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Empirical findings on manufacturing cell design

URBAN WEMMERLÖV†* and DANNY J. JOHNSON‡

Cell design is the most researched topic in the area of cellular manufacturing. The preponderance of studies has focused on the development of models to assist with cell formation, i.e. the initial stage in the cell design process where the parts and equipment are determined. On the other hand, fairly little is known about the broader context in which cell design takes place, and the processes that users follow. The purpose of this study was to learn more about the methods, goals, considerations, and constraints that industrial users apply to cell formation and cell layout, as well as the actual outcomes of those processes (such as cell configurations and staffing patterns). This paper adds to the sparse literature on empirical cell design by reporting on findings derived from a survey study of cell users predominantly drawn from the metalworking industry (related data have previously been published in Wemmerlöv and Johnson (1997)). Supporting evidence is primarily taken from survey and field studies by Wemmerlöv and Hyer (1989), Harvey (1993), Choi (1996), Suri *et al.* (1996), Olorunniwo and Udo (1996), Marsh *et al.* (1998), Johnson (1998), and Hyer and Brown (1999). The findings should be of interest to both students and practitioners of cellular manufacturing, and could serve as guidance for researchers seeking to develop more effective methodologies for solving the cell design problem for industrial users.

1. Introduction

The research literature on cellular manufacturing over the last 15 years has to an overwhelming degree focused on the development of procedures to solve the cell formation problem (i.e. the forming of part families and machine groups for the purpose of establishing cells; Wemmerlöv and Hyer (1986), Wemmerlöv (1991), Singh (1993)). Unfortunately, these research efforts have taken place in a context almost devoid of any empirical foundation that describes how firms actually go about designing cells in industry and what their associated goals and concerns really are. Such knowledge would seem critical to the development of useful and relevant cell formation techniques and design processes (e.g. Olorunniwo and Udo 1996).

This paper relies on a new empirical study of cellular manufacturing users, as well as on the findings of previous studies, to synthesize our relatively sparse knowledge of the process of cell design. In doing so we focus primarily on cell formation and cell layout, and exclude details on infrastructural issues innate to cell design (such as job selection, training, job design, metrics development, supervisory structures, etc.). We hope our findings will benefit researchers as well as practitioners by providing a better understanding of the contexts in which cell formation and cell layout procedures are

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applied, and by providing insights into the concerns and considerations shown by industry users.

The paper proceeds by providing a brief overview of the empirical studies that supplied material for this paper. Next, we examine aspects surrounding the sequential stages in the cell design process—employee involvement issues, design methodologies, considerations and constraints, performance evaluation of preliminary designs, actual outcomes of the cell design processes in the studied plants, and the life cycle of cells. The paper concludes with a summary of the findings and some thoughts regarding future research.

2. Empirical studies on which this paper is based

The primary data source for the empirical findings presented here was an eight-page mail questionnaire that collected information on 126 cells in 46 plants. The majority of the plants were in the metalworking industry. Implementation experiences and performance improvements experienced by the responding plants have previously been reported in Wemmerlöv and Johnson (1997). Since the survey results concerning cell design are presented here for the first time, we will refer to these data as collected for 'the present study'. Supporting data are drawn from other empirical research. Studies relying on mail or on-site survey methodologies include Wemmerlöv and Hyer (1989), Harvey (1993), Choi (1996), Olorunniwo and Udo (1996), Wemmerlöv and Johnson (1997), and Johnson (1998), while studies relying on observational data collected through field studies include Harvey (1993), Suri *et al.* (1996), Johnson (1998), and Hyer and Brown (1999). A brief discussion of each of these studies is provided in the appendix, but the reader is referred to the original sources for a deeper discussion of background, participating firms, methodology, data analysis, and findings.

3. Pre-design issues

3.1. *Factors influencing the adoption of cells*

It is by now well established why firms decide to apply the cellular concept to their organizational design. Foremost among the reasons underlying such adoption decisions are the need to stay or become competitive with respect to time (manufacturing lead time and customer response time), to improve asset utilization by lowering inventory (WIP and finished goods), and to lower cost through better quality (scrap and rework levels). The relative importance of these and other reasons for converting to cells, according to users, is shown in table 1. The desire to reduce lead time, improve quality, and lower WIP inventory has also been found to be the main driver for cell implementation in studies by Burbidge (1979), Wemmerlöv and Hyer (1989), Harvey (1993), Suri *et al.* (1996), and Johnson (1998). There are also, naturally, factors negatively influencing cell adoption, i.e. in effect hindering it from taking place. Such factors are discussed in § 6.3.

While competitive reasons drive the organizational restructuring that leads to cells, the process by which firms reach the conclusion that cellular manufacturing will help them accomplish their goals and should be part of their manufacturing strategy is less clearly mapped out. For example, do firms chose cellular manufacturing because a serious analysis indicates it is the best choice among alternative courses of action, or do they apply a follow-the-leader approach and analyse a well-known solution to see if it would make sense in their environment (and, thereby, risk missing other, more potent alternatives)? Johnson (1998: 358), in an in-depth field study of a

Rank	Reason	Average score
1.	To reduce throughput time	4.51
2.	To reduce WIP inventory	4.33
3.	To improve part/product quality	4.22
4.	To reduce response time to customer orders	4.22
5.	To reduce move distances/move times	4.14
6.	To increase manufacturing flexibility	3.81
7.	To reduce unit cost	3.80
8.	To simplify production planning and control	3.62
9.	To facilitate employee involvement	3.57
10.	To reduce set-up times	3.43
11.	To reduce finished goods inventory	3.41

Note: each reason was scored on a scale from 1 to 5 where '1 = Unimportant' and '5 = Very important'.

Table 1. Reasons for establishing manufacturing cells (*Source:* Wemmerlöv and Johnson 1997: table 3).

small group of cell users, came to the following conclusion: '… it has not been possible to ascertain whether an analysis of the problems faced, and the identification of the actions needed to resolve the problems, resulted in the solution (i.e. the implementation of cellular manufacturing), or if cellular manufacturing was first considered as a potential solution to the problems faced by the plant and then analysed to see if it would resolve the problems faced'. More research is necessary before this question of 'problem vs solution' can be satisfactorily answered.

3.2. *Performance targets for cell design*

As part of the present study, we asked the respondents from the 46 participating firms—in regards to the one cell in the plant they were most familiar with—whether any quantitative goals were established before the cell was designed and, if so, to specify these goals (we chose to ask for data from the most familiar cell in order to increase response accuracy). Responses concerning performance targets were requested for the 11 improvement areas listed in table 1. Almost one-third (30%) of the firms in the survey claimed that no goals, neither numeric nor non-numeric, had been established for the cells before they were developed. Furthermore, in only 61% of the cases in which one or more goals had been formulated did the firms also supply a quantitative response (in other words, only 42% of the respondents provided numerical goals for the cells). Quantitative goals were most commonly set for reductions in throughput time, WIP inventory, set-up time, and unit cost, with average desired reductions amounting to 63% (27 responses), 56% (21 responses), 52% (18 responses), and 28% (17 responses), respectively (see table 2). The data also show that the most ambitious improvement targets were set for throughput time and move time/distance reductions—in many cases well over 90%. Quantitative goals were least frequently set for 'facilitation of employee involvement', 'simplification of production planning and control', and 'increases in manufacturing flexibility' (only three, six, and three responses each, respectively). This is undoubtedly due to the difficulties of establishing metrics for these more intangible variables.

Since the quantitative goals asked of the respondents only pertain to one specific cell, while the performance data that we collected from the firms represent averages for all cells in operation at the plants, we are not able to compare targets directly

Area of improvement	Improvement goal* (%)	Average reported performance† (%)
Throughput time	62.6	61.2
WIP inventory	55.6	48.2
Set-up time	52.3	44.2
Unit cost	27.5	16.0

*Data from present study. Represents one specific cell in the respondents' firms.

†Data from Wemmerlöv and Johnson (1997). Represent the average of all cells in the respondents' firms.

Table 2. Performance targets vs achieved performance.

with actually achieved results. That said, it is still of interest to contrast the reported numerical targets with the associated performance improvements for the same variables. Table 2 shows, under the assumption that the goals set for one cell correspond with the average goals set for all cells in each firm, that the actual performance improvements achieved lag the desired targets of improvement. However, the deviations for throughput time, WIP inventory, and set-up time are not excessive. In contrast, the firms set quite ambitious targets for improvement in unit cost that clearly were not met for the average cell.

It is not known how the firms determined the performance goals for their cell projects. Without going through a modelling exercise (which only about 10% of the firms had done; see § 7), performance targets can be based on previous experiences, the reported experiences of other companies, consultants' suggestions, and/or on an NRN (nice round number) approach. Since the single most popular improvement target for throughput time and WIP inventory reduction was 50% (which is conveniently located right between 0 and 100%), it is likely that the NRN approach was commonly used. We observed this 'half-way mark' tendency in the Suri *et al.* (1996) study as well. In many cases, these targets represent 'carrot' goals, established without knowing how, or if, they could be accomplished through the cell design process. On the other hand, as shown in table 2, the use of a 50% performance improvement goal actually has some empirical justification when it comes to achievable time and inventory reductions.

4. Organizing for cell design

4.1. *Involvement in the cell formation process*

Cell design is a process that combines hard data, such as parts codes, routeing information, and demand volumes, with people's intimate knowledge and experience of the personnel, products, and production processes in the plant. This study suggests that the design process many times is fairly unstructured and informal, implying that the human element plays an important role. Furthermore, as discussed later, the design process is multi-objective in nature and seeks to satisfy sometimes conflicting goals. It is reasonable, then, to involve personnel from many different groups (functional areas) and positions. In this way many factors and aspects are likely to be considered since each group brings a different perspective to the design process. This should, ideally, generate cells that are better performing, more acceptable, and easier to implement.

Participants in the present study were asked to indicate which departments or personnel groups were involved in the selection of parts and equipment for the cells.

As seen from table 3 (middle column), the groups most frequently represented during the cell formation process were manufacturing engineering and floor supervisors, closely followed by manufacturing management, operators, industrial engineering, production planning/control, and maintenance. On the other hand, the involvement of the quality control, design engineering, and purchasing groups was fairly low. This is surprising given that requests for product redesign arise naturally during cell design (whether they are adhered to or not depends on whether cell design is seen as a mutual product/process adaptation process; see also § 8.5.), and that lot sizes, quality requirements, and material supply frequencies are likely to change in connection with cell conversions. In addition, although the minimal involvement levels indicated for accounting and human resources may seem understandable, at least at an initial stage, firms are inevitably faced with issues such as personnel selection, training, job classification, reporting structures, and job and labour tracking. These infrastructural issues impact cost accounting, compensation systems, and industrial relations, and may be instrumental in driving their revision (also see Åhlström and Karlsson 1996, Harvey 1993, Huber and Brown 1991, Wemmerlöv and Johnson 1997).

The data in table 3 are aggregated over all firms, and the pattern of participation in the cell formation process at each company is not shown. However, the underlying data show that the extent to which the various groups were involved varies greatly from firm to firm. For example, all responding firms had at least two groups, and four firms had 10 or more personnel groups, participating in the design process. The majority of the firms involved between three and eight groups (median = five). (We do recognize that not all firms formally use the names of the departments or employee categories listed in table 3. However, we assume the respondents understood the tasks that each group normally performs and responded accordingly.)

4.2. *Involvement in the cell layout process*

Cell layout is a detailed phase of cell design focusing on physical placement, seeking local workplace efficiency, preventing manufacturing quality problems,

Department or personnel group	Percentage of firms involving this group in part/product and equipment selection	Percentage of firms involving this group in laying out the cell
Manufacturing engineering	92	88
Floor supervisors	82	84
Manufacturing management	73	*
Operators	73	77
Industrial engineering	57	57
Production planning/control	43	35
Maintenance	41	47
Quality control/assurance	35	18
Design engineering	22	8
Purchasing	18	2
Accounting	10	0
Human resources	8	4

* Data not available.

Table 3. Departments or personnel groups involved in cell design.

and satisfying workers' ergonomic and socio-psychological requirements (Nyman 1992). One would expect, then, that fewer personnel groups get involved, and that operator and supervisory personnel have greater involvement in this process than during the preceding cell formation phase. Table 3 (right-most column) shows that this conjecture is supported by the survey data. The firms typically involved between two and seven personnel groups, with the median being four groups. As with the cell formation process, manufacturing engineering and floor supervisors were the most frequently represented groups, while human resources, purchasing, and accounting were the least represented. Supervisors, operators, and maintenance show slightly increased degrees of participation as compared to cell formation. It can be noted that the top five personnel categories listed in table 3 correspond with those that Choi (1996), in a 28 plant survey study, found to be the most actively involved with 'cell conversion' projects.

4.3. *Comments*

A noteworthy finding is that only about three-quarters of the plants had their workers take part in the design of their own work place. This is somewhat unexpected given that 'operator considerations' was found to be the most important concern during the layout process (see § 6.2). However, it appears that the nature of the employee involvement changes as organizations learn how to design and implement cells. The need to engage affected personnel, and operators in particular, early in the process was one of the lessons learned by firms participating in the Wemmerlöv and Hyer (1989) and the Wemmerlöv and Johnson (1997) studies. Such learnings, applied to subsequent cell projects, are likely to create greater participation. Some specific evidence for this proposition can found in Johnson (1998). For the very first cell designed by one of the firms in that study, manufacturing engineers were charged with cell formation (i.e. identifying parts and equipment) while a consultant was brought in to assist with the implementation. The role of the operators was minimal and passive—to comment on the layout of the equipment and to walk through the already built cell to suggest modifications. After several cells had been implemented, consultants were no longer deemed necessary. In addition, layout drawings are now posted on the walls for everybody to see several weeks in advance of any equipment moves, thereby facilitating and promoting early operator involvement in the design process.

Another company in the Johnson (1998) study had experimented with two high-volume cell lines in the past, and discovered numerous problems relating to equipment, union issues, lack of operator training, improper supervisory structures, etc. A new philosophy was adopted for the design and implementation of future cells. Now, the plant manager, manufacturing engineering, process engineering, plant engineering, production supervision, industrial relations, maintenance, and production control are all involved in the design process from the start. Operators are not only actively participating in the design and layout processes, but they also have input into equipment acquisitions. That the degree of involvement can be a reflection of learning from experience, and adjusting to new ways of operating, is also supported by Harvey's study of cells in the metalworking industry: 'There was, almost without exception, very little worker input into the first cell in any of the firms studied. [. . .] the practice now is to involve workers, though not necessarily the union, as much as possible in the design and the re-design of cells' (Harvey 1993: 265, 266).

While several firms in the present study advocated early involvement of various groups, especially operators, in the design process, one company drew a different conclusion based on its mixed experiences of having employee teams do the cell design (‘Some teams did very well, some did not.’). As a result, future cells would be designed by a team of experts rather than by those who are to work in the cells. However, as also observed by Harvey (1993), this sentiment appears rare: ‘One firm did admit to not involving workers in the design of the cell, noting there was little to be gained [. . .] This firm was more the exception than the rule’ (Harvey 1993: 266).

We do recognize that our knowledge of organizing for cell design is incomplete and that no large-scale study to date has covered this issue in sufficient detail. For example, our survey data suggest participation of diverse functional groups within the organization, but not whether this involvement was active or passive (i.e. took the form of full team membership, requests for *ad hoc* consultation, or was reduced to simply informing the employees of the status of the project). Neither do we know the extent of the time commitment for each group, or how this varies depending on the stage of the design process. Further research is necessary to map out the design process from a work organization perspective to answer these questions.

5. Design methodologies

5.1. *Approaches to cell formation*

Cell formation is the early activity in the cell design process where part or product families and associated machine or process groups are identified. There are only two basic sequences in cell formation: (1) determining the part/product families first, and then allocating equipment and people to these families, or (2) determining the equipment and/or operator groups first, and then allocating parts/products to these (Chan and Milner 1982, Wemmerlöv and Hyer 1986).

The approaches to cell formation used by the responding firms in the present study are shown in table 4. The vast majority (98%) of the 44 cells for which data were supplied were identified by first finding part or product families and then determining the equipment needed to satisfy the production requirements for these families. A variety of characteristics were used, often in combination, to determine the product/part families. These can be classified as follows: (1) demand/production volume, (2) shape, size, features, and function, (3) raw material, (4) manufacturing

Approach used	No. of cells formed with this approach
1. Parts/products were first selected based on certain characteristics, necessary equipment was then determined for this family:	
(a) Both part routeings and part coding systems were used.	16
(b) Only part routeings were used.	20
(c) Only part coding systems were used.	2
(d) Neither part routeings or part coding systems were used	5
2. One or more pieces of equipment were selected first and this equipment determined the initial parts/products to include. Other equipment and parts/products were then added as required.	1
Total number of cells	44

Table 4. Basic approaches used to form cells.

process steps, and (5) products affiliated with key customers, and/or components affiliated with key product lines (these factors can be compared with those found by Choi (1996) to be the most important: (1) shape/size, (2) routeings, (3) material handling requirements, and (4) demand/production volume).

Table 4 also shows the extent to which part routeings and coding systems were relied on during the cell formation process. Thirty-six of the 44 cells (82%) were formed using part/product routeings while 18 (41%) were formed using a ‘coding system’ (this category is not restricted to specialized group technology-based classification and coding systems, but can also indicate simple coding structures found in intelligent part numbers, MRP and CAD systems used to trace raw materials, customers, end products, etc.). Sixteen cells (36%) were designed using both part/product family routeings and code systems. From the brief descriptions given by the respondents, it can be surmised that at least half first used the code system to form broad part families. Part routeings were then used to determine equipment needs. Two cells (5%) were identified using only coding while five cells (11%) were identified based on part/product characteristics but without relying on either routeings or code systems (it can be hypothesized that these firms relied purely on informal knowledge regarding part characteristics and routeings to form the cells). Further analysis of the data show that 10 of the 43 cells that were formed based on part or product characteristics were established to supply key components for a product line. In two of these cases, neither routeings nor code systems were used to identify the components.

Finally, only one firm (2%) indicated that it began the cell identification process by selecting equipment. In this case a cell was built around two existing but ‘underutilized’ CNC lathes to which a four-spindle drill press was added to expand the part family (routeings were used to find the parts).

5.2. *Use of computerized assistance in cell formation*

According to the respondents, the following type of computerized data were consulted during the search for similar parts and affiliated equipment: bill of materials (BOM) ‘where used’ data (47% of the firms), part routeing data (41%), MRP systems’ parts record data (38%), classified and coded GT data (14%), and CAD data (12% of the firms). These statistics show that firms often rely on multiple data sources. At the same time, however, a fairly large portion of the plant population, 14 of the 46 firms (30%) did not rely on any computer support to identify part/products and equipment for the cells. This result is similar to findings by Wemmerlöv and Hyer (1989) and Harvey (1993) who reported that the fraction of firms not using computers in cell formation was 34% and 27%, respectively.

When asked whether there is a need for computerized techniques to support the identification of part families and equipment for cellular manufacturing, 28% of the respondents claimed that this problem was ‘not that complex,’ that a solution only requires ‘common sense,’ and that ‘computers cannot match human creativity.’ The majority (72%), however, agreed that computer support was needed. Several respondents commented, though, that problem complexity was related to part population size and/or company size and that software may only be required for large firms (e.g. ‘Common sense … do it on a flipchart or white board … GT and software techniques are only for ‘giant’ companies … overkill for folks in the $100M and down group’ and ‘I feel it [i.e. need for software] is dependent on quantity and complexity of parts in process, i.e. 15 000 parts active and up—yes, 1000 parts active and less—

no'). Similarly, Wemmerlöv (1990) reports on a firm that, after having already installed eight cells, acquired GT software due to the increasing complexity of the problem. Further evidence of the linkage between complexity and need for computer support is provided by Choi (1996) who shows that the use of visual and manual techniques for cell formation declines in favour of computer-based coding systems as the product variety and degree of cell penetration increases.

5.3. *Users' knowledge of cell formation techniques*

In order to determine the firms' knowledge of published cell formation techniques, the respondents in the present study were asked the following question: 'Are you familiar with any techniques for forming part families and cells that have been presented in trade and scholarly publications?' In case of affirmative answers, the respondents were asked to provide specific information or references to literature sources. Twenty-five of the 32 respondents who answered this question claimed to have some knowledge of published cell formation techniques. However, only 18 of these respondents provided any additional information. Based on their comments it is clear that the general principles behind group technology were well known by the respondents, as were classification and coding systems. There was no indication, however, that the firms had familiarity with—or had applied—any specific method developed by researchers in the field (the same conclusion can be drawn from Wemmerlöv and Hyer (1989), Choi (1996), and Olorunniwo and Udo (1996)).

This lack of knowledge did not seem to be an impediment to cell design in the user firms. Identifying parts/product families for cells was in no case mentioned as a critical problem. In fact, in two firms the opposite was true. These firms claimed that equipment dedicated to part families already existed and the only real change was that these families and their associated equipment were managed as cells. Said one respondent: 'Our cells were obvious candidates that begged to be implemented'. That cell formation is not viewed as a difficult problem in industry has previously been noted by Wemmerlöv (1991) and Johnson (1998).

Despite the low concern shown for the cell formation problem, several respondents, when asked about problems with their cell implementation, provided answers that had clear relations to the way products are selected for cell work. Those include choice of equipment, capacity balancing and product flow, set-up times/tooling problems, product design considerations, training, and job rotation (see Wemmerlöv and Johnson 1997). Thus, it can be hypothesized that firms that spend little time at the early stages of the conversion process selecting the parts and products for cellular manufacturing, and thereby neglecting fully to analyse load/capacity issues and operator requirements, end up devoting much time at later stages making the cells perform as intended. Support for this hypothesis can be found in the frequency of comments related to the need for better planning (Wemmerlöv and Johnson 1997: table 7). The notion of continual adaptation and improvement of cells has also been suggested by Marsh *et al.* (1998) and Hyer and Brown (1999). More research is needed to verify this conjecture.

5.4. *Conversion scope and strategy*

While academic (and some practitioner) writers on cell formation often seem to perceive the problem as one where multiple cells emerge from a single analysis of the factory (e.g. Miltenburg and Montazemi 1993, Nyman 1992), the reality is that most cells in industry are created and implemented sequentially over time. No less than

79% of the 46 firms in our survey indicated that their cells were created one-by-one over time on an ad hoc basis (in Olorunniwo and Udo (1996), the corresponding figure was 86% for the 57 plants surveyed). The remaining 21% of the firms claimed to have followed a broad master plan for cell conversion. At some of these plants, cells were developed as an outgrowth of first having reorganized the factory according to 'focused manufacturing' principles. In this vein, one firm remarked that 'If manufacturing cells are not part of an overall strategy of improvement in each department, they can have great local success but very little overall impact.' This view supports the concept of applying a master plan first rather than just implementing cells on a piece-meal basis without a larger strategy of integration in mind (also see Nyman 1992). However, although this group of firms applied a global perspective to their cell planning, most of them appeared to follow a sequential process of forming the cells proposed in the master plan (i.e. cells were implemented one-by-one rather than all-at-once; a similar observation is made in Johnson (1998)).

The sequential implementation of cells is conducive to learning and some firms indicated that a deliberate learning strategy was followed. A pilot cell was first established to gain experience with the concept of cellular manufacturing. Additional cells were then formed as experience was acquired and the problems with the existing cells were solved. For example, one respondent answered the question of whether the firm followed the sequential or total conversion approach this way: 'one by one . . . learn then build . . . extremely management intensive—draining ... cannot do wholesale conversions and get employee involvement at the same time'. This approach to experimentation and learning was found by Harvey (1993: 233) as well: 'Cells were implemented in piecemeal fashion, ironing out problems as they are faced, with an emphasis, for most part, on increasing productivity.'

5.5. *Comments on cell design*

Four survey studies of cell users have gathered data on cell formation techniques: Wemmerlöv and Hyer (1989), Choi (1996), Olorunniwo and Udo (1996), and the present study. Comparing the findings regarding frequency of use of various techniques turns out to be elusive, however. There are several reasons for this. First, the definitions and the categories used are different. It is, therefore, very difficult to know exactly which technique is used, or in what category it has been placed by the researchers. Second, in some cases the questions have been framed in terms of specific techniques (e.g. from-to diagrams), and in others in terms of general approaches (e.g. use of coded data). Third, it is not clear whether the respondents were asked to indicate the approach that was used in the very beginning of the cell formation process, or usage at any time during this process. Finally, since cells of different types (e.g. assembly vs machining cells) are likely to be created using different approaches, a meaningful comparison would need to include data on the cell populations.

Despite these difficulties, there is a set of findings shared by these four studies: (1) formalized cell formation procedures developed by academic researchers are not known and not used in industry, (2) companies rely on multiple data sources and multiple approaches during the cell design process, and (3) cell formation, although assisted by computer support, involves strong elements of human judgement and decision-making.

6. Design considerations and constraints

6.1. *Considerations guiding the cell formation phase*

Cell formation is influenced and guided by a variety of objectives and concerns. Johnson (1998: 109, 112) provides a concrete example of a set of considerations provided to a group of manufacturing engineers in connection with the design of the plant's very first cell. The plant manager asked the engineers to identify parts that: '(1) were simple to make, (2) were experiencing delivery problems, (3) had a lot of WIP inventory, (4) required machines that were relatively easy to move, (5) required machines whose non-cell processes could easily be transferred to other machines [i.e. operations performed by machines selected for the cell on parts not chosen for the cell would have to be reallocated to non-cell equipment], and (6) required machines that could be staffed by operators who would readily accept the change to a cellular concept.' It can be noted that these guidelines consist of a mixture of suggestions on how to identify the part family: find one with performance problems (items 2 and 3), minimize the rearrangement efforts (item 4), maximize cell independence (item 5), and minimize the staffing problem (items 1 and 6). The plant manager issued this charge based on the premise that the first venture into cellular manufacturing needed to be successful, and that a simple design and implementation process would have the best chance of success.

We asked the plants participating in the present study to evaluate the importance of several detailed design considerations that come into play during the cell formation process. The responses are shown in table 5. Only one consideration, that 'parts/products should be fully completed in the cell' (possibly the most fundamental of all cell design objectives), received an average score greater than 4 when rated on a scale from 1 (unimportant) to 5 (important). Conversely, only one factor, 'high flexibility in selecting alternative routes through the cell', received an average rating of less than 3 (the midpoint of the scale). The other nine factors all received average ratings between 3 and 4. The detailed data further show that each factor was considered 'important' by at least three respondents and 'unimportant', with one exception, by at least one respondent ('high operator utilization' was the only factor not viewed as unimportant by any of the respondents). Thus, even though most of the considerations in table 5 are viewed as fairly important to the user firms when designing

Rank	Design considerations	Average score
1.	Part/products to be fully completed in the cell	4.31
2.	High operator utilization	3.94
3.	Fewer operators than equipment	3.50
4.	Balanced equipment utilization in the cell	3.48
5.	The number of part/products assigned to the cell	3.38
6.	Unidirectional (linear) material flows	3.35
7.	The number of cell operators	3.34
8.	High utilization on expensive equipment	3.33
9.	The number of workstations/machines in the cell	3.13
10.	High equipment flexibility to ease new product introductions over time	3.00
11.	High flexibility in selecting alternate routes through the cell	2.75

Note: each reason was scored on a scale from 1 to 5 where '1 = Unimportant' and '5 = Very important'.

Table 5. Importance of design considerations on part/product or equipment selection.

manufacturing cells, the emphasis placed on each factor varies from company to company.

It is interesting to note that designing cells for flexibility was of little apparent concern to the plants in our survey. Considerations regarding product and process flexibility (i.e. ability to introduce new products and selecting alternate routes through cells, respectively) received the lowest importance scores, well below the traditional objectives of achieving high and balanced operator and equipment utilization levels in the cell (table 5). This finding conforms with the one by Harvey in his study of cells in 11 firms: 'Batch size in the majority of cells was fairly high and part variation fairly low. Cells, therefore, are not noted as much for flexibility as for increases in productivity' (Harvey 1993: 290).

It can further be noted in this context that 'high operator utilization' and 'fewer operators than equipment' were the second and third highest ranked design considerations, while high utilization of expensive equipment ranked eighth. This indicates that labour issues enter quite early in the design process and are relatively more important than high equipment utilization for many firms. This finding is supported by Harvey (1993: 199) who notes: '. . . the tendency in American firms [as opposed to German firms] is to put emphasis on having the cell operator work all the time, rather than, say, having the machinery run continuously.' The fourth-ranked consideration in terms of importance dealt with achieving balanced capacity/load patterns in the cells (table 5). Load balance is clearly one of the most common operating problems encountered for cells (Dale and Russell 1983, Wemmerlöv and Hyer 1989, Wemmerlöv and Johnson 1997).

Lot size reduction may be the most important cause of lead time reductions attributed to cellular manufacturing (Johnson and Wemmerlöv 1996, Suri *et al.* 1996, Johnson 1998). Set-up time reduction is a critical element of lead time compression since it frequently must precede a switch to smaller lots (to avoid overload). Surprisingly, although set-up time reduction was given as one of the reasons to convert to cells (table 1), few of the respondents mentioned this activity as a design consideration. However, in his field study of four firms, Johnson (1998) reports that set-up time is viewed as an important factor in cell design. Achieving set-up reduction through the grouping of similar parts/products is, of course, the essential group technology idea that underlies cellular manufacturing (Mitrofanov 1970). However, in cases where the reduction in change-over time is deemed insufficient for a given part family/equipment group combination, the search for further reductions becomes an important consideration in the design process. Johnson (1998) found that splitting the size of the family (and the machine groups) to achieve greater degree of similarity—and thereby avoiding set-ups—was one approach firms used to reduce set-ups and lot sizes.

6.2. *Considerations guiding the cell layout phase*

While the internal layout of a cell may be partially determined by available space, and the size, shape, and special requirements of the chosen equipment (such as mountings, exhaust fans, etc.), considerable flexibility still exists in the placing of the equipment. However, other factors, such as material flows, operator walking patterns and working space, ergonomics and safety issues, and the need for work tables, production control boards, buffer inventory, and tooling space, etc., must also be considered.

We asked the companies in this study to rate the importance of factors influencing the layout process. As seen from table 6, the three most important considerations were ‘operator considerations’, ‘short move distances within the cell’, and ‘tooling and inspection devices to be located in or next to the cell’. These three factors—focusing on the interplay between the operators and the work environment in order to maximize efficiency and safety—all received average ratings exceeding 4 on a scale from 1 (unimportant) to 5 (very important). The majority of the comments made by the respondents pertaining to ‘operator considerations’ dealt with ergonomic concerns, followed by issues such as the amount of skill and education required of flexible cell operators, the ease by which the workers could be trained to operate multiple machines, and operator utilization. To illustrate, one respondent was concerned that plant management demanded that all operators be fully trained on all equipment in a very large cell with 25–30 operators and 30–50 separate operations: ‘Management read this in a “book” and has hung on to the concept.’ The conclusion of this respondent was that cross-training under such circumstances is an impossible task. Two other plants had experienced operator resistance to the multi-machine concept, and had also achieved lowered productivity due to rotation among machines in the cell. Achieving complete cross-training increases the demand on the operators’ skill levels and can take a long time to accomplish, especially when complex equipment and high quality expectations are present (see Johnson 1998).

‘Buffer space sizes’ and ‘ability to use material handling equipment within the cell’ were the only design considerations to receive 1s (one explanation may be that buffer space and materials handling equipment are less important issues in cells operating on the one-piece flow principle). On the other hand, all factors in table 6 received at least seven 5s each. The high average scores for the listed factors show that most of them were considered quite important by the respondents, and illustrates again the multi-objective nature of the cell design problem. Other layout considerations mentioned, but not rated by the firms, included future expansion potential of the cell, accessibility to the machines by maintenance personnel, and the flow of material in and out of the cell.

6.3. *Constraints imposed on the cell design process*

In addition to the question on design considerations, the firms were also asked to comment on the constraints that had been imposed during the cell design activity. Altogether, the respondents listed 51 constraints that can be grouped into seven categories (see table 7). The most common constraints were that the cell project

Rank	Design considerations	Average score
1.	Operator considerations	4.31
2.	Short move distances within the cell	4.29
3.	Tooling and inspection devices to be located in, or next to the cell	4.15
4.	Straight part flows through the cell	3.79
5.	Visibility of part progress	3.75
6.	Buffer space (queue) sizes	3.60
7.	Ability to use material handling equipment within the cell	3.06

Note: each reason was scored on a scale from 1 to 5 where ‘1 = Unimportant’ and ‘5 = Very important’.

Table 6. Importance of design considerations when laying out a cell.

Rank	Constraints	No. of comments
1.	Financial constraints imposed	12
2.	No new equipment purchased	10
3.	Parts to be fully completed within the cell/design stand-alone cells	10
4.	Product/process constraints: one piece flow of parts, no queues, allowed balanced work flow, no change to process sequences, capability to produce similar products in cell, certain equipment excluded from cell	6
5.	Floor space restrictions (incl. investment restrictions)	5
6.	Labour restrictions: no. of operators per cell, use existing work force, cell set up for one man operation, operators must be involved with design of cell	5
7.	Volume or cycle time requirements	3

Table 7. Constraints imposed on the cell design process.

must pass a financial justification hurdle (e.g. exceed a specified IRR level) or that capital was limited (12 comments), that no new equipment could be purchased for the cell (10 comments), that parts must be fully completed in the cell or that a stand-alone cell should be designed (10 comments), and that floor space is restricted (6 comments). Constraints involving labour (5 comments), as they affect cell staffing, are commented upon in § 8.4.

The constraints in table 7 fall into two major groups. One group, consisting of 24 comments, is concerned with 'technical' aspects of cell design (i.e. constraint 3—parts to be fully completed in cell, 4—product/process constraints, 6—labour restrictions, and 7—volume/cycle time restrictions), while the other group of 27 comments deals with economic hurdles (i.e. constraint 1—financial constraints, 2—no new equipment, and 5—floor space restrictions). Of these two sets of constraints, only the items in the financial limitations category can be considered absolute constraints (such as 'no new equipment') while many of the technical design constraints appear softer and probably serve as considerations rather than hard constraints. For example, even though 'parts be fully completed in the cell' was listed as a constraint by some firms, it was at the same time rated as the most important consideration by the respondents (see table 5).

Clearly, economics can play an important role in affecting and even hindering cell design and implementations. For example, Wemmerlöv and Hyer (1989) found the cost of relocating equipment to be the most common reason why firms identified part families and dedicated equipment to these families without actually creating cells. Likewise, the single largest expense category for cell projects reported by the firms in that survey was equipment relocation and installation. Furthermore, even though the cost of additional equipment is often argued as a reason for not creating cells, Johnson (1998) makes the important observation that equipment duplication may require labour duplication as well. A firm could well be more reluctant to increase its staff than to increase its machine population. This reluctance could serve as another obstacle to cell adoption.

Johnson (1998) provides further insights regarding the role of financial constraints. Of the 150 responses to his mail survey, 118 plants had cells and 44 of these had assessed the feasibility of establishing cells in the past but decided against it (39 of these plants still had other cells in operation). When asked about the reasons the intended cells had not been implemented, 31% of the responses indicated failure to cost justify, 31% indicated inadequate volume or excessive demand instability, and 5% indicated that the cost of moving equipment was too high (the remaining reasons are omitted here). Given that demand volume and stability both have impact on cost (through operator and equipment utilization, need for investment, change-over costs, lost efficiency, etc.), they are in that sense economic factors as well.

The notion that cost justification and demand volume/stability are related is reinforced by an analysis of the responses to a set of questions examining factors that may have prevented further cell penetration (Johnson 1998). That analysis found statistically significant correlations between the factor 'cannot cost justify further cells' and the factors 'cannot identify part families with enough demand volume to form cells' ($r = 0.39$, $p = 0.00$), 'cannot identify part families with enough demand stability to form cells' ($r = 0.26$, $p = 0.01$), 'remaining parts require one-of-a kind service processes which make them difficult to put into cells' ($r = 0.18$, $p = 0.07$), and 'equipment needed for further cell formation is too costly to move' ($r = 0.17$, $p = 0.08$). It is not possible to conclude, based on the survey responses, whether in some cases formal cost justifications actually had taken place but failed to overcome the financial hurdles, or whether plants simply ceased to pursue certain cell projects at an early stage based on the belief that lowly utilized cells were simply not worth designing (since the prospect of cost justifying them under those circumstances would be bleak). However, it is not unreasonable to assume that many non-financial measures serve as surrogates for financial considerations and shape decision-making regarding adoption and design.

7. Performance evaluation at the design stage

The most common method used by the responding firms to evaluate cell performance before the cells were built, as also found by Wemmerlöv and Hyer (1989), involved load calculations to verify equipment and operator capacity needs (as reported for 65% of the cell projects in both studies; the four plants observed in Johnson (1998) also followed this approach). Interestingly, however, almost a quarter of the firms (24%) in the present study 'admitted' to not having performed any cell evaluations before the cells were built. Despite this, over half of these firms had still specified performance expectations for their cell projects.

Only 10% of the firms claimed to have used computer-based stochastic simulation modelling. In the absence of advanced modelling (based on queuing theory or simulation) or extensive experience, firms may design and build cells that can handle the anticipated work load but the performance in terms of lead time and WIP inventory will not be revealed until the cell is in operation. This implies, de facto, that the design process is a learning process characterized by trial and error, and that adjustments will take place either in performance expectations and/or in the design or operation of the cell itself. As a case in point, one of the firms claiming not having undertaken any evaluations at all stated that a cell was built and used as a real-world test case simply to get performance data (also see 'one by one ... learn then build' comment in § 5.4.). The experience a firm reaps from its own implementation process will obviously influence employee acceptance, increase confidence in performance projections, and facilitate future adoption decisions. One plant manager interviewed by Johnson (1998) illustrates this point: 'When you get to the point where you're operating the cell and showing the results that you said you were going to, ... even though you couldn't previously quantify them, people now understand that the benefits claimed in the justification process will occur' (Johnson 1998: 146).

8. Design outcomes

This section provides aggregated data on 126 cells designed and operated by the 46 surveyed firms. Complementary data on all the cells, such as number of cells per plant, degree of cellularization, achieved performance improvements, and implementation experiences can be found in Wemmerlöv and Johnson (1997).

8.1. *Types of products manufactured*

The majority of the firms participating in the survey were in the metal working industry (the types of products and parts manufactured by the plants are detailed in Wemmerlöv and Johnson 1997). Although this reinforces the notion that this industry continues to house the dominant portion of all cells implemented in the U.S., it should be noted that the subject firms in this study were not randomly sampled and are not necessarily representative of the manufacturing industry at large. The same holds true for plants participating in the other empirical studies cited in this paper. These studies have either performed biased sampling in selected sectors or simply included plants known or suspected to have cells. Regardless of the selection method, however, the end result is that our knowledge of cellular manufacturing gathered from systematic empirical studies overwhelmingly derives from cells in the metal working industry (but not solely from cells performing metal working tasks; see § 8.3).

8.2. *Number of parts or products processed per cell*

The cells on which data were collected generally handled a relatively small number of part or product types. Specifically, 10% of the cells processed (we use the generic term 'process' to cover both productive and non-productive activities) only a single part/product type, 56% processed 25 part/product types or less, 76% processed 50 part/product types or less, and 86% of the cells processed 100 part/product types or less.

8.3. *Types of operations performed in the cells*

The 126 cells performed a variety of operations. For overview purposes, the cells were classified according to types of operation using the following process categories: (1) casting & moulding, (2) forming & metalworking, (3) finishing, (4) joining & assembly, (5) machining & material removal, (6) heat treating, (7) testing, (8) packing, and (9) other (for the specific processes covered by each category, see DeGarmo and Kosher (1984), Yankee (1979), Amstead *et al.* (1979), and Roberts and Lapidge (1977)).

Table 8 shows the percentage of cells that house each of the nine different process types listed above. These data reveal that many cells contain multiple types of processes. While the majority (60%) performed machining or metal removal processes, over half of the cells performed joining or assembly processes, over one-third performed finishing or washing processes, and a quarter of the cells carried out testing, packing, and forming/metalworking operations.

Further analysis of the combinations of process categories found in the cells highlights the large diversity of cell types that exists. For example, only 28 of the 126 cells (22.2%) were involved with a single process category. These cells were either pure machining/metal removal cells (12.7%), pure joining/assembly cells (5.5%), pure packaging cells (2.4%), or pure testing cells (1.6%). The remaining 98 cells all performed multiple processes (e.g. casting/moulding *and* machining). Although the machining cell remains the single most frequently implemented cell type, these statistics illustrate that the cell concept is applicable to many different types and combinations of processes. Specifically, they demonstrate that cells are designed to handle not just part manufacturing, as traditionally was the case, but to house resources and processes inside the cell to manufacture, test, and package products fully, ready to be distributed through the supply chain.

8.4. *Size of cell operator teams*

The practice of staffing cells with fewer workers than pieces of equipment or processes is commonly seen as the norm, derived from the idea that higher efficiencies and utilization of resources (specifically humans) can be gained by having cross-trained operators who can 'float across tasks' without boundaries. That the participating firms sought to accomplish this is evident from the fact that 'high operator utilization' and 'fewer workers than machines' were viewed as the second and third most important considerations, respectively, during cell design (table 5). An achieved equipment-to-operator ratio greater than 1 was also confirmed by analysing sketches of cells provided by the survey respondents. Further evidence of this type of staffing was found by Harvey (1993) who collected detailed data on 75 machining cells. For these cells, the average ratio of machines to operators ranged from 2 to 7, with a mean of 3.5.

The size of the cell crews in the present study varied highly. The range of operators per cell spanned from 1 to 40, with the 'average cell' being manned by 4.8 operators per shift. More specifically, 27% of the cells were run by a single worker, 57% of the cells had three or fewer workers, and 72% had five or fewer workers. The number of operators and equipment in a cell clearly depends on the volume and type of operations performed in the cell. For example, the cells in the present study with the largest number of operators per shift (i.e. 11 or more) were either pure packaging cells or cells that contained assembly operations—with or without additional types of processes (frequently testing and/or packaging). These cells processed a variety of parts/products, from batteries and moulded components to gaskets, cables, and leather products. One common dominator for these large cells appears to be volume. For several of the cells the output per year was in the millions

Process category	Number of cells with this process category	Percentage of cells with this process category (%)
Machining/metal removal (MM)	76	60
Joining/assembly (JA)	64	51
Finishing/washing (FW)	44	35
Testing (T)	32	25
Packing (P)	32	25
Forming/metalworking (FM)	31	25
Other	14	11
Casting/moulding (CM)	11	9
Heat treating (HT)	3	2

Table 8. Frequency of process usage (Source: Wemmerlöv and Johnson 1997: table 2).

of components. Conversely, pure machining cells (with typically longer cycle times) tended to have the fewest number of operators, with the majority having between one and four operators, and with the largest cells being staffed by eight operators.

Although cells are often associated with (or even seen as synonymous with) teamwork, slightly more than a quarter of all cells included in this study were operated by single workers (it is interesting to note that one plant maintained that its greatest successes had been achieved with single operator cells). This aspect of cell manning has received little attention in the literature to date, but appears to be commonplace for machining cells. For example, of the 39 single operator cells in the present study, 42.4% were pure machining cells, and another 24.2% performed machining as well as other operations. Further, in his study of 11 primarily unionized manufacturing plants, Harvey (1993) found that 78.9% of 267 machining cells had only a single operator. He speculates that the existence of such cells, as compared to having cells operated by teams of workers, may be due to resistance by unions or management to abandon individual incentive schemes (piece rate systems) in favour of group-based or pay-for-knowledge compensation schemes.

Certainly, other factors underlie the existence of single operator cells. For example, Johnson (1998) found, as can be expected, that the degree of automation affects the need for operators in the cell. Designing cells so that they could be staffed by one worker was also a deliberate attempt by one firm in that study to avoid worker-related conflicts of an inter-personal nature.

8.5. *Changes in part/product designs, routeings, and processing equipment*

As was demonstrated in § 5, most firms rely on part routeings to form cells. However, the routeings used in a functional layout are not likely to be ideal in a cellular manufacturing context since they were created without concern for group technology concepts and may have been designed to maximize machine utilization (Dekleva and Menart 1987). But part routeings are not fixed and a number of alternative routes (using different machines and/or operation sequences) may be feasible to produce the same part. Routeings are also affected by the introduction of new equipment, and the modification of parts or products to fit processes allocated to a cell. Thus, replacement of old technology, part re-design, and revisions of process plans are all elements of the cell design process.

Reflecting this, most of the firms responding to this survey indicated that the original part routeings were substantially changed in connection with cell formation (all data in this section refer to one cell selected by each responding plant). The extent to which operations had been reallocated from their original equipment to alternative equipment averaged 3.80 when rated on a scale from 1 (not at all) to 5 (all routeings have been changed). Sixty-nine per cent of the firms indicated extensive routeing changes (using scores of 4 or 5), while only 11% of the firms stated that the original part routeings had been left intact.

Re-routeings of parts are often driven by equipment replacement. Approximately 70% of the respondents claimed that *some* new equipment was purchased specifically for the cell, 16% said that *all* of the equipment was new, and 29% said that only existing equipment had been used. As a comparison, Wemmerlöv and Hyer (1989) found that 68% of the firms with manned cells claimed that 20% or less of the equipment in the cells was new, while 36% stated explicitly that no new equipment was purchased to establish the cells. Harvey (1993) reports a more prevalent investment pattern—all of the 75 cells for which he collected detailed data had been set up with at least some new machinery.

Products may be redesigned as part of cell formation to facilitate or enable their processing in the cell (to quote one respondent in the present study: 'The products had to fit on our machines according to tool matrix and size—many engineering changes were implemented'). The average degree to which parts/products were redesigned to suit the processes chosen for the cell was 1.96 when rated on a scale from 1 (not at all) to 5 (substantial re-design). This relatively low number reflects the fact that for 45% of the 46 cells covered by this segment of the survey, the designs of the parts and products did not change at all. For cells where part redesign had taken place, 48% of the respondents used a score of 2 to indicate the extent of the redesign, while 33% used a score of 3. Thus, while the aggregate result show that part/product redesign did take place in connection with cell establishment in more than half of the cells studied, the scope of these changes was relatively minor.

8.6. *Extent of inter-cell moves and cell independence*

In order to assess the degree of control the cells had over the parts processed, we asked—for each of the 126 cells—whether the parts leave for additional processing and then return to the cell. In close to one-third (31%) of the cells, parts relied on such 'inter-cell moves' to complete processing (note that the term 'inter-cell' here denotes situations where parts return to the cell; thus, cases where parts leave the cell for completion in other cells, in the non-cellularized part of the factory, or at subcontractors are not covered).

When inter-cell moves were needed, the parts underwent the following operations: additional finishing operations (such as plating, finish grinding, painting, metallizing or anodizing; 33% of the cases), heat treating (23%), cleaning or degreasing (15%), additional machining (8%), additional forming (5%), additional assembly processes (such as wave solder or wire welding; 5%), impregnation (5%), moulding (3%), and laminating (3% of all cases). Many of these operations are 'service processes' that require specialized and often bulky equipment (Burbidge 1989). It is frequently not cost effective to duplicate this type of equipment since the volume from each cell tends to be low compared to the overall capacity of the resource. Additionally, the process equipment may not be reduced economically to a size fitting the space for a cell, or its toxicity may preclude its inclusion in a cell (Pullen 1976). In such cases, the resources must be shared by several cells (and other departments). Johnson (1998) identifies an additional reason for excluding certain processes from cells—cycle time imbalances. Manufacturing processes like heat treatment, oxidizing, etc., operate in batch modes with fixed cycle times. Thus, they can process a single part as fast (or slow) as a large batch. Because of this they are not well suited to be placed in cells that operate on a one-piece flow basis, but are preferably allocated to separate, functional-style departments that allow the equipment to be simultaneously shared by many different parts or products.

Inter-cell dependency was in Wemmerlöv and Hyer (1989) measured by the extent to which machines/processes were shared among cells. In that study, 80% of the manned cells were claimed to be operating independently. Further, on the average, parts completed 78% of their required work content in the cell to which they were allocated. Using a different metric for assessing cell independence, i.e. fraction of cells that machine a part fully, Harvey (1993) found that approximately 45% of the cells he investigated made parts complete (it should be stressed that these were machining cells only while the cells in the current study typically contained more process types). Finally, Choi (1996) discovered that the degree to which completely independent cells exist in a plant is related to two factors: (1) the scope of the conversion (measured by the number of components manufactured in cells as a percentage of all components manufactured) and (2) the levels of the financial hurdles (available capital and minimum return on investment). Choi argues that as the scope increases, equipment sharing among cells increases, and the cells' autonomy goes down. Likewise, when plants face stricter financial constraints, the cell independence goes down (due to less investment in equipment; also see Pullen 1976). Taken together, these studies demonstrate convincingly that many manufacturing cells do not control their part families fully but are connected to a larger manufacturing system for complete processing.

9. Redesigning and dismantling cells—a life cycle perspective

A treatise on cell design would not be complete if it omitted a discussion of cell redesign or cell disbanding. Cells originate as organizational structures at certain points in time. Due to altered external and internal conditions, cells may require changes to remain efficient and effective. Such adaptation mechanisms could include replacing, adding, or removing equipment, systems, or products, and adding, removing, or retraining of operators. More drastic would be changes involving the terminal dismantling of the cell, ending its life as an organizational and productive entity.

There has been surprisingly little discussion of 'the lives of cells' in the literature, although this notion has been mentioned by Wemmerlöv and Hyer (1987, 1989). Perhaps the only empirical study to date has been conducted by Marsh *et al.* (1998) who studied 15 firms from the perspective of cell dynamics. The authors recorded 32 'life cycles' related to the 185 cells in the sample (the life cycle concept was in this study interpreted rather freely in that *any* change to a cell would terminate its current life cycle—and initiate a new one). Of these life cycles, 53% involved layout changes in order to improve materials flows or the operators' work situation, but did not involve machine replacements. Johnson (1998) cites one company's perspective on such changes: 'The managers at CIC stressed the need to be willing to update and change the cell as needed to improve the efficiency or change it to meet changing market conditions. As stated by the plant manager, "If an operator doesn't like where this machine is sitting [. . .] we'll move it for him".'

In 35% of the 32 life cycles in the Marsh *et al.* (1998) study, equipment was exchanged, or new equipment added, in order to enhance the cells' capabilities to process parts, to take advantage of new technology (the most common reason was to achieve better quality or equipment reliability, although capacity was gained as well), or to meet capacity needs due to increased volumes. In only 6% of the cases was the machine configuration modified (equipment added or removed) in response to part redesign. Finally, in another 6% of the cases (two cells in one firm) a complete shutdown of the cells had taken place (the penultimate definition of 'life cycle') due to a decision to outsource production. The study further shows that the majority of the cells were still in existence, aided by various improvement activities or operating decisions to help them meet market volume demands, product mix shifts, or the need for higher uptime or part quality improvements (examples of actions include over-time, equipment upgrades, automation, set-up time reduction, cross-training, re-routeings, etc.). In short, as the authors also conclude, cells appear to be remarkably resilient to environmental change.

Perhaps the most noteworthy finding in Marsh *et al.* (1998) is that although cells in the plants studied were initially established between 10 and 12 years ago, in only one out of the 15 plants, and in only two of the 32 recorded life cycle cases, were the cells' lives terminated. In contrast, 47 of the 150 respondent plants in the survey by Johnson (1998) claimed to have dismantled cells in the past. Based on the 64 comments provided as reasons for this, only 16% of the comments indicated that cells were simply reconfigured and, thus, are still operative—although in a modified mode. On the other hand, fully 73% of the respondents' comments indicate that cells at their plants had been terminally dismantled (while 11% of the survey responses were not conclusive). Firms that had dismantled cells, as expected, had implemented their first cells earlier, and had more cells in operation, than firms that had not dismantled cells. Although we cannot draw definitive conclusions regarding the pervasiveness of dismantled cells in these organizations (since some firms provided multiple reasons), it appears evident that cells, as can be expected, in some cases do have finite lives.

The most commonly cited reasons for dismantling cells in the survey by Johnson (1998) were that the production had been discontinued or moved to other plants within the organizations. Interestingly, only five of the 64 reasons provided indicated that inadequate performance of the cells was the cause of the dismantling. This low number may be a reflection of the conclusion in Marsh *et al.* (1998) that firms improve cells over time after they have first been established so that performance expectations are continually met. Although not directly evident from either Johnson (1998) or Marsh *et al.* (1998), it can be surmised that when cells are disbanded, but the products continue to be manufactured in the plant, they are processed on equipment in a functional mode (and possibly on the same equipment as before). That is, the plants regress to the state of origin. We have seen a couple of examples like that in our field observations of cells. The fundamental reason for reverting back to functional layouts seems to be problems with load imbalances (due to part mix variations) that are resolved by grouping similar equipment previously placed in separate cells. Once such a (re)grouping occurs, it may lead to a complete abandonment of the cells involved.

Wemmerlöv and Hyer (1989) also provide a small glimpse into cell dynamics. About half the companies in their survey stated that the cells processed parts or products for which they had not been originally designed. The fraction of new part numbers ranged from 5 to 25%. The most common implications of such changes in product mix were the need for additional tooling and fixtures, and increases in equipment utilization (i.e. most of the original equipment was still in the cells). Some firms, of course, deliberately try to fit new parts into existing cells to avoid investing in new tooling: 'You have to get by with the same tools in the cell. We've been known to write engineering changes and request to change parts to be able to use our existing tooling packages' (quote by industrial engineer in Johnson 1998: 150; also see § 8.5. above). These responses also verify the notion that cells can withstand changes over time due to shifting market demands (as reflected in new or redesigned parts/products).

Reinforcing these findings, Harvey (1993: 158) makes the following remark regarding cell design practices in the plants he observed: 'Cells are not etched in stone, but changed much over time. However, when change to the cells occur, this is likely to be the addition (or subtraction) of machinery or workers, rather than new parts or even variations of parts.' Harvey also claims that only one of the 75 machining cells he surveyed in detail was producing parts for which it was not originally designed, while in over half of the cells equipment had been added or replaced (Harvey 1993). An insight into this phenomenon is offered by Knight (1971: 941–942): 'The considerable work carried out on workpiece statistics [. . .] would indicate that, although the actual components produced within a particular company may alter with time, the distribution of component types will remain substantially constant, and, therefore, the new components will fit into the established families formed for GT production.' In short, the studies cited here converge in their findings that a cell can remain relatively intact over an extended period of time with respect to its core processes and product families, although some of the equipment (including tooling) as well as individual products may be subject to change. Inevitably, however, some cells cease to exist due to structural and/or strategic changes driven by market forces.

10. Conclusions

Although the majority of the research efforts in the area of cellular manufacturing have been focused on methods for identifying parts and equipment for cells, very little has been written about the broader organizational context in which cell design takes place. The purpose of this study was to learn more about the realities of cell design in industry by mapping out the drivers, the project organization, the approaches, tools and data employed, and the considerations and constraints that frame cell formation and cell layout processes. In addition, we were interested in documenting typical cell configurations to aid understanding of the type of work cells are designed to perform, and to provide insights into how cells adapt to changing operating conditions and expectations over time. The core empirical data presented here derive from a mail survey study of 46 users of cellular manufacturing. Additional supporting evidence on cell design was taken from previous surveys and field studies of industrial cell users. A summary of the major findings is presented next, followed by suggestions for future research.

The following general picture emerges from this study. Companies are driven by competitive reasons to seek improvements in time, cost, and quality. Cellular manufacturing is in many instances seen as the vehicle through which such improvements can be achieved, although financial hurdles, or unsatisfactory projections for surrogate measures such as volume or demand stability, may prevent cell projects from going forward. Teams are set up to identify promising products for cells and to do detailed design work. These teams typically involve many different categories of personnel, although management, manufacturing engineers, supervisors, and operators are the most common groups involved. Only three-quarters of the firms involved operators in the cell design projects, but evidence suggests that firms recognize that their participation facilitates implementation. Accordingly, the role of operators in the cell design process is likely to be greater in firms with previous experience of cells compared to those that face conversion for the first time.

It appears that firms design and implement cells using rather unsophisticated approaches. Industry's knowledge of mathematical cell formation procedures developed by academic researchers is non-existent, as is the actual usage of such procedures. Users do not see cell formation as a difficult issue, except when the complexity of the problem (as measured by the size of the part population) gets large. Most often, firms rely on routeings or other part-related data to begin the identification of cells. This process is carried out in an unstructured fashion using a variety of search and sorting procedures, taking advantage of multiple data bases containing routeings, MRP records, or information stored in CAD files. The selection of parts is frequently based on them being 'critical' components of major products. During the design process the original routeings tend to get changed to fit the targeted part/product families, and/or the infusion of new equipment and tooling. Likewise, parts that do not fit the envelope specified by the equipment and/or tooling and fixtures are in certain cases redesigned to conform to those specifications.

The degree of sophistication is also low when it comes to projecting and evaluating cell performance at the design stage (i.e. before they are put in place). Almost one-third of firms do not set performance targets for their cells, and about a quarter of firms do not perform any evaluations at the design stage. Furthermore, many firms that do establish targets for their lead time and inventory improvements (frequently 50%), have no means of knowing the realism of those targets beforehand. Most cells are designed and built one-by-one, and firms use this approach as a deliberate learning mechanism. Thus, cells go through evolutions so that subsequent improvement phases make up for possible inadequate planning efforts (i.e. cell designs are revised during implementation until targets have been achieved).

Cell formation and layout is not just about parts and equipment. Consideration of the human operator clearly plays a very important role in the design process—whether it is about building a safe and ergonomically correct work place, maximizing the labour utilization, or creating versatile, cross-trained cell operators. Contrary to common belief, which equates cells with team work, cells run by single operators made up over a quarter of all cells in our survey. The majority of these cells housed machining operations.

Manufacturing cells are quite versatile. The cells we surveyed came in many different variations, from pure assembly and machining cells to cells containing multiple processes that make parts or products complete for shipment to customers—demonstrating that this approach to work organization has wide applicability. Cells with only one type of process category, such as only assembly or only machining, seem rare. For example, the original and most traditional type of cells, the machining cell, represented only 13% of all cells in our sample. Rather, cells appear in a large variety of configurations, and most contain multiple process categories. The data also show that cells, despite the universal goal of completing parts in the cells, often share equipment with the rest of the plant and have parts leave the cells for further processing.

Finally, despite the fact that building cells that are flexible enough to handle products different from those for which they were designed is not an important design objective, cells appear to be quite robust in their general designs to withstand the test of time. Thus, the fear that these dedicated units may have short life cycles is contradicted by the research discussed in this paper. It appears, rather, that cells are in constant evolution and are improved by new equipment, processes, and methods to produce higher volumes, and more parts variants, at faster speeds. However, the foundation for this robustness seems to be that product families remain fairly stable with respect to their demand and basic configurations.

There are several aspects of cell design that have direct implications for researchers involved with the development of cell formation techniques: (1) firms think in terms of part or product families and are seeking efficient ways to manufacture these—i.e. methods should be focused on grouping parts and subsequently solve the equipment allocation problem, (2) routeing information is the predominant data source for determining cell configurations—specialized group technology classification and coding systems are rarely used in this process, (3) firms rely on a variety of databases, code systems, and sorting mechanisms, and a variety of considerations and constraints, to finalize families and equipment for the cells—i.e. procedures need to be able to use a variety of input data and handle multiple objectives, (4) existing routeings tend to get modified due to addition of equipment, change of processes, part redesign, or because parts are not fully completed in the cells—cell formation procedures based on fixed routeings are too limited to capture these realities, (5) many cells contain multiple processes, and half of those surveyed here contain assembly or joining operations—such cells cannot be found using the standard linear routeing manipulation approach, (6) equipment is often excluded from cells due to reasons such as size, toxicity, batch processing cycles, etc., requiring cell formation procedures to be able to distinguish between different types of equipment in the plant—Burbidge's SICGE system (Burbidge 1989) holds some promise in this regard, (7) cells are built one at a time, and need to be linked to existing cells and departments to operate—the manipulation of one large part/machine population to create a set of independent cells, as done in most cell formation techniques, does not fit this pattern and does not consider this linkage need, and (8) many firms think that considerations of the operators are among the most important aspects of cell design—but few existing cell formation procedures take operators into account.

The lack of industry use of published cell formation techniques may be attributed to many different reasons (the problem with diffusion of research into practice being one). However, the industry practices summarized above will certainly influence the face validity of any prospective technique. Accordingly, mathematical sophistication needs to be moderated by pragmatic concerns if formal techniques are to be adopted by industry. At the very least, designers of such techniques need to be able to describe how their method fits into the larger process of cell design and how issues such as the ones we have outlined can be handled.

Many important issues surrounding cellular manufacturing and cell design remain to be investigated. Specifically, we need to understand, in more detail, the approaches taken and processes followed by firms in their design work—and who the participants are in these projects. In doing so, we need to distinguish between different types of cells, and stratify our knowledge accordingly. We also need to learn when, why, and how firms modify their cell designs over time. With that knowledge we can develop better tools and design processes to support the goal of creating well-performing cells with long lives. The latter task will by necessity encompass consideration of both structural and infra-structural issues. Hyer and Brown (1999) have recently theorized what well-performing cells should look like. Verifying and extending those ideas is an important research task.

Appendix: Background notes on the empirical studies

Present study and Wemmerlöv and Johnson (1997)

The data for these studies were obtained using a mail survey of 'high-probability' cell user plants. An eight-page questionnaire was sent to 249 individuals working for 131 different organizations at 145 different locations. The effective response rate based on individuals in returning useful survey instruments was 32%. The final response set covers 126 cells in 46 plants. About half of these plants employed 400 people or less.

The survey form contained questions related to the design and implementation of cells. Each respondent was also asked to describe the essential characteristics of up to three company cells and provide a sketch of the layout of each cell described. In addition, each of the respondents was asked to answer a number of questions about the one cell in their organization with which they were the most familiar. A detailed description of the methodology used for this study, as well as the characteristics of the responding firms, has been presented in Wemmerlöv and Johnson (1997).

Wemmerlöv and Hyer (1989)

A 200-item questionnaire was administered to 285 firms throughout the U.S. believed to be high-probability users of cells. Of the 53 firms returning usable survey forms, 32 had implemented cellular manufacturing. This study covered a wide variety of topics related to the design, implementation, and operation of cells.

Harvey (1993)

This study involved on-site interviews with operators, union officials, and management at 11 metalworking firms. The focus of the study was to look at the implementation of cells and their impact on industrial relations (all but one firm was unionized). Written questionnaires were administered on site at the 11 plants and data were collected on 75 of the firms' 267 cells. In addition, intensive field observations were collected at three of these plants (five firms in Germany were also studied). All cells included in the study were machining cells.

Suri et al. *(1996)*

This multi-year action research study involved 14 firms whose goals were to compress lead times on the plant floors or in the offices. Each plant was assigned a research team consisting of faculty and students whose responsibilities were to observe the current operations, to propose solutions for the long lead times experienced, and to assist in the planning and implementation of those solutions. Several of the projects involved cellular manufacturing. Complete implementation experiences were not observed.

Choi (1996)

This is a mail survey sent to 52 plants, known to have cells, culled from the literature or personal contacts. Twenty-eight plants made up the sample with usable responses. The objective of the study was to explore 'contingency variables' such as conversion scope, financial constraints, and product characteristics, and their relationships to variables such as cell design techniques, layout configurations, and cell independence.

Onorunniwo and Udo (1996)

This mail survey focused primarily on mapping out the usage of cell formation techniques in industry. Questionnaires were sent to 221 firms suspected to have cells, and 57 usable survey forms were returned.

Johnson (1998)

This study administered a mail survey to 527 firms in six states belonging to the 'Industrial and Commercial Machinery Group' of the SIC Code. The survey supplied data on cell design and implementation from 118 respondents with cells (out of 150 usable responses). Four plants from this group were subsequently chosen for case study research. The focus of this study was to determine the conditions that (a) influenced firms' decisions to convert to cellular manufacturing and (b) limited continued cell penetration.

Marsh et al. *(1998)*

This paper describes a field study of 15 metal-machining companies that had implemented cells. Together, the firms had 185 cells, varying from one to 40 at each site (pure assembly cells were excluded). The purpose of the study was to explore the existence and causes of cell life cycles through the collection of both quantitative and qualitative data. A total of 32 such cycles were found.

Hyer and Brown (1999)

This study is based on the authors' long-time observations of industrial cell users. Specifically, 15 firms were visited for close observation and interviews for the purpose of developing a better understanding of the nature of the cell concept, and how cells should be designed and operated for best performance. The outcome is a proposed theory of 'real cells'—cells that have reached their potential.

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