Re-aligning research objectives in Cellular Manufacturing System Design: A User's Perspective

B. Mahadevan
Indian Institute of Management Bangalore

Re-aligning Research Objectives in Cellular Manufacturing Systems Design: A User's Perspective

B. MAHADEVAN
Professor, Production & Operations Management
Indian Institute of Management Bangalore
Bannerghatta Road, Bangalore 560 076, India
mahadev@iimb.ernet.in

S. VENKATARAMANAIAH
Assistant Professor, OM and QT Area
Indian Institute of Management Indore
Pigdamber, Rau, Indore - 453 331
svenkat@imidr.ac.in

ABSTRACT

Designing appropriate cells is the first step towards configuring a cellular manufacturing system (CMS). During the last three decades of research numerous algorithms have been developed to solve this problem. However, there is a concern of the widening gap between research and practice. This paper seeks to provide an understanding of the reasons for this. A scrutiny of over two hundred and seventy five research papers written during the last thirty years suggests that increasingly CMS design research has not been able to adequately satisfy user requirements. Several new directions for future research in the area of CMS design has been proposed to correct this anomaly. These include re-examining the notion of focus as applied to CMS design, developing efficient solution procedures to handle large problem sizes and difficult to handle data and problem structures and efforts to improve the portability of research to practice.

1. INTRODUCTION

Group Technology (GT) has become an accepted philosophy today to solve many problems that manufacturing organisations face in the shop floor. The implementation of GT principles in the shop floor is often referred to as Cellular Manufacturing. Researchers in the past three decades have addressed various issues concerning design and operational control of Cellular Manufacturing Systems (CMS). These include cell design, cell layout, operator allocation issues, short term scheduling and performance evaluation. However, amongst others, researchers and practitioners have evinced keen interest in the cell formation problem. Such a phenomenon is underscored by the fact that cell formation issues address the basic design problems in a manufacturing system.

A properly designed cell seeks to provide a structural basis on which other issues could be studied further. Although the pioneering work of Mitrafanov paved the seeds, it was

Burbidge, who was responsible for initiating widespread interest through his Production Flow Analysis (PFA) approach. Cell formation issues have ever since caught the attention of researchers and the interest appears to remain even today. Despite over three decades of research in the area of cell design, researchers have often reported that much of the research in cell design is not being used in practice (Wemmerlov and Hyer (1989), Choi (1996), Olorunniwo and Udo (1996), Marsh et al. (1999), Wemmerlov and Johnson (1999)). This is a matter of concern and it calls for a detailed inquiry into the causes for this anomaly. We propose to address this issue in this paper. We motivate this research by the fact that such an approach to understand the literature has not been attempted in the past. Reisman et al. (1997) presented a fairly comprehensive analysis on this issue. Their research focused on how much CMS research exhibited theoretical vs applied orientation using a seven-part classification scheme for pure theory vs applied research. However, we build on this idea and include additional dimensions to understand the extent to which CMS research addresses real life requirements.

One significant reason for the widening research-practice gap is the changing market mechanisms, user perspectives and manufacturing complexities over the last several years. Consequently, several new concerns have arisen in the business that seems to influence the cell formation problem also. At the business level, we identify some significant factors that affect the performance of an organisation. These include excellent performance in customer satisfaction measures, greater emphasis on lead time reduction, and efficient customer response. The manufacturing strategy an organisation adopts is arguably derived from the overall business strategy and all organisational choices pertaining to manufacturing are made in the context of the manufacturing strategy. Expectedly, these considerations will significantly influence the cell design problem. For instance, the apparent conflict between resource utilisation and customer focus has diminished with the former playing a subservient role to the latter. However, from a cell design perspective, the notion of focus needs to be re-examined.

Before we proceed further, we would like to clarify our definition of the term user in the context of this paper. Our definition of the term user includes practitioners belonging to manufacturing organisations who are involved in the design and implementation of cellular manufacturing systems. It also includes other practitioners such as executives in consulting firms directly involved in restructuring manufacturing systems. The rest of the paper is organised as follows: We begin the paper with a longitudinal classification and analysis of CMS design literature spanning over the last three decades. In the section 'The Notion of focus in CMS design' we discuss the notion of product focus. We show that, CMS design objectives need to address the new market realities. In the section 'User Perspectives' we identify some user perspectives and possible consequences to cell design problem. We examine the contributions of the literature in the light of these perspectives and identify areas for future work in the section 'Re-aligning Research Objectives'. In the final section called 'Conclusions' we draw certain conclusions.

2. CMS DESIGN – LITERATURE DEVELOPMENT

We begin the paper by a longitudinal analysis and classification of the research papers pertaining to CMS design spanning over the last thirty years. Ten leading research journals that have significantly published CMS literature were scanned for selecting the papers. These include Computers & Industrial Engineering, Computers & Operations Research, Decision Sciences, European Journal of Operational Research, IIE Transactions, International Journal of Production Research, Journal of Operations Management, Production Engineer, Production & Inventory Management Journal, and Production Planning & Control.

We have employed three dimensions to classify the data and analyse it. As we would see later, the choice of these dimensions facilitate our understanding of some of the reasons for the existing practice-research gap. Two hundred and seventy nine papers have been classified using the following dimensions:

2.1 Size

In the current study, the problem sizes handled in the past have been classified into small, medium and large on the basis of maximum number of entries possible in a machine-part incidence matrix. While entries below 1,000 will be classified as small, those in the range of 1,001 to 4,000 will be classified as medium and the others as large. This allows for a machine-part incidence matrix of size 25 x 40 or 20 x 50 to be classified as small and those of the order 40 x 100 or 20 x 200 as medium sized problems. These have been arrived on the basis of earlier studies (Gupta 1991, Kaparthi and Suresh 1994) and the experiences of the authors with a few manufacturing firms.

2.2 Theoretical vs Real Life Applications

For the purpose of this classification the basis as defined in Reisman et al. (1997) has been adopted.

2.3 Data Type

Studies in the past have used different types of data. The predominantly used data is the 'zero-one' machine-part incidence data. Such studies are grouped under binary data. There are studies that have employed processing time and set-up time data. These have been classified under interval level data. The other category includes use of data such as sequencing information for cell design and part geometry and other design related data for grouping.

Table 1 presents the literature on the basis of the above dimensions. Figure 1 is a graphical representation of the data. The literature building clearly has three stages; slow initial growth, rapid development and maturity (saturation). The situation resembles the classical product life cycle phenomenon. Reisman et al. (1997) also refer to the notion of life cycle literature of cellular manufacturing. However they neither provided an

TABLE 1: Classification of the Existing Literature on Cell Formation Issues in CMS (1968–98)

Period	*Total*	*Theory*	*Applied*	*Data Type*			*Problem Size*		
				Binary	*Interval*	*Others**	*Small*	*Medium*	*Large*
Up to 1970	2	1	1	0	0	2	1	0	1
1971–74	12	6	6	6	1	5	3	3	6
1975–78	4	2	2	2	2	0	3	0	1
1979–82	6	3	3	2	4	0	4	2	0
1983–86	11	10	1	9	2	0	6	4	1
1987–90	57	49	8	33	16	8	39	10	8
1991–94	77	66	11	42	24	11	47	16	14
1995–98	110	88	22	57	35	18	63	18	29
Total	**279**	**225**	**54**	**151**	**84**	**44**	**166**	**53**	**60**
% of total	**100**	**80.65**	**19.35**	**54.12**	**30.11**	**15.77**	**59.50**	**18.99**	**21.51**

* – Others include use of design and part geometry information and sequencing information.

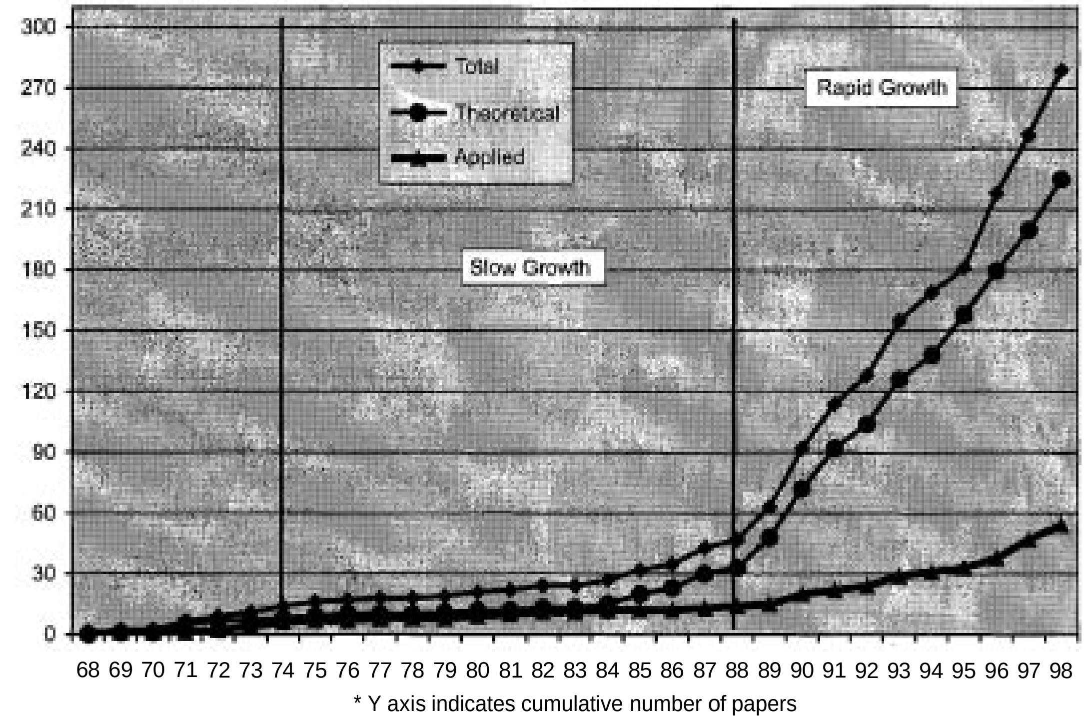


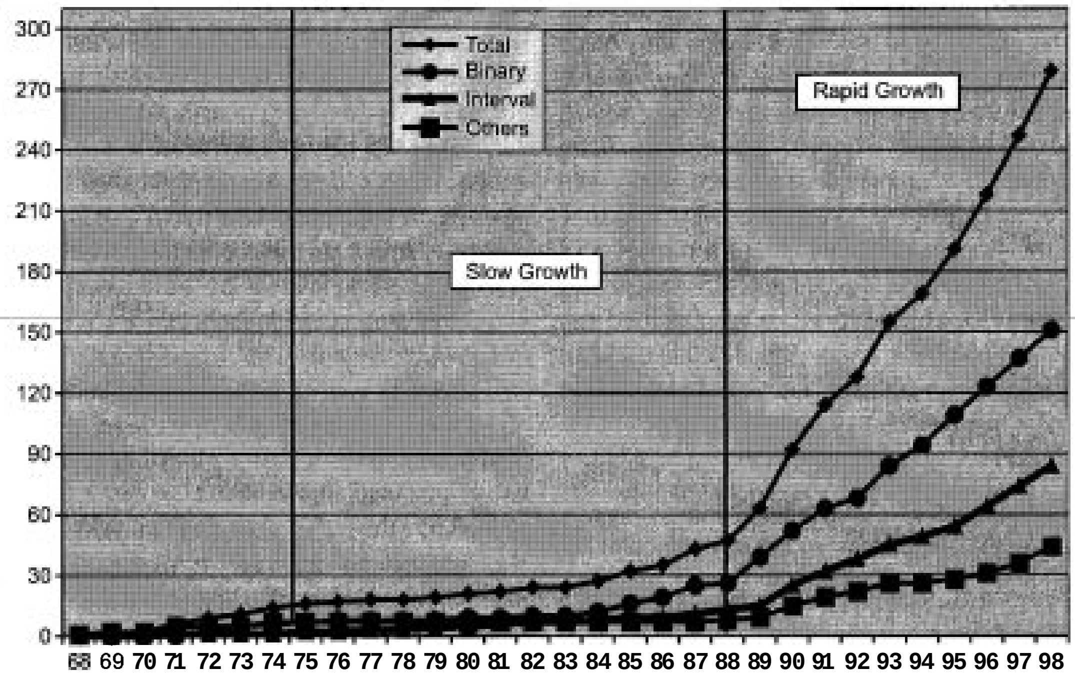
FIGURE 1 Life Cycle of Literature Pertaining to Cell Formation (1968–98)

explanation of the life cycle literature nor the potential uses of identifying it. On the other hand Skinner (1996) employed the 'S' curve associated with new product to study the development of manufacturing strategy literature over time. We employ a similar approach to position CMS design literature.

During the initial stage (1968–74), efforts were to gain an understanding of the problem. During the second stage (1975–88), the growth of literature was rather slow. The slow growth is attributed among other things to the status of computing technology available at that time. Until mid 1980's, microcomputers were not widely available nor were there adequate platforms for evaluating the models developed. The need to involve large matrices and numerical computations typical of real-life problems and the lack of adequate computing technology made further development of early models impractical. Consequently, heuristics, particularly those of a simple nature were probably considering the 'user perspectives' in CMS research in a limited fashion.

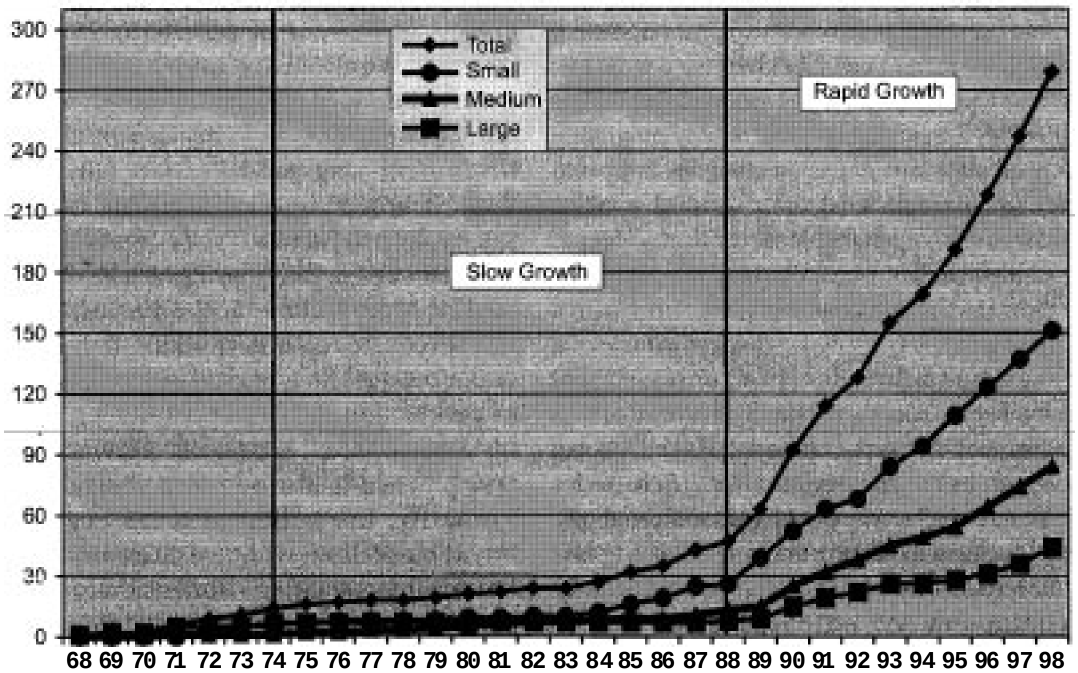
However, the last ten years account for the period of rapid growth. This was partly due to developments in the area of computing and software technologies. However, over the years the emphasis has shifted away from applications. The number of theory papers pertaining to cell formation was far more than application papers. Figures 2 and **3** graphically represent the data on the basis of the other two dimensions.

The findings closely follow that of Reisman et al. (1997), though their survey included papers other than cell formation issues. The figures clearly indicate that the life cycle of literature is in the stage of a transition from rapid growth phase to maturity phase. The research goals are expectedly different in various stages of literature building. Obviously, in a maturity stage, the



* Y axis indicates cumulative number of papers

FIGURE 2 Data Structure Employed in Cell Formation Studies (1968–98)



* Y axis indicates cumulative number of papers

FIGURE 3 Problem Sizes Handled in Cell Formation Studies (1968–98)

expectations of the users of the literature also mature. There will be an increased emphasis on leveraging the past research into useful applications. Certain subtle dimensions will be brought forth and researchers will be expected to align their research goals. We particularly identify two important issues, viz., the notion of focus as understood and applied in research studies in CMS design and the extent to which literature has fulfilled the expectations of the users. We discuss these in detail in the next two sections before we identify the research priorities.

3. THE NOTION OF FOCUS IN CMS DESIGN

The fundamental building block of CMS design is the philosophy of focus. Skinner (1996) suggested that focus is a state of mind and focusing is the management process of designing coherent structure to accomplish a strategic task. Focus provides broad guidelines for organisations while they make certain structural choices. First, it helps organisations align their manufacturing management goals to business goals. Mukherjee et al. (2000) reported that studies done by consulting firms such as McKinsey and Anderson Consulting indicated substantial improvements in operational performance of over 2,000 factories worldwide through implementation of focus. Focus also helps organisations in making appropriate trade-offs while allocating scarce resources.

Pesch and Schroeder (1996) observed that factory focus forces a clarified view of the customer and market needs. Based on an empirical study of several firms, Schroeder and Pesch (1994) reported that focus at the plant level invariably means combining the manufacturing tasks for similar products and/or customers. Al-Mubarak et al. (2003) defined 'focused cellular manufacturing' (FCM) as a means of designing cells on the basis of end-items (products) and discussed several advantages of such a design.

Traditional manufacturing organisations employed a process focus. However, CMS design studies sought to redefine the scope for focus. By focusing on manufacturing similarities, CMS designs ensured that dissimilar machines could be rearranged into machine groups to process a family of parts. Consequently, much of the research focused on the problem of arriving at non-overlapping machine and part groups using a variety of information on 'machine-part'. Such a redesign, it was argued, would reduce set-up time, material handling, lead time and WIP and allow for better planning and control of operations.

However, the manner in which CMS designs were arrived at in practice was somewhat different. Organisations do not seem to use the pure 'machine-part' frame work that cell design researchers have been advocating. On the other hand they have endeavoured to design product focused cells (Schonberger 1990). In many cases practitioners relied on market requirements and business strategy for guidance (Berry et al. (1991), Levasseur et al. (1995), Powell, Jr. (1995)). Wemmerlov and Johnson (1999) reported that a vast majority of the firms that they studied (98 per cent) designed cells by first identifying product/part families and then determining the equipment needed to satisfy the production. While creating product focused cells is fairly straight forward in the case of high volume and a narrow product line it requires careful thinking in the case of wider product lines and relatively low volume of production.

The apparent 'stand off' between theory and practice is attributed to several factors. Primarily, the notion of focus needs to be broad based than what we currently attempt. From a 'machine-part' dimension to the CMS problem we need to graduate to 'machine-product-part' dimension. The inclusion of product into the CMS problem at the outset may seem redundant. For instance, one can argue that if the plants within a plant are already pre-selected on the basis of product families, the need for including product related information into the 'CMS design problem do not arise. On the contrary, even after a clear understanding of how to create plants within a plant, limited availability of resources such as machines and manpower will necessitate a basis for allocation of resources to various plants. Product-oriented decision making for resolving such trade-offs are crucial today. In the absence of this, the linkage between the business goals and the manufacturing goals may be lost in the process.

Moreover, a cellular shop structure based on a family of parts may appear to be a very attractive alternative for day-to-day shop floor planning and control. It is at best narrow and effective at the cell level but will be ineffective at the organisation/market level. For instance, if the part families associated with the cells consist of components belonging to different products and market segments, it may result in poor performance in customer satisfaction measure and may call for several administrative mechanisms to compensate for loss of focus at the market level. Wemmerlov and Hyer (1989) echoed a similar view in their survey of CMS practices, '. . . one approach to cell design is to combine parts and products belonging to the same product line . . . such an approach would not be a pure group technology solution, since similar parts used in different product lines can obviously turn-out to be separated instead of consolidated during manufacturing. . . . The expected benefit of such an approach would be the ability to react quickly to market demand changes . . .' as pointed out by Al-Mubarak et al. (2003).

A case in point is the cellular structure proposed for a manufacturer of medium voltage circuit breaker. Table 2 shows the cells formed by grouping together 175 parts belonging to six product families using the 'part-machine' dimensions. The resultant cells had fewer inter-cellular movements.

TABLE 2: Cell Design Summary using 'Part-Machine' Dimensions

Product Group	*Components belonging to the Product Group*			
	Total	*Cell 1*	*Cell 2*	*Cell 3*
1	45	9	17	19
2	20	6	12	2
3	22	3	9	10
4	19	9	1	9
5	53	7	26	20
6	16	9	4	3
Total	175	43	69	63
Inter-cell moves*	41	6	19	16

* Inter-cell moves are the number of operations performed outside the designated cell for the parts.

However, as shown in the table, at the product level, the cells are out of focus. Each product assembly will obtain its components from all the cells. Such a design will introduce several problems at the organisation level and will call for intensive coordination efforts. On the other hand, creating separate product focused cells in this case was not feasible due to resource constraints. It therefore follows that there is the third alternative of designing cells using 'product-part-machine' dimensions that would not only seek to minimise the inter-cell movement but more importantly the lack of focus at the product level. Table 3 shows an alternative solution to the problem that has a better product focus and fewer requirements for administrative co-ordination. Based on a study of 57 firms, Olorunniwo (1997) reinforced this aspect of CMS design by suggesting that the practice of forming part families for cellular manufacturing by combining parts belonging to the same product line could result in better success, especially in the case of more product lines. Al-Mubarak et al. (2003) study clearly showed for instance that FCM design resulted in shorter assemble waiting time as all components of an end-item are processed together in one cell.

It clearly follows that we need newer

TABLE 3: Cell Design Summary using 'Product-Part-Machine' Dimensions

Product Group	Components belonging to the Product Group			
	Total	Cell 1	Cell 2	Cell 3
1	**45**	43 *	**2**	–
2	**20**	1	**19**	–
3	**22**	–	**19**	**3**
4	19	*2*	**17**	–
5	**53**	–	–	**53**
6	16	14	–	*2*
Total	175	60	**57**	**58**
Inter-cell moves**	**57**	11	**24**	**22**

* Numbers in bold indicate the designated cells for the products on account of majority completion of the processing requirements.

** Inter-cell moves are the number of operations performed outside the designated cell for the parts.

measures of performance for the cell design problems that will employ 'product-part-machine' dimensions. Researchers have often resorted to a wide range of non-cost measures that employ several variations of the extent of block diagonalisation (such as inter-cell moves, grouping efficiency and efficacy and maximisation of similarity or minimisation of distance measures). These measures need to be modified to suit the new requirement. Moreover, use of customer-oriented performance measures will be desirable over other non-cost based measures. One such measures, viz., product ownership was suggested by Mahadevan et al. (1999). The other reason for cell designers not utilising the existing literature relates to how much the literature has addressed the 'user' requirements. We discuss these issues in the next section.

4. USER PERSPECTIVES

Several survey papers in the area of CMS design have concluded that existing literature has not adequately fulfilled the requirements of the actual users (see for example Singh (1993), Reisman et al. (1997)). Although some indicative limitations such as inability to solve large sized problems have been discussed, they have not brought out elaborately the issues to be tackled. In order to do this, we begin by gaining an understanding of the user perspectives to the problem on hand.

In addition to issues related to focus, user perspectives to assessing the usefulness of the literature have three basic requirements. First, the issue of size becomes important. Real life problems are often large. Miltenburg and Montazemi (1993) indicated a size of 5,498 parts in one application. We have encountered similar problem sizes in the studies that we have conducted in CMS design. For instance, in a earthmoving equipment manufacturing facility in south India, of the several variations of wheel loaders two models alone accounted for over 270 parts. Moreover, the manufacturer's gear shop was manufacturing 620 different varieties using 107 machines (40 machine types). These gear components were used in seven product lines that they were manufacturing in three locations. Similarly, more than 770 metal parts were manufactured at the Helicopter division of Hindustan Aeronautics Limited in India using 79 machines in the machine shop for the Advanced Light Helicopter. It is therefore worthwhile to understand the manner in which the literature has handled this aspect.

Second, real life applications lay an emphasis on the extent to which the data set is representative and complete. This, for example, would mean the use of actual process routings, bill of material, projected production volumes, process times and set-up times, batch sizes adopted, capacity availability, etc. Incorporating this information would amount to designing cells using interval level data. While the use of zero-one incidence matrix is a welcome first step in the cell design it calls for logical extension of the work to incorporate the above requirements. Furthermore, use of interval level data could capture the problem more accurately and help the cell designer make better decisions with respect to exceptional parts, machine capacities and additional investment in machines.

For example, if a part has an 'inter-cell move' to another cell, then the cell designer will be in a better position to decide on the alternatives if he/she also has an idea of the extent of inter-cell movement. The decisions will vary significantly if the extent of inter-cell movement of the part in question is 1 per cent of its total processing requirement as opposed to 15 per cent. In the former case, there will be a greater motivation for process plan changes, whereas in the latter, the cell designer would like to explore design changes and outsourcing opportunities. Such dimensions could play a useful role (Cantamessaand Turroni 1997) when it comes to, configuring cells in a CMS. An understanding of the extent to which the literature has addressed this issue is equally important.

The third aspect relates to the portability of the research into practice. Portability involves two significant aspects. Users would be able to implement solutions when it requires no more analysis or assumptions. For instance, if the CMS design incorporates other issues such as available manpower, alternative scenarios for projected capacity variations, ability to accommodate special constraints arising out of technology, market and organisational limitations, then it has a better chance for acceptance. CMS design for a brown field operation will often face these additional constraints. Moreover cost based performance measures that includes the cost of re-allocation, additional capacity to be procured, and costs associated with re-skilling of existing workforce will capture the reality more effectively. Table 4 is a list of 'other' issues that were considered for conversion of the engine plant of an automobile manufacturer from functional focus to CMS. Many of these issues have not been considered in a simultaneous fashion in CMS literature. The second aspect of portability is the ease of implementation of the CMS design proposed by researchers.

TABLE **4:** Other Considerations in Redesign of Engine Plant of an Automobile Manufacturer

Sl. No.	*Additional Parameter Considered for Re-design*	*Basis for Estimating the Parameter*
1.	Additional Investment Required	Capital Budgeting Plan for capacity augmentation
2.	Manpower Constraints	Projected retirement plan of the existing workforce
3.	Manpower relocation constraints	Skill inventory of availability and requirement as per the new design
4.	Constraints in resource relocation	Number and Technical complexities of resource relocation involved as per the new design
5.	Owning/Sharing of resources	Percentage of facilities (capacity) exclusively owned by the cells vis-a-vis shared with others
6.	Ease and cost of implementation	(a) Implementation lead time (b) Overall cost of the plan and the opportunity cost for lost production

Cantamessa and Turroni (1997) observed that '. . . because of these limitations, the gap between academic research and industrial practice is known to be quite significant: hardly any company surveyed during Wemmerlov and Hyer's (1989) empirical research designed its cellular manufacturing systems by using solution techniques found in academic literature . . .'.

5. RE-ALIGNING RESEARCH OBJECTIVES

A closer look at Table 1 and Figures 1–3 highlight some significant aspects of research in CMS design and the extent to which it addresses user requirements. We use this data to identify a few areas for future directions for research.

5.1 Ability to Solve Large Size Problems

Nearly 60 per cent of the studies in the area of cell formation have employed only small matrices. Figure 3 indicates a significant trend in the use of small matrices for cell formation studies during the rapid growth stage. Such small sized matrices are often hypothetical and result in theoretical studies. This confirms our earlier observation based on Figure 1 that the extent to which real life studies have been conducted is far less.

In the future CMS design studies will require greater attention to complications arising out of large size problems. Solving such problems require special solution procedures. Often such procedures would involve decomposition of the problem into stages and solving them progressively. More research is required to develop specific solution methodologies for this requirement. Mahadevan (1999) proposed three alternatives for creating a plant within a plant and using them as the basis for decomposing the problem into smaller ones. There has been considerable research in recent years in the use of meta-heuristics such as Simulated Annealing, Genetic Algorithm, Tabu search, and Neural Networks for solving large optimisation problems. In the future, more research is required for gainful exploitation of these methods to solve large sized problems.

Developing solution procedures for large problems will invariably shift the focus of attention of the researchers from optimal solutions to sub-optimal but 'good enough' solutions. It will further call for a better understanding of the practical aspects, which will aid in designing efficient heuristics. Moreover, developing tighter bounds will also aid the process. The efficiency and quality of the final solution will directly depend on the methods used to decompose the problem. Recently, there are a few attempts to consider newer approaches to tackle these issues (see for example, Cantamessa and Turroni 1997, Chen and Heragu 1999).

5.2 Use of More Production Information in Cell Design

The current study indicates that although there is a general tendency in recent years to employ interval level data (such as process plans, production volume, time (see for example, Beaulieu et al. 1997) for the cell formation problem, the use of binary data continues to be widely prevalent. Nearly 55 per cent of the studies have resorted to using binary data for cell design. Even recent studies such as Chen (2003) proposed newer solution techniques for binary data. While binary data offers considerable advantages for the researchers, it often moves the problem and the solution away from reality. Measures such as inter-cell movement, and bottleneck machines and parts computed using binary data are often inaccurate and sometimes misleading also. On the other hand, solving real life problems involves use of several production-related information. These include production volume, set-up and processing time of components, bill of material of products, machine availability and quality parameters of the processes.

Solving problems of this nature is a challenging task for the researchers. The complexity and problem size will increase. The problems will defy known structures, thereby disallowing exploitation of known solution methodologies. However, attempts in this direction will add more value and new knowledge in the field.

5.3 Increased Emphasis on Solving Brown Field Issues over Green Field Issues

Researchers in the area of cellular manufacturing in the past have rarely made their position clear on whether their work pertains to designing cells for a new factory or for converting an existing one. However, by and large, the nature of assumptions made and the conclusions drawn suggests that bulk of the work addresses issues pertaining to designing cells for a new factory.

Designing cells in the case of a factory already working in a functional basis poses numerous other constraints as we have discussed in the previous section. Typically, there is a predetermined set of machines available. There are often constraints in forming new layouts. Worker skills, tooling and process planning are the other areas that add more constraints to the problem. Solving such a problem calls for a different approach. Since converting an existing factory is often encountered in practice, researchers need to address this area in more detail.

5.4 Improving the Portability of Research to Practice

Many research studies in the area of cellular manufacturing design often promises to provide application potential. However, the portability suffers on account of lack of additional features, and interfaces that suit real life applications. A 'canned' software with the core logic derived from research as the black box with additional features for interfaces in an integrated fashion can greatly improve the portability. The success of recent Supply Chain Management Software such as i2 technologies is partly attributed to their ability to build this aspect around the optimisation algorithms that form the core logic of the software. We specifically identify the following three basic features for such a software:

- A mechanism to import information from an industrial database application
- The core logic developed by the researchers in the form of a set of processing routines and
- A mechanism to export data in the manner an industrial database can put it to other uses

Furthermore, linking a cell design programme with a layout generation and evaluation utility will increase the usefulness of the cell design logic itself. Often this can be achieved through the use of computer simulation modelling techniques. One recent example in this direction is available in Saad et al. (2003). Several such initiatives are required in the future to improve the portability of research. It calls for collaborating with the industry and extending the work to other peripheral areas.

6. CONCLUSIONS

Research pertaining to cell formation problem in CMS is in a transition from rapid growth to maturity phase of life cycle. Such a transition demands that researchers realign their research objectives to the emerging business reality. The study has identified certain lacunae in the manner the research efforts have addressed the requirements of the users. Consequently, several new directions for research have been identified. These include developing solution methodologies that guarantee product focused cells and the use of more production information in solving the restructuring problem. There is an immediate need to develop solution methodologies for solving large sized real life problems. Researchers need to pay more attention to the issue of portability of research to practice. Such initiatives will help plug the gap between practice and theory and help create new knowledge in this area of research.

ACKNOWLEDGEMENT

This work has been partly supported by the research grant from the Ministry of Human Resources Development, Government of India.

REFERENCES

Al-Mubarak, F., C. Canel and B.M. Kumawala, 'A simulation study of focused cellular manufacturing as an alternative to batch-processing layout', *International Journal of Production Economics,* vol. 83, 2003, pp. 123–38.

Beaulieu, A., A. Gharbi and Ait-Kadi, 'An algorithm for the cell formation and the machine selection problems in the design of a cellular manufacturing system', *International Journal of Production Research,* vol. 35, 1997, pp. 1857–74.

Berry, W.L., C.C. Bozarth, T.J. Hill and J.E. Klompmaker, 'Factory focus: segmenting markets from an operations perspective', *Journal of Operations Management,* vol. 10, no. 3., 1991, pp. 363–87.

Cantamessa, M. and A. Turroni, 'A pragmatic approach to machine and part grouping in cellular manufacturing system design', *International Journal of Production Research,* vol. 35, 1997, pp. 1031–50.

Chen, J.S. and S.S. Heragu, 'Step-wise decomposition approaches for large scale cell formation problems', *European Journal of Operational Research,* vol. 113, 1999, pp. 64–79.

Chen, M.C., 'Configuration of cellular manufacturing systems using association rule induction', *International Journal of Production Research,* vol. 41, no. 2, 2003, pp. 381–96.

Choi, M.J., 'An exploratory study of contingency variables that affect the conversion to cellular manufacturing systems', *International Journal of Production Research,* vol. 34, 1996, pp. 1475–96.

Gupta, T., 'Clustering algorithms for the design of a cellular manufacturing system – An analysis of their performance', *Computers and Industrial Engineering,* vol. 20, 1991, pp. 461–68.

Kaparthi, S. and N.C. Suresh, 'Performance of selected part-machine grouping techniques for data sets of wide ranging sizes and imperfection', *Decision Sciences,* vol. 25, 1994, pp. 515–39.

Levasseur, G.A., M.A. Helms and A.A. Zink, 'A conversion from a functional to a cellular manufacturing layout at Steward Inc.', *Production and Inventory Management,* III Quarter, 1995, pp. 3742.

Mahadevan, B., *The New Manufacturing Architecture,* Tata McGraw-Hill Publishing Company Ltd., 1999, New Delhi.

Mahadevan, B., S. Venkataramanaiah and J. Shah, 'Design of a cellular manufacturing system for a product oriented plant', *Working paper,* Indian Institute of Management Bangalore, 1999, India.

Marsh, R.F., S.M. Shafer and J.R. Meredith, 'A comparison of cellular manufacturing research presumptions with practice', *International Journal of Production Research,* vol. 37, no. 14, 1999, pp. 3119–38.

Miltenburg, J. and A.R. Montazami, 'Revisiting the cell formation problem: assigning parts to production systems', *International Journal of Production Research,* 31, 1993, pp. 272746.

Mukherjee, A., W. Mitchell and F.B. Talbott, 'The impact of new manufacturing requirements on production line productivity and quality at a focused factory', *Journal of Operations Management,* vol. 18, 2000, pp. 139–68.

Olorunniwo, F.O., 'A framework for measuring success of cellular manufacturing implementation', *International Journal of Production Research,* vol. 35, 1997, pp. 3043–61.

Olorunniwo, O.F. and J.G. Udo, 'Cell design practices in US manufacturing firms', *Production and Inventory Management,* IIIrd Quarter, 1996, pp. 27–32.

Pesch, M.J.and R.G. Schroeder, 'Measuring factory focus: an empirical study', *Production & Operations Management,* vol. 5, no. 3, 1996, pp. 234–54.

Powell Jr., C., 'Work cells at Powell Electronics: Improving response time to customer', *Target,* vol. 11, no. 6, 1995, pp. 4446.

Reisman, A., A. Kumar, J. Motwani and C.H. Cheng, 'Cellular Manufacturing: A statistical review of the literature', *Operations Research,* vol. 45, 1997, pp. 508–20.

Saad, S.M., A. Baykasoglu and N.N.Z. Gindy, 'An integrated framework for reconfiguration of cellular manufacturing systems using virtual