38	2.38	2.38	2.38	2.38	100000	8.63	8.63	59.11	100000	100000	100000	100000	100000	8.63	100000	100000	100000
5	1.5	1.5	100000	2.38	2.38	2.38	2.38	2.38	2.38	8.63	8.63	59.11	100000	100000	100000	100000	100000	100000	100000	100000	100000
6	1.5	100000	100000	100000	100000	100000	2.38	100000	100000	8.63	8.63	59.11	100000	100000	100000	100000	100000	100000	100000	100000	100000
7	100000	100000	100000	100000	100000	100000	100000	100000	100000	8.63	100000	59.11	100000	100000	100000	100000	100000	100000	100000	100000	100000
8	1.5	100000	1.5	2.38	2.38	2.38	2.38	2.38	100000	8.63	100000	59.11	100000	100000	100000	100000	100000	8.63	8.63	8.63	8.63
9	1.5	1.5	1.5	100000	2.38	2.38	2.38	100000	100000	8.63	8.63	59.11	100000	100000	100000	100000	100000	8.63	8.63	8.63	8.63
10	1.5	100000	100000	2.38	2.38	2.38	2.38	100000	100000	8.63	8.63	59.11	100000	100000	100000	100000	100000	8.63	8.63	8.63	8.63
11	1.5	1.5	1.5	2.38	100000	2.38	2.38	2.38	100000	8.63	100000	59.11	100000	100000	100000	100000	100000	8.63	100000	100000	100000
12	100000	100000	100000	2.38	2.38	2.38	2.38	100000	100000	8.63	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
13	1.5	1.5	1.5	2.38	100000	2.38	2.38	2.38	100000	100000	8.63	59.11	19.53	19.53	20.87	19.53	19.53	100000	100000	100000	100000
14	100000	100000	100000	2.38	100000	100000	2.38	2.38	2.38	8.63	8.63	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
15	1.5	100000	100000	100000	100000	100000	2.38	2.38	100000	8.63	8.63	59.11	100000	100000	100000	100000	100000	100000	100000	100000	100000
16	100000	100000	100000	2.38	2.38	2.38	2.38	2.38	2.38	8.63	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000

Note: A big penalty cost is use for those assignments in which a worker does not have the skill

Appendix H

```
!Network Flow Model;

Model:

DATA:

a = @ole(); !operators,the capacity of each worker will be 1;
b = @ole(); !demand, each cell has a particular demand(it could be in hours,days,weeks or
months);
p = @ole(); !periods(it could be in hours,days,weeks or months);
C_1 = @ole(); !amount of cells;

ENDDATA
Sets:

operators/1..a/;
operations/1..b/;
cells/1..C_1/;
periods/1..p/;
links(operators,cells,operations,periods):x; !(i,j,k,l);
links1(operators,operations,periods):costs,pesos,w,cx;  !(i,k,l);
links2(cells,periods):demand;             !(j,l);
links3(operators,operations);             !(i,k);
links4(operators,periods):capacity;       !(i,l);
links5(cells,operations);                 !(j,k);
links6(operations,periods);               !(k,l);
links7(operators,cells);                  !(i,j);

endsets

!objective function;


min=@sum(links(i,j,k,l):(1-w(i,k,l))*cx(i,k,l));!minimize the cost of assign and transfer the
operators;

!para reducir la funcion objetivo;
```

```
@for(links1(i,k,l):w(i,k,l)=@sum(links(i,j,k,l):pesos(i,k,l)*x(i,j,k,l)));
@for(links1(i,k,l):cx(i,k,l)=@sum(links(i,j,k,l):costs(i,k,l)*x(i,j,k,l)));

rrer=@sum(links(i,j,k,l):costs(i,k,l)*x(i,j,k,l));


!constraints

1)Demand and Capacity;


   !Demand (in some of the demand constraints were used #LE# and #GT# to differentiate
the operations within cells)

    -This constraint establish a number of operators that must be assign in the cell;

    !@for(links2(j,l):@sum(links3(i,k):x(i,j,k,l)) = demand(j,l));
     @for(links2(j,l)|j#EQ#1:@sum(links3(i,k)|k#LE#3:x(i,j,k,l)) = demand(j,l));
     @for(links2(j,l)|j#EQ#2:@sum(links3(i,k)|k#GT#3#AND#k#LE#9:x(i,j,k,l)) =
demand(j,l));
     @for(links2(j,l)|j#EQ#3:@sum(links3(i,k)|k#GT#9#AND#k#LE#12:x(i,j,k,l)) =
demand(j,l));
     @for(links2(j,l)|j#EQ#4:@sum(links3(i,k)|k#GT#12#AND#k#LE#17:x(i,j,k,l)) =
demand(j,l));
     @for(links2(j,l)|j#EQ#5:@sum(links3(i,k)|k#GT#17#AND#k#LE#21:x(i,j,k,l)) =
demand(j,l));
    !@for(links2(j,l)|j#EQ#3:@sum(links3(i,k)|k#EQ#10:x(i,j,k,l)) = demand(j,l));!a -
@sum(links2(j,l):demand(j,l)));

   !Capacity

    - Operators capacity are 1, therefore 1 worker should be assigned in one of the operation
in each period;


    @for(links4(i,l):@sum(links5(j,k):x(i,j,k,l)) <= 1);

!2)To assurance that all stations are covered (operators assignments can be in fractions);

   @for(links6(k,l):@sum(links7(i,j):x(i,j,k,l))<=1);

   @for(links6(k,l):@sum(links7(i,j):x(i,j,k,l))>.25);
```

```
Data:

demand= @OLE();

costs=@ole();
pesos=@ole();

@ole()=x; !to print solution in excel;

enddata


end
```

Appendix I

Pre Questionnaire Technical Results

Some important technical data was found regarding the manufacturing environment when the first questionnaire was administered. As shows in average the most important weight (i.e. type of operation) for operators in this type of environment.

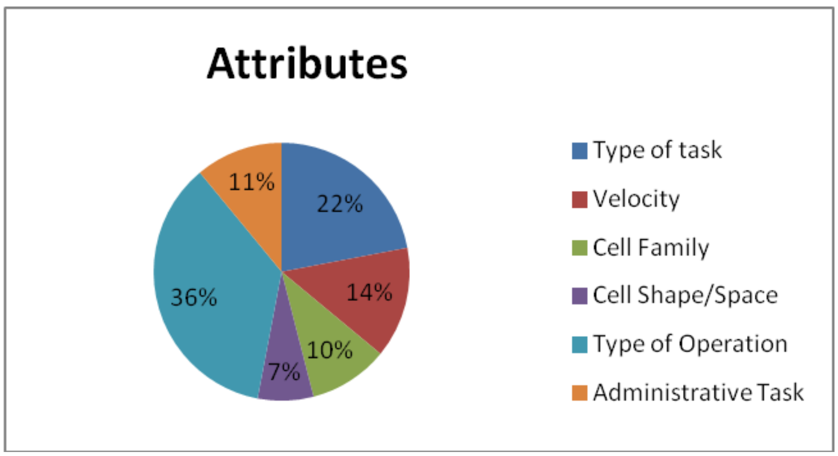


Figure Ia. Attributes Weights

Figure Ib decomposes the type of operation into subattributes.

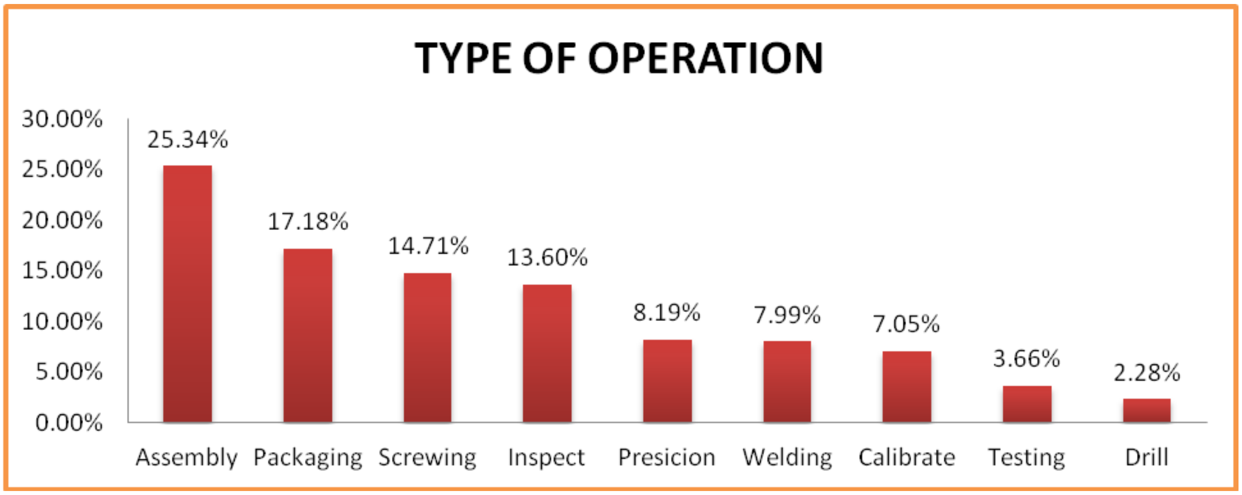


Figure Ib. Type of operation subattributes

As shows the figure the assembling and packaging areas are the ones that operators prefer

Appendix J

UNIVERSIDAD DE PUERTO RICO EN MAYAGÜEZ

DECANATO DE ASUNTOS ACADÉMICOS

COMITÉ PARA LA PROTECCIÓN DE LOS SERES HUMANOS EN LA INVESTIGACIÓN

(CPSHI/IRB-- 00002053)

9 de febrero del 2011

Wilfredo Robles

Estudiante Graduado

Ingeniería

UPRM

Estimado estudiante:

El comité revisó su proyecto: "Understanding Operator's Preferences towards manufacturing cell task assignments" y luego de evaluar la documentación sometida le aprueba el mismo. Recordándole que esta aprobación será hasta el 9 de febrero del 2012.

Atentamente,

Dafne Javier

Presidenta Interina

CPSHI