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CELLULAR MANUFACTURING SYSTEMS: ORGANIZATION, TRENDS AND INNOVATIVE METHODS

A. Attila İŞLİER*

Prof. Dr., Industrial Engineering Department, Eskisehir Osmangazi University, Eskisehir

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Abstract

Interchangeability is the distinguishing feature of modern manufacturing. A huge production capacity to satisfy the people is reached thanks to that concept. Yet that prospect brought up a dilemma too. Efficient but inflexible flow lines for very limited product types on one side and unproductive flexible batch production for numerous diverse parts on the other side. The remedy is thought of as Cellular Manufacturing (CM). That seemed a brilliant idea but the proliferation of CM has never reached to the expected levels. This paper discusses the probable causes of this discontent by referring both academic and practical issues and tries to give some clues to improve the achievements of further CM applications by emphasizing of the contemporary tools like computer techniques, especially emerging approaches of artificial intelligence as well as organizational and social issues.

Keywords: Production Systems, Cellular Manufacturing, Group Technology.

Jel Code: D2, L61, O33

HÜCRESEL ÜRETİM SİSTEMLERİ: YAPI, EĞİLİMLER VE YENİLİKÇİ YÖNTEMLER

Özet

Montajda kullanılan parçalardaki değiştirilebilirlik, modern imalatın belirgin bir niteliği olmuştur. Günümüz insanlarına doyum sağlayacak muazzam bir üretim gücüne de yine bu kavram sayesinde erişilebilmiştir. Ancak bu kavramdan yararlanma gayretleri, bir ikilemi de beraberinde getirmiştir. Bir yanda değiştirilebilirlik sayesinde yüksek verimlilikle ama son derece sınırlı tipte ürün üreten ve esnek olmayan seri üretim hatları diğer yanda da çeşit çeşit ürünü üretebilen esnek ama verimsiz parti tipi üretim sistemleri ortaya çıkmıştır. Her iki üretim tipinin üstün yanlarını birleştirecek çare de, uzun bir süreden beri Hücresel Üretim (HÜ) olarak görülmüştür. Fakat ilk bakışta, çok parlak bir düşünce olarak görünen bu yaklaşım da, hiçbir zaman kendinden beklenen hızla yaygınlaşamamıştır. Bu makalenin amacı da, buradaki çelişkinin kuramsal ve uygulamaya yönelik kaynaklarını irdeleyip, özellikle bilgisayar gibi araçlar ve yapay zekâ gibi yeni tekniklerin sağlayacağı olanaklar yanında işin örgütsel ve toplumsal yönlerini vurgulayarak HÜ uygulamalarındaki başarı düzeyini yükseltebilecek bazı ipuçlarını ortaya koymak olmuştur.

Anahtar Kelimeler : Üretim sistemleri, Hücresel Üretim, Grup Teknolojisi

Jel Kodu : D2, L61, O33

1. INTRODUCTION

This paper points out some basic concepts which modern manufacturing is based on; explains the rationale behind CM; calls attention to the important points, assumptions and formulization of Cell Formation (CF) Problem; briefs the classical methods and introduces advanced techniques developed for CF by taking design, layout and operational aspects into account. Meanwhile some clues to encourage successful CM applications are

* aislier@ogu.edu.tr (Corresponding author)

given. Organizational and social perspectives are also concerned to encourage the possible practical applications and academic research.

In his time-honored article Maslow (1943) states that "The average member of our society is most often partially satisfied and partially unsatisfied in all of his wants. Thus man is a perpetually wanting creature". Accordingly manufacturers bear the mission to fulfill these everlasting demands to innumerable kinds of products.

A typical end product, meeting the requirements of end users consists of several subassemblies which in turn are made of certain parts. Parts are the leaves of the conceptual tree that resembles the Bill of Materials (BOM) of that product. Each entity on that tree is called as a component. Parts are special kinds of components at the lowest level of that hierarchy. It is not possible to separate them meaningfully into lower level articles.

In fact, very few of these parts are inclined to be produced by a single operation. Since any usual machine is specialized to perform only a certain simple operation; a series of operations, hence a sequence of machines are needed to attain the final characteristics of the part in concern. These attributes might be related to crystal structure, consequently the crucial mechanical characteristics of the material; the shape, dimensions, tolerances, texture, color or surface quality of the part, or like.

Specifications explicitly describe technical characteristics of an item or product. They document the requirements of what that particular product should be. The verifiable details stated on specifications, enable the producers to manufacture interchangeable parts. Interchangeability is the distinguishing feature of the parts produced by modern manufacturing facilities. These parts are assembled to form end products. Since they are practically identical, no custom fitting like filing, leveling or smoothing is needed to assemble them. Replacing of worn or damaged components by spare ones is also easy thanks to interchangeability since they are made to specifications that ensure that they are so nearly identical to fit into any device of the same type. Therefore the time and degree of skill required by the person doing the assembly or repair are dramatically reduced.

All the objects manufactured as a certain part number are interchangeable. Here, two key concepts arise: Quantity and diversity. Kwok, (1992) emphasizes the steering role of these concepts in production systems design and he discusses the P-Q diagram originally devised by Muther to reveal their comparative weights. Here, each part number produced in a certain manufacturing concern is resembled by a vertical bar where the length of the bar is proportional to the quantity of corresponding item. Those bars are sorted from left to the right by descending order of their lengths, as in ABC analysis. The few items at the leftmost of the chart are the ones possessing of the highest demand. They lend themselves to be produced in a line by a flow type production system.

Flow type systems are also called as serial production systems since the employed machines are arranged as one after the other. They are special purpose machines in general. Their production rates are high. But they are quite expensive and special orders are needed to procure them since they are not standard utensils. Anyhow they run economically, producing huge amounts of parts, distributing of the fixed costs to a larger number of products so reducing of the unit costs due to economics of scale. A stable production is provided and handling costs are minimized by serial production.

Processes like investment casting or machining on a multi-coordinated machining center bring about the parts into their final shape in one step only. In fact these types of processes are not so common. Therefore each part to be produced requires a particular sequence of operations at a sequence of machines in general. At the end of each successive operation, raw material gets more similar to the end product. The sequence of operations is called as routing. Each part number has its own routing. If the machines are lined up by the same sequence, that series of machines progressively gives the shape to the part. Anyhow merely arranging of the machines in a line is not sufficient to get a flow system. Synchronization of operations is also required. In other words, operation times on each machine should be the same or nearly same to avoid interruption or accumulation of flow between machines.

Providing of synchronization in operations is a tough problem requiring a considerable concordance between product, process and tooling. Additional drawbacks of this type of production are the basic prerequisite of high production rates and their inherent inflexibility. As production rate increased, unit costs reduce as explained above and expensive equipment is more easily paid off. But higher production rates are only possible with high demands to specific parts whereas this is not the case in general. Inflexibility of these systems on the other hand, arises from the parallelism principle to be followed in constructing of flow lines. In fact, each of the machine types on the line must coincide the routing of the parts planned to be produced on that line to get the maximum benefit of flow lines. If some machines are passed over and some others are revisited, smoothness of the flow is lost. So only those parts with identical at least very similar routings are prone to be produced on a certain line. As a result neither number of part types nor production rates are flexible.

Thus a very small fraction of goods are produced in series systems since high demand and low variety items are quite rare. At the other extreme of P-Q diagram, low quantity-high diversity parts take place. This kind of parts requires superior flexibility to be produced. Universal machines provide that flexibility by expense of efficiency. These universal machines produce a larger spectrum of items. A universal lathe machines virtually all the cylindrical parts while a universal milling machine machines any prismatic part. But positioning and fixing of different items on these machines require a substantial skill and time. Either skilled operators or jigs and fixtures are needed for this purpose. In any case, a setup time and an expense are in concern.

Setup requires a considerable time compared to operation times. A press for instance might produce several parts within a minute but several hours of work is required to align the die to the machine in general. So manufacturers tend to produce as much parts as possible following their noteworthy effort for setup. Anyhow, demand is not the unique upper limit in determining the number of parts in a batch. As batch size gets larger, the cost of setup time is distributed to a larger number of parts. Consequently unit costs reduce. On the other hand, a larger number of items mean an increase in holding costs. The trade-off between these two costs is Economical Batch Size which is conceptually the same with Economic Order Quantity in inventory control.

A greater part of the world manufacturing is carried out by batch type production systems, by lot sizes of lesser than say a hundred. Batch type manufacturing is flexible enough. These systems are capable to produce a large variety of parts to meet a range of demand levels within an extent of due dates. They are adaptable but inefficient. The reason for their inefficiency is not the setup times alone. Effect of non-operating times on inefficiency is more severe. Machines employed by batch type shops are flexible but they are neither lined up nor synchronized. So a vast amount of time is lost between machines. The machine for following operation is distant, busy, and even indeterminate in general. If operation times are in the order of minutes, setup times are measured with hours. In practice, a week of non-operating time is thought for each operation as a rough cut.

Here the question arises “Is there a way to amalgamate the flexibility of batch type production systems with efficiency of series systems”. The answer lies on the relation of quantity and variety since distinguishing factor in choosing of production system lies behind their relative importance.

If the parts requiring the same machine sets are grouped as part families and they are allocated to certain production units encompassing the required machine sets, diversity in any unit (cell) reduces to one while the quantities increase considerably. Consequently efficiency of flow lines is combined with flexibility of batch production (Wu et al, 2007). Some major benefits offered by CM include reducing the lead time, setup time, material handling, and work in process. These benefits lead to better delivery times, quality improvements, more efficient management and customer satisfaction. The application of CM is also an appropriate first step towards unmanned production (Spiliopoulos & Sofianopoulou, 2008).

Although this idea seems very impressive, achievement stories form practice is very rare and level of satisfaction is quite low. Clegg et al (2002) reminds that overall rates of success of the practices are moderate, with some successes but also high rates of failure too. Likewise Manning & Jensen, (2006) remarks the machines isolated into a cell by accentuating the loss of pooling synergy of the shops moving from a departmental to a cellular layout and presents a spreadsheet approach to deal with consequent underperformance. Human and organizational factors in new manufacturing system implementation also play a central role. It is thus crucial to identify and reduce those performance obstacles for more effective CM implementation. Park & Han (2002) lists the important factors in CM implementation as training, education, information, teamwork skill, supervision, and scheduling. Of course, technical aspects are also worth to mention.

The objective of this chapter is to discuss the possible reasons of frustration caused by limited success of CM applications and to give some clues to improve the achievements of further ones by emphasizing of contemporary tools like computer techniques, especially emerging approaches and artificial intelligence as well as organizational and social issues after identifying of the basic concepts and explaining of the rationale behind CM..

2. BACKGROUND

Group Technology (GT) is launched by Mitrofanov in Russia at forties and developed by Burbidge in England later (Singh, 1993). That technology is based on the idea of ‘getting similar parts together to make use of their similarities in design and production’ (Kamran & Parsai, 1992).

A flange, for example, is a circular flat part used to connect the pipe ends to each other. Flanges are welded to pipe ends, in turn; these flanges are fastened facing to one another by bolts, so pipes are connected. A flange is basically a disk with a large central hole which fits to pipe diameter, and several smaller holes around large central hole for bolts. In fact, thickness and diameter of the disk itself, diameter of the large hole, numbers and sizes of the small holes and their locations differ. Part may has recesses, chamfers, or other secondary shape features. So, hundreds of flange types are being manufactured on production lines. Anyhow the machines, to manufacture any kind of flange is limited merely by lathes, drills, maybe of milling machines, regardless of its inherent shape characteristics and dimensions.

Bushings, connecting rods and so on are also apt to similar considerations. Consequently a large variety of similar parts are most likely produced in distinctive production units by making use of the improved expertise, reduced handling costs and better control. In an extreme - and ideal- case, all the parts are grouped into part families and all the machines are arranged as manufacturing cells.

Spiliopoulos & Sofianopoulou, (2008) regards the CM as the key production strategy, in the framework of GT. Mansour et al (2000) assesses CM as an important application of GT. Tsai & Lee, (2006) states that CM has found extensive use in just-in-time (JIT) production and in flexible manufacturing systems (FMS). Durmuşoğlu et al (2003) relates CM directly to Lean Manufacturing. Pattanaik & Sharma (2009) also discusses the requirement of new cell design methodology to minimize several non-value added activities/times such as bottlenecking time, waiting time, material handling time, etc.

The general idea is to decentralize processing by creating manufacturing cells. In other words, processing of each part family in a single machine cluster. The main objective is to cluster machines and parts into machine cells and part families respectively so that the minimum of intercellular part movements will be achieved (Ameli & Arkat, 2008).

Consequently CF is the main step in designing of a Cellular Manufacturing System (CMS) (Arkat et al, 2007). Due to NP completeness of CF problem, many heuristics have been developed (Mahesh & Srinivasan, 2006). The natural tool used in CF is the incidence matrix. Columns of this matrix are the parts to be produced and the rows are available machines. If a part needs a certain machine to be produced, the corresponding matrix entry is one; otherwise it is zero. That matrix representation can be interpreted as binary numbers both at the rows and the columns.

Binary Ordering Algorithm makes use of that interpretation. Although it is a naïve idea, with a low discriminating power as a clustering algorithm, it is a useful means to explain the block diagonalization concept. A five parts four machines incidence matrix is given at the leftmost edge of Figure 1. If the first row of that matrix can be interpreted as the binary value of 10011, its decimal equivalent is 19 as shown at the right of the first matrix. Values of the other rows are 12, 19 and 12, respectively.

The rows are sorted in descending order by their values. Second and the third rows are interchanged and the second matrix is obtained. Second matrix is copied as third matrix for clarity purposes without any change. Now the columns are interpreted as binary numbers. They are 12, 3, 3, 12, and 12 respectively as seen at the bottom of the third matrix. If the columns are sorted likewise, this time columns 2 and 4 as well as columns 3 and 5 swaps and the forth matrix is obtained. By noticing that the values at the rightmost edge of the figure (decimal equivalents of the binary values of the rows of the last matrix) are in descending order, the algorithm stops.

	P1	P2	P3	P4	P5	*
M1	1	0	0	1	1	*19*
M2	0	1	1	0	0	*12*
M3	1	0	0	1	1	*19*
M4	0	1	1	0	0	*12*

Initial values (Prepare to sort the rows)

	P1	P2	P3	P4	P5	*
M1	1	0	0	1	1	19
M3	1	0	0	1	1	19
M2	0	1	1	0	0	12
M4	0	1	1	0	0	12

After sorting of the rows

	P1	P2	P3	P4	P5
M1	1	0	0	1	1
M3	1	0	0	1	1
M2	0	1	1	0	0
M4	0	1	1	0	0
+	*12*	*3*	*3*	*12*	*12*

Prepare to sort the columns

	P1	P4	P5	P2	P3	*
M1	1	1	1	0	0	*28*
M3	1	1	1	0	0	*28*
M2	0	0	0	1	1	*3*
M4	0	0	0	1	1	*3*
+	12	12	12	3	3	

Stop the algorithm (Block diagonalized)

* row values, + column values

Figure 1. Block Diagonalization by Binary Ordering Algorithm

The column and row operations are also applied to machine and part names. Consequently the information on the matrix is not destroyed. As seen, two clusters are obtained at last. The first cluster corresponds to the first cell. Machines 1 and 3 as well as parts 1, 4 and 5 takes place there. Machines 2 and 4 are at the second cell. They will operate on parts 2 and 3 there. Entries with a value of 1 are completely diagonalized at last. In other words, blocks of ones are placed on the main diagonal of the matrix. Of course this is not the case in general. And more powerful methods are needed to diagonalize larger and more difficult matrices.

Another methodology to form manufacturing cells is based on similarity coefficients concept in conjunction with clustering procedures. These coefficients are devised to reveal the similarities of part pairs to decide whether they belong to the same part family or not. For each possible part pairs a coefficient is determined. The most common type of these coefficients is defined as 'the ratio of the number of machine types required by both parts to the total number of machine types in the system'. Further types of coefficients are also defined of course. Yin & Yasuda (2006) develop a new taxonomy to clarify the definition and usage of various similarity coefficients in designing of CMSs. They also proved that similarity coefficients based methods are more flexible than other CF methods.

A variety of clustering algorithms are defined to reveal the meaningful groupings by making use of similarity coefficients. Murugan & Selladurai (2007) examines three array-based clustering algorithms, namely rank order clustering (ROC), rank order clustering-2 (ROC2) and direct clustering analysis (DCA) for CF, with a real-life example to demonstrate the effectiveness of various clustering algorithms.

Burbidge (1992) argued that design, shape and other characteristics are not useful in CF but the processing requirement for each part is the only information that is needed. However a survey of many companies that use CM found that only in rare circumstances were companies able to identify mutually separable clusters of machine cells and part families (Wemmerlov & Hyer, 1989). In practice, the creation of completely independent manufacturing cells is very seldom feasible so one attempts to decrease as much as possible the intercellular traffic, that is, the traffic generated by parts visiting machines in different cells.

The example shown in figure 1 is reached into a perfect solution. In other words, all the non-zero terms are in diagonal blocks (highlighted by surrounding rectangles) and none of them remain outside. Probable non-zero terms outside the diagonal rectangles refer to exceptional parts that require intra-cell movements. They also mark the shared machines to be duplicated for complete partition, in other words, solutions are not prefect, in general.

These no perfect clusters necessitate a tool to evaluate the goodness of groupings. Efficiency is one of the well-known criteria employed for this purpose. It is based on the density of the non-zero elements in the diagonal blocks, and the density of zero elements in off-diagonal blocks. Kumar & Chandrasekharan (1990) critically discuss the efficiency concept and advocate the concept of efficacy to measure grouping goodness. Efficacy is defined as the ratio of the ‘number of in-cell operations’ to the ‘number of all operations plus zero entries in diagonal blocks’. Many data sets ranged from perfectly groupable to the most ill structured ones are analyzed by Chandrasekharan & Rajagopalan (1989) to determine the major factors affecting of the groupability. They found that groupability is mainly based on standard deviation of Jaccard similarity coefficients where Jaccard coefficient between two rows of incidence matrix is defined as the ratio of ‘number of pairs which both are non-zero’ to ‘number of pairs which either are non-zero’. They concluded that if standard deviation of Jaccard coefficients falls outside of the range of 0.2 -0.35, such matrixes can safely be rejected as unsuitable for GT applications.

Kumar & Vannelli (1987) developed two algorithms to determine the parts to subcontract to minimize the total cost while increasing the groupability of system. Recently, fuzzy clustering has been applied in GT because the fuzzy clustering algorithms can present partial memberships for part-machine cells so that it is suitably used in CMSs for a variety of real cases (Yang et al, 2006). Namely, other numbers between 0 and 1 are also allowed reflecting of the membership value of a certain part to a machine. As a consequence the crisp problem of groupability softens.

In CF problems, the number of cells is also a critical factor in view of the fact that it is not apparent before solving of the CF problem. Won & Currie (2006) proposed a new p-median formulation considering real-world production factors such as the operation sequences and production volumes for parts to determine optimal number of machine cells and associated part families. Yin, (2009) also introduce a mathematical model to find the economic number of cells that minimizes the total sum of intracell and intercell movements costs without solving the CF problem. Anyhow virtually all the techniques leave the determination of optimal number of cells to conclusion of the algorithm itself. In fact some administrative and technical factors like skilled manpower or equipment restrictions necessitate a priori awareness of cell numbers.

Siemiatkowski & Przybylski (2007) focus on process planning within facilities of definite processing capabilities, under the consideration of multiple choices of process routings. They investigate alternative process flows by simulation. Safaei et al (2007) and Mehrabad & Safaei (2007) deal with dynamic and uncertain conditions due to imprecise nature of product mix and part demand.

Mahdavi & Mahadevan (2008) states that sequence data and flow patterns of various jobs has been a least researched area in CF. In fact that patterns also provide valuable information on appropriate sequence of machines to be located. Ahi et al (2009) appreciate the importance of machine locations and they determine CF, intracellular machine layout and cell layout as three basic steps in the design of CMSs. Arkat et al (2007) uses simulated annealing (SA) as an optimization tool and states that CF and cellular layout design as two main steps in designing of a CMS.

Ameli & Arkat (2008) focus on the configuration of machine cells considering production volumes and process sequences of parts. They also examine alternative process routings for part types and machine reliability considerations. Chan et al (2008) lists the recent problems to be dealt as production volume, operation sequence, alternative routings, allocation sequence of machines within the cells (intra-cell layout) and the sequence of the formed cells (inter-cell layout). Hu et al (2007) propose an integrated approach to consider cell system layout and material handling system selection simultaneously.

If the major concern of management is the cost cutting strategies, they should also deal with spatial coordinates of machines as well as their assignments to cells, to minimize the transportation cost (Sarker & Yu, 2007). Similarly, Lei & Wu (2006) presents a multi-objective tabu search algorithm to minimize the weighted sum of inter-cell and intra-cell moves and the total cell load variations. Angra et al (2008) presents a workload-based model. They balance the workload of the cells keeping in mind the even distribution of processing times.

Further, Koufteros & Marcoulide (2006) seeks external integration by forming strategic partnerships involving customers and suppliers to coordinate activities across the value chain. Kumar (2004) remarks the need for conducting research in the areas at the interface of mass customization and supply chain management where mass customization is defined as, ‘technologies and systems that deliver goods and services that meet individual customer’s needs with near mass production efficiencies’. That is exactly what CM is aimed.

Satoglu et al (2006) advocates decentralized mini-storages against using of central storage sites as a continuation of the past habits. They also claim that such storage centralization both violates the independence of the cells from the entire production system in terms of facilities and prevents the reduction of both materials and parts transportation.

Braglia et al (2001) characterize material handling systems selection for manufacturing cells is a complex and risky affair due to intangible factors, a large number of possible equipment alternatives; the high investment required and uncertainty of market environment. Sujono & Lashkar (2007) proposes a method for simultaneously determining the operation allocation and material handling system selection in a CM environment with multiple performance objectives.

Kizil et al (2006) evaluates the effects of various dispatching rules on the operation and performance of CMSs which uses automated guided vehicles. Das et al (2007) proposes a preventive maintenance planning model for the performance improvement of CMSs in terms of machine reliability, and resource utilization. They also urge to minimize the total system costs and maximize the machine reliabilities.

Andrés et al (2007) examined a disassembly system with a cellular configuration. And they offered a two-phase approach to determine the optimal disassembly sequence to achieve good utilization levels of the equipment Copuroglu (2000) solved the CF problem by simultaneous consideration of tool shearing in aviation industry. Defersha & Chen (2006) proposed a comprehensive mathematical model to match the tooling requirements of the parts with the tooling available on the machines in CMS design. They also considered dynamic cell configuration, alternative routings, lot splitting, sequence of operations, multiple units of identical machines, machine capacity, workload balancing among cells, operation cost, cost of subcontracting, part processing, tool consumption cost, setup cost, cell size limits, and machine adjacency constraints in that model. Tsai & Lee (2006) developed a general purpose model which offers the suitable modules that include the different objective functions and constraints for user to solve the related problem.

As an alternative, modular machines are considered as production units consisting of some basic and auxiliary machine modules. By changing the auxiliary modules, different operations can be performed on these machines. Pattanaik et al (2007) devised a reconfigurable manufacturing system considering minimization of inter-cell movement and the total changes in auxiliary modules for the given production horizon. Baykasoglu (2003) proposed the capability-based distributed layout approach for job shops which are working under highly volatile manufacturing environments in order to avoid high reconfiguration costs.

As a substitute to conventional cells, Virtual Manufacturing (VM) cells can significantly improve the performance of manufacturing systems by developing of flow patterns as well as providing higher efficiency, simplified production control, and better quality. A virtual cell is a group of machines that is dedicated to the manufacturing of a part family, though this grouping is not reflected in the physical structure of the manufacturing system. Organizing of production control systems along with such groups offers the possibility of achieving the advantages of CM in non-CMSs.

Nomden et al (2006) reviews the literature and results in a comprehensive framework which identifies the underlying principles of VMs and classifies the different VM concepts. An extensive simulation study conducted by Nomden & van der Zee (2008) showed that a small number of alternative routes will mostly suffice but a chained distribution of routes is preferable, and additional secondary resources are relevant only under specific conditions. Akturk & Yayla (2006) selected the technology of each cell individually and developed a hybrid of flexible and dedicated manufacturing systems at the same facility to manage the product variety in unstable markets.

To incorporate product mix changes into an existing CMS many important issues have to be tackled. Bhandwale & Kesavadas (2008) presents a methodology to fit new parts and machines into an existing CMS thereby increasing machine utilization and reducing investment in new equipment.

Once a need for change has been identified, then the complex nonlinear and black box process of changing commences. This period will comprise a number of different tasks, activities, and decisions for individuals and groups both within and outside of the organization (Dawson, 2005). Chakravorty & Hales (2008) studied the CM failures reported in industry and tried to explain how and why manufacturing cells evolve over time. They advised 'conflict management skills' to resolve the dominant human problems at the beginning and 'formal problem-solving methods' to resolve the technical problems at a later phase. And they claim that in the third stage, both human and technical problems improve, and cells begin to perform at the optimal level.

Today's complex, unpredictable and unstable marketplace requires flexible manufacturing systems capable of cost-effective high variety–low volume production in frequently changing product demand and mix. Fractal organizations are capable of processing a wide variety of products by allocating all manufacturing resources into multifunctional cells to achieve system flexibility and responsiveness.

Montreuil et al (1999) introduced the fractal concept by dividing a plant into several quasi-identical micro-factories where each fractal has the ability to produce a wide variety of parts. Multi-channel manufacturing (MCM) systems, proposed by Meller could be considered as a type of fractal entity (Ozcelik & Islier, 2003). Saad & Lassila (2004) indicated the need for a trade-off between machine quantities and material traveling distance in fractal layout design.

Even though CM is a several decades old initiative; continuous academic research and accumulation of experience in practice still encourage inspiration, simulation, and confirmation even realization of new CM versions. Heragu (1994) provide thorough literature surveys and classification schemes. Venkatadri et al (1997) assert that holonic layouts with their robust structure are advantageous if very little information available about products and their specific routings. Islier (2000) regards functional, cellular and fractal layouts as special cases of holonic layouts. Irani & Huang (2006) list the versions of cellular layouts as: agile, dynamic, holographic, hybrid, robust, flexible, holonic, multi-channel, responsibility networks, modular layout and virtual cells.

Reisman et al (1997) analyses 235 articles starting from 1969 and examines the research strategy employed by the authors and concludes that the literature is dominated by articles classified as pure theory using synthetic data.

Marsh et al (1999) lists the well-known 10 presumptions on CM as: CM group the similar equipment to make part families; CM conversions are comprehensive, not incremental; cell design is a difficult problem; objective is to minimize intercell transfers; larger cells lose efficiency; reminder cells (cells formed by grouping of off diagonal machines) are common; subcontracting and equipment duplication are useful alternatives; cell workload balance is important; flexibility loss is a disadvantage of CM. By following a study conducted in 14 CM case sites they concluded that 'many of the problems researchers are investigating' are not those that 'managers are actually concerned with', due to different perspectives and understandings of two groups. At last they propose to increase communication between these two parties to rectify this situation.

Wemmerlov & Johnson, (2000) list their empirical findings on manufacturing cell design after a survey on 46 cell users as follows: CM is recognized as a tool for improvement of time, cost and quality; unsophisticated approaches are used in designing and implementing of cells; routing data is used as the primary source but it is distorted; strict targets for success is not set forth; single operator cells are common; safety and ergonomic considerations are kept in mind; cells are quite versatile (they contain multiple processes); implemented cells are quite flexible and robust.

Murugan, & Selladurai (2007) reports a reduction of 34.89 percent in material handling distance and an improvement of 20.21 percent in productivity by using of CMSs in a submersible pump industry which leads to a faster response than the current system and increased production accuracy, to yield more timely responses and more competitive business ability. Da Silveira (1999) developed a three phase methodology to implement a CM. The phases he devised are: Preparation (determination of objectives and constraints, customization of the environment), identification (data gathering, grouping, scaling, and aligning) and installation (planning, assignment, application and final adjustments).

Durmuşoğlu et al (2003) examined 207 manufacturing cells at 44 manufacturing firms, which are the leaders in their sectors in Turkey with international qualifications. As they report, the advantages achieved are enumerated by managers are as follows: Reduction of materials handling distances / times, increase in throughput, saving from process area, flow time reduction, reduction of WIP, reduction in setup times, decrease in scrap, production cost cut down, improvement in response time.

In the last years different metaheuristic methods have been used to solve the CF problems. Andrés & Lozano (2006) presents a population-based evolutionary computation technique based on a social behavior metaphor, namely particle swarm optimization (PSO) algorithm designed to address this problem. Islier (2005) and Kao & Fu (2006) developed Ant Colony Optimization (ACO) methodologies to solve the problem. Numerous Genetic Algorithm (GA), Simulated Annealing (SA) and Tabu Search (TS) techniques are also found in literature developed to solve CM problems.

3. PROBLEMS IN CMS AND RECOMMENDED SOLUTIONS

Above literature survey revealed several remarkable points related to CM design and implementation practices. Additionally some drawbacks of the paradigm and tools used in CM design became apparent. This section will address some clues to cope with the problems and some recommendation after itemizing of the remarkable points faced in current research.

3.1. Remarkable Points and Problems in Paradigm and Implementations

As seen from the discussions on previous section:

- Potential and real improvements brought by CMSs on materials handling, throughput, space utilization and flow time are considerably appreciated both by academicians and practitioners. So it is not possible to imagine a modern manufacturing system without prospects offered by CMSs.
- Anyhow success stories from real world are very limited compared to vast amount of theoretical study and high level of expectations.
- Each hypothetical study on CM covers only a very restricted part of the problem by disregarding of the whole view. Nevertheless each study is a minute but a stable step and a contribution to final solution.
- CMS design is not an isolated process. It is related with GT, JIT, FMS and even with Lean Manufacturing.
- GT is not a good starting point for a CMS implementation since it is based on shape similarities rather then process similarities in general. Anyway shape similarities provide incredibly valuable information for product design and drafting phase. This information and material may support parts and tooling standardization, save the unnecessary effort and time lost by repetitive work.
- A FMS is basically a manufacturing cell with central computer control plus computer controlled machines and materials handling system. Such systems are automation islands in shop level and they are considered as stepping stones to wholly automatic unmanned production systems. This impression leads to exaggerate the unrealistic expectations from CMSs.
- Theoretical studies are naturally based on lots of assumptions, idealizations and neglecting of many important issues of real world. This lead to successful but inapplicable models.
- On the other hand practical approaches overstate local improvements disregarding of a global approach. Kaizen in lean production scope especially is presumed as a traditional productivity improvement effort and used to achieve prompt and confined results. Anyhow a systematic and full-blown approach is a must for a complete accomplishment.
- Another shortcoming of cell design procedures is to pay greater importance to cell independence then that of cell flexibility. Consequently life cycle of the cell is curtailed. In addition, staring of CM projects by low level targets reflects the short sighed expectations of firms (Durmusoglu et al, 2003).
- The role of incidence matrix in cell design is over emphasized. This tool orientates to an ‘either all or not’ understanding. Vague characteristic of real world is disregarded. Exceptional part and sheared machine problems are left unsolved. Subcontracting possibilities and using of potential machines are overlooked.
- Resource identities to be allocated into cells are taken as machines although there is no exact one to one correspondence between machines and capabilities. This consideration does not decrease the flexibility of assignment decisions only but it also cause unfavorable effects on machine utilization and investment costs.
- Developed algorithms decide on the number of cells by themselves, in general, without leaving any degree of autonomy to designers. In fact the resources, for instance, number of potential cell leaders is limited in most cases. In addition, the Law of Diminishing Marginal Returns is valid for number of cells, so decision makers might willing to form only the most promising cells. Furthermore risk aversive decision makers tend to gradual and prudent implementations.
- Cost of each cell implemented is most likely at the same order but benefit of each added cell diminish ever more, that is, system is saturated gradually so there should be a trade off between costs and benefits. Consequently a break even analysis should be done to determine the optimal number for cells. This number can be interpreted as an indication of rational level for interest on CMSs. A lower interest means lost of some opportunities while an immoderate enthusiasm lead to resource misuse.
- Unjustified dependence on conventional incidence matrix for CF entails to disregard other essential information like sequences, times and capacities. As a result potential opportunities from optimal number of machines and the favorable locations to place them are missed.
- CM implementation starts with a CMS design, in turn, it begins with a CF study. This step is based on incidence matrix which is formed by using of routing data. In fact routing data is inaccurate, vague and out of date in general. Alternative routings are disregarded as a general rule.
- Another problem is dynamic -even volatile-nature of production environment. Routing data are static, specifically; they reflect only an instantaneous picture of

the shop in general; even if that representation is precise. So more robust techniques are required to avoid from the effects of probable errors and changes in product mix, demands and routings. VM cells with distributed capabilities seem as a prospective solution to respond to that dynamic structure.

- Although some studies deal with other issues beyond CF such as intercell and intracell layouts, materials handling equipment selection and arrangement of storage units; administrative and managerial issues are mostly kept in the background.
- Human factors like effect of unions, teamwork, synergy, competition, incentive plans, and disabled people are not sufficiently concerned. Environmental factors are also disregarded.
- Guidelines or a general purpose roadmap to switch to CM is not available for those who plan to switch to CM.

An old adage used for layout problems can be applied to CM problems as ‘CM problems look like birds, both their numbers and types are virtually infinite’. Consequently a unique roadmap, a unique approach, a unique model is not possible in fact. Anyhow a check list might be useful for practitioners. Such a list will also encourage the theoreticians for further studies. To reach such a list, CM related issues, controversies and problems faced in literature survey are brought together in Table 1.

Table 1. CM related issues and problems

ISSUES		**ASPECTS**
Category of studies		A vast majority of studies are theoretic Success stories from real life implementations are very rare
Realism of models		High degree of assumptions, facilitated the modeling but impeded the applicability
Contribution of theoretic studies		Incremental contributions by dealing with remarkably restricted hypothetical problems
Most dealt problem		Cell Formation
The most common tool		Incidence matrix
Insufficiencies of incidence matrix		Inflexible presentation (zero or one only) Completely independent manufacturing cells is very seldom Missing information (sequence, time, so on)
Implication of other contemporary manufacturing technologies	GT	Related to shape similarities rather than process similarities
	FMS	Leads to unrealistic expectations from CMSs
	JIT	Reduced WIP, decreased material handling, increased production control, and decreased scrap rate resemble to that of JIT.
	Lean Manufacturing	Prompt but confined results due to Kaizen like productivity improvement efforts. Overemphasizing of local improvements.
Similarity coefficients based methods		Claimed to be more flexible than other CF methods.
Criterion for groupability and goodness of groupings		Distribution of Jaccard coefficients for groupability. Efficiency -preferably- efficacy for goodness of groupings.
Means to augment groupability		Fuzzy clustering, subcontracting, considering of capabilities
Related operational aspects		Alternative routings, load variation
Aspects related with facilities		Materials handling systems, inter and intracell layouts, storage
Administrative factors		Unions, teamwork, incentive plans, synergy, competition
Grouping strategy		Fractal and capability based groupings are promising
Techniques employed		Meta heuristics are faster and more powerful
Computer aid		Compulsory in design and supportive in operation

3.2. Clues to Cope with the Problems and Some Recommendations

Modern manufacturing systems reached to a huge production capacity thanks to interchangeability concept. Anyhow this potential brought two contradicting problems to be solved for a successful production: Flexibility and efficiency. CM is launched as a solution to that dilemma by searching of a trade off. At the moment, even we knew the right thing to do is a CM application to cope with that challenge; we also have to know the right way doing it. That is what this chapter aims to answer.

The first step in solving of a problem should be to investigate its relevance, its scope, the environment it takes place, existence of the appropriate data. The factors related to firm culture, such as, understandings, behavior, doubts, expectations, trends, and so on, are also crucial factors in real life projects. Some questions to reveal these key factors at the start of a CM project are given on Table 2.

Table 2. Questions to be answered in CM design and implementation

Concerns	Questions to be answered
Existence of the problem	Is a CM implementation unavoidable, necessary, useful, required, at least, feasible?
Scope of the problem	How many cells are rational? Is a gradual solution adequate?
Problem environment	Will the problem held in scope of GT, FMS, JIT or Lean Manufacturing?
Demand pattern	Is production stable in long range?
Routings	Is routing data precise and permanent? What about alternatives?
Machines	Are machines modular? Are capabilities defined?
Human resources	Are operators, especially leaders available?
Tooling	Will tooling shared or duplicated
Parts	Will all the part numbers subject to production? What about subcontracting?
Expectations	Are targets set forth? What about under and over expectations?
Capacity	Are loads and number of available machines known?
Space	Is available area sufficient as amount and quality?

A CM project is either completely, partly or conditionally feasible or infeasible. If it is infeasible there is no problem from CM design point of view since no attempt is in concern then. Complete feasibility on the other hand, seems to be an ideal but unusual case. A perfectly block diagonalized incidence matrix with an efficiency and efficacy of 1 resemble to that case. Incidence matrices in real life are not prone to give such prefect solutions. They are quite sparse and the entries of ones are not realistic.

Routing data is also questionable at the start. It may be erroneous, not updated, and alternative routings are not considered. An incidence matrix which displays a complete partition might be impressive. Or an improvement of efficacy in the order of ten thousands may be attractive for mathematicians. But appraisal of managers will be different.

One of the well known Murphy's Law states that 'Wisdom consists of knowing when to avoid perfection', so partial and conditional feasibilities should be examined well for a rational accomplishment rather than seeking of perfect mathematical solutions. Break even analysis is a simple but amazingly powerful tool to determine the reasonable scope of the problems in hand.

It will be appropriate to begin with a cell only. It is not difficult to determine the most favorable cell configuration. That cell will be so apparent to detect by using of any classical clustering technique. Partial solutions may incorporate overlapping projects too. At the implementation stage of the first cell, design of second one may commence. Each additional cell will improve the productivity lesser and lesser. Soon a point is reached where improvements by additional cells cease. This gradual implementation is also a conservative way to reduce the risk. Pitfalls detected more easily and eliminated readily.

Conditional feasibility of CF then may necessitate the reexamination of routing data. Revised data may lead to a partial feasibility. Consideration of subcontracting and duplicating of cheap machines also release the grouping problem. Another way to deal with conditional feasibility is to consider non-conventional cell versions. Virtual and fractal cells and their derivatives are competent alternatives to be considered.

Virtual cells are physically easy to construct since no relocation is needed. They are not only practical but also robust. All the machines remain in their places so no relocation cost is suffered; only part assignments are changed. So VM cells are both practical and economical. In addition simulation studies proved their robustness. This is a crucial feature in dynamic environments of course.

Baykasoglu (2003) aims to locate each machine so that the distance to the following operation is minimized. In fact the following machine is a vague concept. Any part at any machine will require a different 'following machine'. Determination of 'next machine frequencies' may provide a better tool to design such systems.

Linguists study on a similar concept. In western languages a Q is most probably followed by a U, for example. In a similar way a hardening operation is most likely followed by a grinding. Another example might be the letter X and a packaging operation. There is virtually no word beginning with X similarly packaging as a first operation sounds very strange.

A 26 by 26 matrix prepared by examining of a large amount of text may give frequencies of letters to follow each other. A similar study may be done on production operations. Here routings are replaced by words and operations are by letters. If routings are grouped by sector, location, season and so on, multiple but more uniform matrices are obtained. If these data structures, say frequency matrices, are used to locate the next operation, probably more successful layouts are obtained by employing of such a biased randomization.

Another alternative to conventional cells is the fractal ones. Conventional cells, strictly share both the machines and the parts. In other words a part can be assigned to a certain cell only, whereas a part might be produced in more then one fractal cell. As depicted in Figure 2, same resources may be duplicated at different fractal cells. Replicated subgroups of AB, CD and PQ are in distinct cells as noticed at the center of figure 2. As an extreme case, some versions of fractal layouts consist of identical cells only.

A	B	C	R	S	T
D	P	Q	U	Q	B
C	D	Q	P	R	S
S	A	T	D	B	D

Conventional Cells

A	B	P	Q	R	S
C	D	R	S	T	U
P	Q	P	Q	A	B
T	U	R	S	P	Q

Fractal Cells

A	B	C	D	P	Q
C	D	P	R	Q	S
T	U	C	D	P	Q
R	S	A	B	C	D

MCM Cells

Figure 2. Comparison of cell types

Multi Channel Manufacturing (MCM) can be thought of a linear version of fractal cells. Ozcelik (2001) and Ozcelik & Islier (2003) also considered the capacities and flows in MCM design. These systems are quite flexible and adaptive, since a part likely follow a different channel if a certain channel is blocked in real time. For instance, a part with a routing of CDPQ can be manufactured at the first, second or at the third channels (at three topmost rows) of the system shown at the right of figure 2. In addition, it is also possible to line up the machines to minimize materials handling costs.

Structure of fractal and MCM cells are not based on strict partition, that is, their ability in adapting to real life conditions are not restricted by the nature of incidence matrix, in contrary to conventional cells. So these non conventional cells would be more preferable in CM design. A similar shortcoming of incidence matrix is confronted in graph theoretic CM design methods since they are based mainly on graph partitioning techniques. Anyhow unconventional interpretations of nodes and edges may lend the powerful tool of graphs to researchers' service in solving of CF problems.

Fuzzy logic and multi dimensional incidence matrices are two other ways to avoid the accurate structure of incidence matrices. Fuzzy logic enables to use fractional values of membership functions in place of ones and zeros. Consequently the information there softens and gets more applicable.

Baykasogu & Gindy (2000), advocates to use Machine Capabilities as Resource elements in place of machines themselves, in formulating of CF problems. This is an innovative idea with a significant contribution potential. It would be better to define routings as capability sequences instead of machine sequences of traditional understanding in Process Design phase. A three dimensional matrix with dimensions resembling to parts, machines and capabilities may incorporate the data structure of a potential technique. Here parts maybe assigned directly to capabilities and indirectly to machines. This way of thinking may lead a higher flexibility and result in a higher success.

The last recommendation to mention is the power of Artificial Intelligence (AI) techniques to solve NP hard CF problems. Especially, Ant Colonies Optimization (ACO) is apt to solve the problems related to objects in motion by its ability to accumulate and share the information gained from experience. Islier (2005) verified superiority of that technique to other AI techniques in CF problems. As known, ACO simulates behavior of ant colonies in their struggle to survive. Consequently a new technique where parts are resembled by ants and machines are resembled by nests or food sources might be developed as a more powerful CF technique.

Nesting of various AI procedures into a larger general purpose CF program will increase the benefits obtained from cell design approaches, AI techniques and computers simultaneously. Tsai & Lee (2006) already announce such a general purpose model which offers the suitable modules that include the different objective functions and constraints for user to solve the related problem. This model or an equivalent of it might be used as the prototype of a meta-program, designed collectively to support the problem solving efforts of CM community members.

4. FUTURE RESEARCH DIRECTIONS

Since the majority of present research is on theory, the major need is to understand the industrial reality surrounding CM, through additional, and more rigorous empirical research. (Nomden et al 2006). Most opportunities for future research are in the extension of testing more proactive versions of CM cells, incorporation of material handling and human aspects.

Decisive step towards more successful implementations seem to be to violate the non-natural restrictions of basic CF tool, namely, the incidence matrix. Fuzzy entries or extended data structures covering machine capabilities are potential means. Upcoming versions of CF techniques probably assign parts to capabilities, not to machines directly.

The consideration of new layout types is also very promising. Fractal structures are not thoroughly investigated yet. New prospective versions will not only improve but may radically alter our understandings of CM and change our expectations, too. MCM with its proven success might be a starting point for such an investigation.

Sequencing, scheduling, dispatching and expediting of parts as well as machine set up and operation sequencing are the issues which are not explored thoroughly. Developing of related strategies and their validation with simulation studies and pilot applications may be an enlightening endeavor. In addition, foundation of a computer based control systems to monitor the production without human interference is another subject open to be investigated.

Enormous diversity of CM problems is the major challenge for practitioners. An open structured multi purpose meta-program reflecting of that multi facet, dynamic, multi criteria, multi decision maker nature of CM design and implementation problem may provide an appropriate problem solving environment. Such a program can be developed on WEB environment by contribution of CM community members, prone to be expanded continuously. Commercial programs are prepared professionally but they are closed to users' interference and contributions, by their nature. Consequently their adaptability is quite limited. So an amateur deal will not light the way only but will also promote the professional efforts. A site encompassing such facilities as, information, archive and links may also provide a proper environment to communicate.

Real time control of production cells is another domain where the ability of computers is not fully utilized yet. Especially MCM like applications require close on line control to utilize the resources more efficiently. A model to reflect the objectives and instantaneous constraints as well as peripheral units to transfer data are needed for such a control. Bar code or radio frequency like equipment is necessary to avoid probable errors of manual data input.

5. CONCLUSION

Production is an essential tool to survive and improve for human beings. Production systems meanwhile urge a simultaneous efficiency and flexibility for their success and long-term survival. CM is one of the means to get a trade off between those two requirements. Anyhow CM is not a widespread practice yet. The aim of this chapter was to examine the literature to detect the shortcomings of present concepts, techniques and paradigm of CM to offer clues and better tools for further success stories.

A general assessment of the past studies revealed the following facts:

- Papers on real world applications are quite rare.
- Studies are heavily relied on defective routing data and a restrictive tool of incidence matrix.
- General engineering problem solving procedure is not followed by practitioners, in general.
- Complete partition is sought; non conventional CM versions are not acknowledged enough.
- Machine and capability is thought of two identical concepts.
- Power of AI techniques is not credited as they worth.

Consequently an encouragement to try the non-familiar concepts like capability, VM and distributed manufacturing is a must. Making the practitioners aware on emerging CM versions, especially VM and MCM, as well as on the might of computers, real time solutions and AI techniques is another deal. In fact a paradigm shift is required to exclude conventional concepts of incidence matrix, block diagonalization and complete partition,

An offer as Ten Commandments of CM design and implementation is as follows to conclude the subject:

- CM may be the solution you sought.
- You shall not deal with non existent or insignificant problems.
- You shall eat the elephant bit by bit.
- You shall not disregard the problem environment.
- Routing data shall be valid, updated, together with related data and alternatives.
- You shall not urge for a complete partition.
- You shall rely on capabilities rather than machines.
- You shall try new CM versions.
- You shall not forget the use of AI techniques, computer support and WEB opportunities.
- You shall not overlook both the internal and external neighborhoods.

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