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C H A P T E R 2

Literature review

This paper reviews prior research in the area of virtual manufacturing cells. A virtual manufacturing cell (VMC) is a group of resources that is dedicated to the manufacturing of a part family, though this grouping is not reflected in the physical structure of the manufacturing system. Distinguishing such groups in the production control system offers the possibility of achieving the advantages of cellular manufacturing in non-cellular manufacturing systems. The advantages may include improved flow performance, higher efficiency, simplified production control, and better quality. The paper reviews the previous publications on virtual manufacturing cells, to determine the methods and scope of present research. This results in a comprehensive framework which identifies the underlying principles of VMCs and classifies the different VMC concepts. It is shown that virtual manufacturing cells can significantly improve the performance of manufacturing systems. Based on the comprehensive review, many future research issues and high-impact research areas are also identified.

2.1 Introduction

In recent years, there has been a consistently high level of interest in the design and operation of many new types of manufacturing cells (e.g., virtual cells, holonic cells, dynamic cells, etc.). Among these, virtual manufacturing cells (VMCs), proposed nearly two decades ago, appears to be of increasing interest to researchers lately.

In a VMC, a group of resources may be dedicated to the manufacturing of a part family, though this grouping may not be reflected in the physical structure of the manufacturing system. Depending on the job mix at a given time, machines across various departments may be identified as virtual (logical) groups, instead of physically repositioning the machines to be adjacent to each other. This avoidance

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of change in shop layout has been a major feature of many definitions offered for VMCs over the years. Traditional cellular layouts, involving physical repositioning of machines, have also been subject to several years of controversy regarding their relative advantage over functional layouts (e.g., Suresh, 1991, 1992; Suresh and Meredith, 1994). In addition to some doubts on their performance, the limited adoption of cellular manufacturing by industry has also been pointed out as an indication of its restricted applicability in practice (Wisner and Sifer, 1995). The increasing attention given to virtual manufacturing cells lately has also been driven by such factors (Nandurkar and Subash, 1998; Subash et al., 2000).

Identifying logical groups of resources, within the production control system, offers the possibility of achieving the advantages of cellular manufacturing in situation where traditional cellular manufacturing systems may not be feasible. The resulting advantages may include improved flow performance, higher efficiency, simplified production control and better quality.

The design of a manufacturing system can be broken down into physical design and logical design (Nof, 1982). Physical design deals with the topology and configuration of the physical systems (e.g. workstations, people, and material handling systems). Logical design is concerned with the way in which manufacturing activities are organized and controlled.

Virtual manufacturing cells make use of this principle by distinguishing groups of resources in the production planning and control stage that may not be reflected in the layout. This prevents the need for costly and time-consuming reorganization of the shop floor and allows for quick response to changing circumstances. The advantages of this approach include improved flow performance, higher efficiency, simplified production control, and better quality.

Now that the feasibility of VMCs as an alternative to both the functional and cellular layout is being established, there is a need to review the current status of this research area. This initial paper addresses this challenge by attempting to answer the following major questions:

1. *What are virtual manufacturing cells?*
2. *What research has been conducted in this area and what are the findings?*
3. *What are some promising issues for future research?*

The paper also reviews representative works in several areas pertaining to VMCs. This paper is structured as follows. The next section provides an overview of

how various definitions of VMCs have evolved over time. The third section categorizes past studies into those that focus on design issues, operational issues, and those which are based on empirical research with a (partial) focus on VMCs. The fourth section provides a more detailed review of design issues-oriented studies, and provides directions for future research. The fifth section provides a similar review and discussion on operational investigations of VMCs, while the sixth section does the same for empirical research studies. It is shown that the area of VMCs offers a wealth of opportunities for future research.

2.2 Definitions for virtual manufacturing cells

This section introduces and reviews some of the major definitions of virtual manufacturing cells offered by various researchers. These definitions have evolved over time, and each of the definitions appears to provide a different set of challenges for design and/or operation of VMCs.

2.2.1 Evolution of definitions

Although the concept of virtual manufacturing cells has existed informally (e.g., Altom, 1978), it was first labelled as “virtual cells” in the early 1980s. In the early work of McLean et al. (1982), VMCs were defined as follows: *“A dynamic, hierarchical structure was envisioned that could acquire subsystems on an as-needed basis. [...] The virtual cell [...] is no longer identifiable as a fixed physical group of machines, but rather as a computer process, associated data and a dynamically changing set of workstations on the shop floor...”*. It may be noted this initial definition already encompasses several important elements of VMCs: a system that adapts to the requirements of its environment, as well as the need for information and information processing capacity to realize this. Moreover, the groups of resources that are present physically are not necessarily the same groups of resources that are used in the control system. A VMC configuration consists of workstations and may have to change as the requirements change. This can become very demanding if this occurs too frequently, or if the problem of finding a VMC configuration is a complex one.

In the work of Irani et al. (1993), VMCs were defined such that, they *“... allow time sharing of work stations with other virtual cells that produce different part families, but have overlapping resource requirements. Computer control, supported by a flexible handling system, allows the set of workstations in the shop floor to be dynamically reconfigured...”*. This definition stresses that a group of resources may not have to be dedicated to a single part family, but rather also serve as a pool that is available for general use. This means that one of the design goals is not necessarily a

set of independent VMCs. In addition, material handling aspects were introduced, and the presence of inflexible handling systems may limit the applicability of VMCs.

The work of Suresh and Meredith (1994) explored the impact of using part family-oriented scheduling within a functional layout, given the significant loss of routing flexibility when machine pools are partitioned to create traditional (physical) cells. This system, retaining the job shop layout, but utilizing part family-oriented scheduling, was referred to as “FLP” systems. Kannan and Ghosh (1996a, 1996b) and Kannan (1997, 1998) referred to these systems as “virtual cells”, and extended this research stream further by exploring the use of several other part-family-oriented scheduling rules. As noted in Kannan (1998), these VMC systems operate in a dynamic way by “...using family-based (group) scheduling rules to realize scheduling and setup efficiencies, but doing so within a job shop. The result is that [...] virtual cells are formed that require no physical changes in shop layout...”. Thus, in this scheme of VMC, there is no global design effort in creating and operating VMCs, and all the relevant decisions are delegated to the shop floor level. This may result in suboptimization, and only a partial realization of the potential benefits of VMCs. In a similar vein, in the study of Vakharia et al. (1999), “... a virtual cell simply requires the dedication of individual machines within current departments to a specific set of product families...”.

Thus far, all definitions omitted people as a major resource in VMCs. However, later authors are beginning to fill this gap. Kühling (1998) draws attention to workers, stating that VMCs involve “...dedicating workers to part families. The production teams are responsible for the execution of the direct as well as the supporting processes of their part family. They use resources that they share partially or completely with the other production teams...”. This definition suggests that VMCs may not just be a question of assigning parts or products to certain resources, but also a question of how people should cooperate in such a structure. This view is offered by Hyer and Brown (1999) who state that “...a virtual cell can exist when people and equipment are dedicated to a part/product family, and the workflow is closely connected in terms of time and information, but not space...”. This last definition also alludes to the importance of an information structure that enables the cooperation between people in a VMC.

The recent work of Suresh and Slomp (2005) is again based on the definition of virtual cells as the application of group technology (part-family-oriented scheduling) within existing job shops. This work extends the research to the labor dimension, by

including both machines and workers (who are subjected to various levels of cross-training) as dual resource constrained (DRC) systems.

Recent definitions have also pointed out that the need for a VMC configuration may be triggered by new, and changing business requirements in the long term and the short term, and the inability of creating traditional cells in small and medium-sized enterprises in response to these changes (Nandurkar and Subash, 1998; Subash et al., 2000).

Thus it is clear that the definition of virtual manufacturing cells has evolved over time, and there happens to be both commonalities as well as differences among the perspectives of various researchers. These are listed in the next sub-section with a view to identifying key differentiating research factors, and eventually developing a classification of past research studies on VMCs based on these factors.

2.2.2 Key research factors

The major commonality among the various definitions for VMCs, is the separation between the shop layout and the way in which manufacturing activities are organized and controlled. As such, VMCs are a concept for production planning and control that take the manufacturing layout more or less for granted. Nevertheless, the manufacturing layout may also guide the design of a VMC configuration to a certain extent. Therefore, while reviewing the papers below, the consideration of layout aspects was viewed as an important, defining attribute of a publication.

Second, the requirements of a changing environment and the resulting adaptation of the manufacturing system is present in many definitions. The layout of the manufacturing system is considered to be too rigid to change partially or completely in accordance with the new requirements. These changes may take place at different levels, between strategic, tactical and operational levels. This presents a dilemma as to whether VMC configuration has to result from design efforts using global information, at the expense of complex and frequent problem solving, or from operational efforts where only local information is used at the expense of sub-optimization. Thus the second attribute is the level in the production planning and control hierarchy where the VMCs are configured. In some cases it is a medium-term or long-term approach leading to relatively stable VMC configurations, labelled as Master Production Schedule (MPS) level. At the other extreme the VMCs are very dynamic and only exist during a single job, labelled as Shop Floor Control (SFC) level. In between is the situation where the VMCs are under regular or periodical review, which is labelled as Manufacturing Requirements Planning (MRP) level.

A third issue is the consideration of part/product families and the exploitation of similarities in manufacturing requirements, which forms the central aspect of group technology (GT). Similarities may be found either in the routings and/or in the requirements at the work station level, especially tooling. The latter allows for gains in the execution of operations (for example reduced set-up times, reduced processing times), while the former allows for gains in the coordination of operations. Whether or not this GT concept is applied, is another important characteristic of each study reviewed in this paper.

Finally, three different types of resources are considered in the various definitions: machines, people and material handling equipment. Including each of these types imposes different challenges to both design and operation of VMCs. In general, the more resources are included in the design, the more complex the problem becomes. The inclusion of people may introduce the need to consider organizational issues in addition to operational aspects. Thus the types of resources that are considered in the research are also included in the analysis.

Two clear differences exist between the various views. First, some authors explicitly refer to automated manufacturing systems and computer control. This context eliminates (at least partially) several problems that are present in a non-automated contexts such as human factors and changeovers. Second, different research approaches have been used. Past studies are thus divided into three distinct research approaches, the first focusing on the design of VMCs, the second on the evaluation of the operational performance of VMCs and the third on empirical research in the area of VMCs and related concepts such as Group Technology.

2.3 Classification of past research on VMCs

Based on the above reasoning, this section introduces a classification framework and subsequently provides an overview of past studies in each area of VMCs. The following characteristics are used to classify various papers (see Figure 2.1):

- 1. Research type: addressing design issues, operational issues, or study based on empirical research*
- 2. Resources considered: machines, handling equipment, and people resources and related issues*
- 3. Implementation level of VMC: medium-to-long term (MPS), short-to-medium term, or periodical (MRP) and execution-level (SFC)*
- 4. Layout consideration included?*

5. *Use of Group Technology considered?*

6. *Automation or non-automation issues of the manufacturing system.*

Table 2.1 provides a schematic overview of the papers that have been reviewed and classified according to the framework in Figure 2.1. Based on the classification framework presented in the previous section, several interesting preliminary observations can be made.

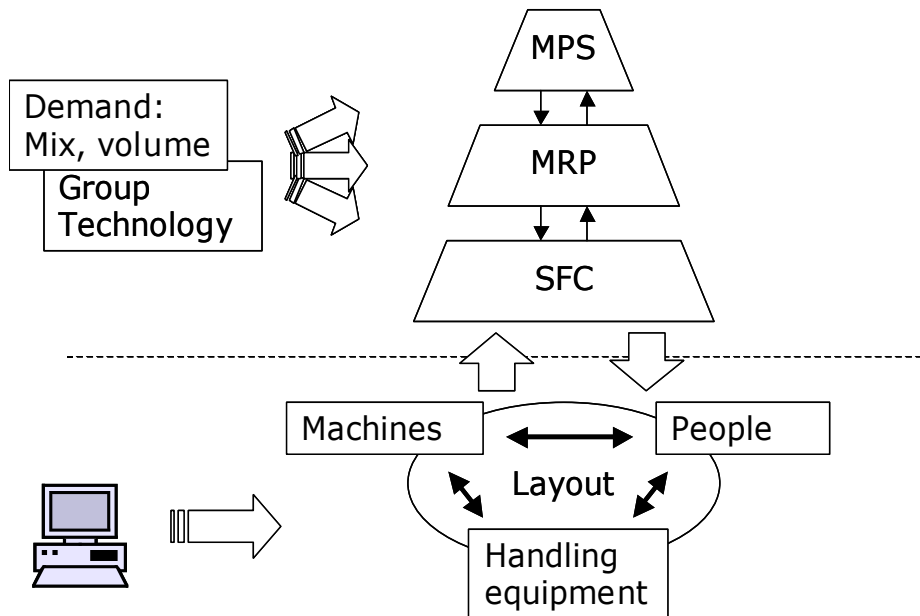


Figure 2.1: Classification framework for virtual manufacturing cells

2.3.1 Preliminary overall observations

The first observation from the list of studies in Table 2.1 is that the interest in VMC research appears to be on the rise, with an increasing number of papers published on virtual cellular manufacturing in recent years. A second observation is that the application of group technology principle appears to be the central philosophy in most of the research studies. GT continues to be of appeal, even when traditional cells may not be feasible due to technological and financial constraints. In addition, VMCs have been applied at all levels of production planning and control, ranging from short-term benefits through smart sequencing of jobs to long-term creation of VMCs and new organizational structures. However, still being in an early stage, research is not yet to cover all relevant aspects in this area.

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

Legend:

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

Table 2.1: A summary of reviewed papers

It is also evident that rigorous empirical research is yet to emerge in the virtual cellular manufacturing area. The empirical research that is present has mainly focused on users of cellular manufacturing instead of a wider range of firms that include non-users as well. Inputs from empirical research can significantly improve the realism of research settings, particularly in the areas of design and operation. This is especially true in terms of inclusion of particular types of resources in model-based research. All researchers have used machine resources, some have considered material handling equipment but most have neglected the key resource of human beings. Comparing different layouts without consideration of material handling systems, or human factors may adversely affect the findings studies comparing the performance of VMCs with other configurations.

It is seen that researchers who investigate operational issues and evaluation of VMCs have tended not to work on design issues of VMCs. Both groups of researchers appear to work separately, despite the fact that design methods can be improved markedly on the basis of operational performance evaluations. Nevertheless, some design papers do incorporate operational performance evaluations by means of simulation, as discussed further in a later section. It may also be seen that the number of studies on design aspects of VMCs appear to be greater than studies devoted to operational aspects, as well as empirical research.

Studies devoted to operational evaluation have had a somewhat narrow focus on shop floor control, while studies on design aspects have been richer in terms of implementation levels, and the inclusion of resources other than machine resources. But researchers in VMC design aspects have also tended to ignore human aspects so far. The inclusion of people into performance studies could reveal more insights into the importance learning effects, in addition to the impact of cross-training schemes, and other labor-related factors. Workers usually have different proficiencies which can be exploited through the application of GT principles in assigning jobs to workers. The parallel with machine dedication is obvious as workers will learn from the similarities between activities and thus become more proficient in the execution of their jobs. Overall, it is clear that much work remains to be done in all areas pertaining to VMCs.

2.3.2 Preliminary observations on future research issues

Based on the preceding discussion and the overall observations, we summarize possible future research directions. Future research directions mentioned here are not confined to the inclusion of different factors into research, but also include, more generally, the types of research that are warranted in this area.

Currently, research on VMCs has been approached as either a design, operation, or empirical point of view. However, combining multiple types of research could significantly enhance the quality and impact of research studies. The inclusion of empirical research into either design or operational studies could enhance the realism of these studies, especially in terms of parameter ranges, data sets, and resource types that need to be considered. Moreover, empirical inputs can be an information source on the major issues that play a role in real world manufacturing systems. Likewise, design research methods developed can be tested in operational evaluations, as some researchers have done with cell formation procedures earlier.

Another possible direction for future research is a stronger consideration of both layout and material handling issues. The performance of the material handling system may be strongly influenced by the use of smaller lot sizes, which has been frequently advocated in cellular manufacturing. The use of transfer batches in non-cellular layouts may even turn material handling into bottleneck operations. To cope with this problem, batching policies (combining multiple handling jobs into one) for material handling may be needed and, in the long run, extra investments or even different handling systems may be required.

The link with the design of the layout becomes clear immediately, as the layout determines a large part of the movements required between successive operations. In this context, the distributed (holonic, holographic or scattered) layout deserves attention in particular. This layout type combines the flexibility of the functional layout with the short handling distances of the cellular layout by spreading different machine types across the shop floor; the machines, however, remain accessible to all part families. The result is that, very often, a short routing for a job can be found. See Nomden and Slomp (2003) for an extended discussion of this issue. A layout may also neutralize positive effects from, for example, transfer batches if machines are very far apart, e.g., in different buildings of a facility. Thus far, material handling issues have been under-investigated and they constitute a promising research area in design, operational as well as empirical research.

Likewise, human aspects deserve more attention in future research. Only a few studies have addressed labor-related aspects in their investigations. The design of VMCs may have to account for the limited availability of workers, and cross-training schemes and constraints. In addition, learning aspects may be incorporated, especially in operational evaluations. This aspect is discussed in more detail below.

Finally, operational evaluations need to look at more pro-active forms of VMC design. In fact, current operational evaluations have only looked at VMC

configurations that emerge as a result of operational decisions. Specifically, the application of part family-oriented scheduling within the functional layout has been investigated extensively in recent years, but this is clearly a passive form of VMCs. Hopefully, this merely forms a transitional phase.

Following these overall, preliminary observations, more detailed discussion of research studies on design, operational and empirical research is presented below.

2.4 Design of virtual manufacturing cells

In this section, past research addressing the design of VMCs and developing various methods for designing VMCs are reviewed, followed by a discussion of future research issues in this area.

2.4.1 Research on design of VMCs

Table 2.2 summarizes the studies devoted to design of VMCs. Columns 2–4 in the table indicate the objectives of the VMC design method, what type of information was used, and the source of information, respectively. The fifth and sixth columns classify the design method and how the design problem was solved. The seventh column shows what constitutes a part family in the paper, while the eighth describes the results of the design method. The last column states if the resulting VMC configurations are independent of each other or not.

The first paper that appears to employ the concept of virtual manufacturing cells is the one by Altom (1978). The goal of this research project was to expand manufacturing capacity of Halliburton Services with resources that were in limited availability, by utilizing group technology principles to reduce setup times, specialized tooling, and purchasing efforts. The parts were coded and classified using the MICLASS classification and coding system, and subsequent analysis was used to form families of parts with similar routings. The machines associated with these part families, however, remained in their original locations. The workflow was supervised by a group coordinator. It is reported that, overall, significant savings in manufacturing capacity were achieved.

The work by McLean et al. (1982) appears to have introduced the term virtual manufacturing cell. They describe the control of an automated manufacturing facility undergoing the evolution of group technology cells through automation to virtual manufacturing cells. It was noted that VMCs have much more flexibility than conventional cells through the sharing of workstations. Important control activities such as the creation of VMCs by combining jobs with the resources needed to

produce them are mentioned. A second important control activity involves decisions about sharing various resources among jobs.

The above paper appears to have inspired many authors to research this area, including Montreuil et al. (1992), who introduced the idea that the organization (logical system) can be separated from the layout (physical system). Simply stated, it means that it is not necessary to have a functional organization if a process layout is in place, and that a product organization is not exclusively associated with a product layout. Other papers in this stream present a link with the eventual ability to move resources to accommodate to changing manufacturing requirements, i.e. the possibility to use dynamic cells (Drolet et al., 1996; Rheault et al., 1995). In this sense, VMCs are to be associated with a specific parameter range of the dynamic facility layout problem (see, for example, Balakrishnan and Cheng (1998)) i.e., when the product mix and volumes change so much relative to the costs of relocating equipment that changing the facility layout is never worth the effort.

In another work, Moodie et al. (1994) presented a control framework for scheduling jobs using VMCs. Each job is assigned to a set of workstations, thereby creating a kind of temporary single product flow line. This problem is solved by a linear programming model, where the objective is to minimize both travel distances and lateness of jobs. Sarker and Li (2001) presented this problem as finding a path through a network of resources for each job, solving it with an algorithm developed for this problem. The objective is to minimize makespan of a set of jobs. Thomalla (2000) addressed the same problem, but with the objective of minimizing tardiness. In this work, the problem is solved using a Lagrangian relaxation approach. Another approach is provided by Mak and Wang (2002), who developed a genetic algorithm to solve problem with the objective of minimizing total travel distances.

Irani et al. (1993) addressed the problem of layout design, placing emphasis on the possibility to create a hybrid layout, consisting of both process-oriented departments as well as flow line cells. Using basic flow data, some resources are co-located to allow for easy capacity sharing among part families; these resources then become part of VMCs. Using graph theory, the authors solve two example problems. In each solution, several similar machines are clustered into process departments, and several dissimilar machines constitute flow lines.

Kühling (1998) conducted in-depth research into the implementation of VMCs at a forging company. The concept implied the dedication of workers from various manufacturing departments to the production of part families. Resources were shared between these virtual teams, the virtual teams were responsible for

scheduling the orders of the part families assigned to them. The apparent conflict between the virtual teams about the use of production capacity was solved by a “capacity auction”, implemented in the production planning and control system. Mertins et al. (2000) presented a simpler approach to resolve the apparent conflict between the virtual teams in the case mentioned by Kühling (1998). In their view, lot-sizes should have equal capacity use and each virtual team should have access to production capacity on a turn-by-turn basis instead of the original complex bidding system. The researchers report positive effects of this approach from the results of a simulation study, though the exact results of these simulations are not shown.

Vakharia et al. (1999) provided an analysis of VMCs in an actual flow shop using queuing theory. They investigated the trade-off between dedication and pooling of resources in the various processing stages and its effect on flow performance. As a result, the machine in several processing stages were dedicated to a part family, the machines of one processing stage would remain shared among all part families. This approach was shown to lead to an overall decrease of throughput time.

Subash et al. (2000) proposed a framework for virtual cell formation. In essence, the authors tested several clustering algorithms for the formation of virtual cells. Ratchev (2001) and Saad et al. (2002) presented a method to generate VMCs. The first step of this method consists of analyzing the manufacturing requirements of the part mix. These requirements include tool type, motions and tolerances, with one or more machines being available to satisfy the job requirements. Components are then grouped into coherent clusters of parts with similar manufacturing requirements. The next step is to assign machines to these clusters, using several criteria like minimum transport or maximum utilization. The final step allows for what-if scenario analysis to test the effect of using different performance objectives in the previous step.

Saad et al. (2002) also presented an integrated framework for production planning and cell formation. It is a three-step approach, the first step being the loading of the current cell configuration. In the second step, the performance of the current cell configuration with the current workload is tested against pre-defined criteria like throughput and tardiness, using simulation. If the (predicted) performance of the current cell configuration is unsatisfactory, reconfiguration is initiated and new VMCs are created. The framework checks the capabilities of the resources with requirements of the jobs constituting the workload. As jobs tend to

Author(s)	Design Objective	Info Type	Info Source	Design Method	Solution Procedure
Altom, 1978	F, C, U	R, D	C	D (MGI)	-
Irani et al. 1993	H	S	L	M (LP/IP)	Lindo
Ko & Egbelu, 2003.	Ee	Sd	L	-	Algorithm
Kühling, 1998	-	Rd, S	C	CA	-
Mak & Wang, 2002	H	R	L	M (IP)	Genetic algorithm
Moodie et al., 2004	H, L	R	H	M (LP)	-
Prince & Kay, 2003	-	R	C	D (PF/MG)	Algorithm (EPFA)
Ratchev, 2001	Cc	-	C	CA	Clustering algorithm
Saad et al., 2002	I, U, T, Tp	D	C	M (IP)	Tabu search
Sarker & Li, 2001	M	R	H	GrP	Algorithm
Slomp, J. et al., 2004; 2005	U, I, W	R	H	M(IP)	Lindo
Subash Babu, et al., 2000	Md, Ee	Rd	H	CA	Algorithm (BETROC)
Thomalla, 2000	T	R	L	GrP	Lagrange relaxation, algorithm
Vakharia et al., 1999	Q, Tp, U	R	C	Queuing analysis	Trial-and-error

Legend:

Design objectives: C: Capacity savings, U: utilization, F: Financial benefits, H: Handling, T: Tardiness, M: Makespan, Q: Queue time, Tp: Throughput time, Md: Machine duplication, Ee: Exceptional elements, Cc: Cell compactness, I: Inter-cell moves, W: Worker related objectives
Information type: R: routing cards (including processing times), Rd: idem plus demand information, D: drawings/shape information, S: production sequences, Sd: idem plus demand information

Table 2.2: An overview of papers on the operational performance of VMCs

Part Family	Results of the Method	VMC Independence
MP	A part family is produced on a set of dedicated machines, during the planning horizon a machine produces one family	Yes
MP	A hybrid layout with both shared process cells as well as dedicated product cells, a machine in the process cells may produce multiple part families	No
MP	A network of mini-cells, each mini-cell is shared among several parts, during the planning horizon a mini-cell produces different families	No
MP	As in Altom, 1978	No
SJ	Each job is coupled to a set of machines, during the planning horizon, a machine produces different jobs	No
SJ	As in Mak and Wang, 2002	No
MP	A hybrid clustering of both process oriented VMCs and product oriented VMCs, during the planning horizon the process oriented VMCs share all part families, the product oriented VMCs each produce a subset of part families	No (process oriented VMCs) Yes (product oriented VMCs)
MP	As in Altom, 1978	Yes (however, shared machines may be allowed)
MP	As in Altom, 1978	Yes (however, shared machines may be allowed)
SJ	As in Mak and Wang, 2002	No
MP	A part family is produced on a dedicated set of machines and workers, during the planning horizon a machine and a worker produces one family	Yes (however, shared machines and workers may be allowed)
MP	As in Altom, 1978	Yes (however, shared machines may be allowed)
SJ	As in Altom, 1978	No
SP	As in Prince & Kay, 2003	No (process- oriented VMCs) Yes (product- oriented VMCs)

Information source: C: Company data, L: Data from literature (may in turn be empirically based), H: hypothetical data (or no source mentioned)

Design method (see Selim et al. (1998)): D: descriptive method with: --MGI part family formation and subsequent machine grouping; --PF/MG: descriptive method, simultaneous part family formation and machine grouping

M: mathematical programming with: --LP: Linear Programming; --IP: Integer Programming

CA: Cluster analysis

share similar requirements (i.e. need the same tools for example), group technology benefits are realized, while flexible assignment of jobs to resources ensures better utilization of manufacturing facilities. The accompanying mathematical model minimizes inter-cell moves, tardiness, utilization and throughput; it is solved using tabu search.

A somewhat broader view was proposed by Prince and Kay (2003) who presented an enhanced version of Production Flow Analysis (PFA). They create virtual groups by allowing machines to be shared among different part families. As a result, a virtual group can be both process-oriented (a pool of similar machines) as well as product-oriented. The enhanced framework is applied in two industrial cases and indeed results in a combination of both process and product oriented virtual groups.

Ko and Egbelu (2003) presented two algorithms to create VMCs. The first algorithm is used to analyze routing data and create sets of machines that appear frequently in routings. These candidate VMCs are then analyzed using the second algorithm which specifies the final VMC configuration. A machine can occur in multiple VMCs (machine sharing) and a VMC can serve multiple parts.

Slomp et al. (2004, 2005) presented a framework for the design of VMCs, specifically accounting for the limited availability of workers and worker skills. They propose a goal programming formulation that first groups jobs and machines and then assigns workers to the groups to form VMCs. The objective is to use the capacity as efficiently as possible, but also to have VMCs in place that are as independent as possible.

2.4.2 A brief analysis of studies on design issues

An analysis of the papers on design of VMCs, as summarized in Table 2.2, reveal some interesting characteristics. Firm-specific data have been used quite frequently in various papers, and there appears to be close link to practice among these studies. Some authors have used hypothetical data or data from other publications (which can in turn be hypothetical or case based). The level of detail in the information varies; some have used only routing information (a list of machine types used by a part), while others have even inspected drawings as well as routing cards to make a very detailed grouping decision. A wide range of performance objectives has been used, ranging from financial measures through various operational measures to more abstract measures like cell compactness and number of exceptional elements. Several authors who consider layout issues, also use minimization of material handling as an objective. The specific design method may constitute a problem that

is very challenging to solve. Therefore two papers demonstrate the applicability of tabu search and genetic algorithms. Most authors do not use commercial optimization packages, but appear to have developed their own programs instead.

2.4.3 Opportunities for future research in design of VMCs

This section proposes several directions for future research on design of VMCs. A first research direction is the explicit inclusion of human factors into the design and operation of VMCs. The design of VMCs could account for the various skills available within the workforce and create worker teams that carry all the capabilities needed for successful production of their part family. Especially in the context of dual resource constrained systems (DRC) this may be a difficult task. However, DRC systems are the norm in practice and therefore deserve our attention. VMCs may however cause several problems when it comes to workers. Periodical review of VMC configurations may result in frequent shifts in team memberships. Other organizational problems include those associated with the creation of matrix structures. Tackling these issues requires different research skills than were deployed for past VMC research.

Several authors have included some material handling aspects into their design methods, mostly modelled as time-delays. There is clearly a close link to layout design. Especially when consecutive operations can be carried out on machines that are close to each other, a different handling method may be employed, like for example a mobile conveyor belt and overlapping production. Design methods could consider such possibilities explicitly.

The possibilities of information technology are constantly growing and the increasing penetration of Enterprise Resource Planning (ERP) systems increase the availability of data that can be used for VMC design. Data on various manufacturing requirements like tooling, fixtures and tolerances allow for a more thorough match with the capabilities of the manufacturing system. Therefore, VMC design methods should incorporate the possibilities of using data from ERP systems. On the other hand, the academic community is also interested in the comparison of various VMC design concept under the same circumstances, i.e. benchmarks testing. For this purpose, existing data from the literature might be used as a common ground for such tests. Those VMC design concepts that use hypothetical data could be developed towards the use more realistic data, either from literature or from practice. A variety of new methods such as tabu search, genetic algorithms and neural networks has started to be used for this area, which open up many new branches of inquiry as well.

Author(s)	Methodology	Experimental Factors	Performance Measures	Information Source
Flynn & Jacobs, 1986	S	L, PM	FT, WIP, U, S, W, Q, D	C
Flynn, 1987.	S	L, SP	FT, WIP, U, S, W, Q, L, D	C
Flynn & Jacobs, 1987	S	L, CF, FA, PM	FT, WIP, U, S, W, Q, L, D	C
Jensen, J. B. et al., 1996	S	L, SP, ST, IT, ITV, PM	FT, WIP, T, E	H
Jensen, J. B. et al., 1998	S	ST, SP, FA	FT, T	C
Kannan & Ghosh, 1995	S	ST, SP, FA, LS	FT, T	H
Kannan & Ghosh, 1996a	S	L, ST, PM, FA, LS	FT, WIP, T	H
Kannan & Ghosh, 1996b	S	L, ST, PM, FA	FT, WIP, T	H
Kannan, 1997	S	ST, FS, FN, FA	FT, T	H
Kannan, 1998	S	L, ST, IT, LS	FT, T	H
Suresh & Meredith, 1994	S, Q	L, ST, STV, PT, PTV, ITV, MHT, SP, MHS, LS	FT, WIP, U	H
Shambu & Suresh, 2000	S	L, ST, MHT, SP, FA, LS	FT, WIP, U	E
Suresh & Slomp, 2005	S	L, ST, STV, PT, PTV, ITV, MHT, SP, MHS, LS, CT, LAB	FT, WIP, U	H

Legend:

Methodology: S: Simulation, Q: Queuing analysis

Experimental factors: L: Layout, CF: Cell formation method, ST: Setup time, STV: Setup time variability, PT: Processing time, PTV: Processing time variability, IT: Inter-arrival time, ITV: Inter-arrival time variability, MHT: Material handling time, PM: Product mix distribution, FS: Family size, FN: Number of families, SP: Sequencing procedure, FA: Family allocation, MHS: Material handling strategy, LS: Lot sizes, TB: Transfer batches, CT: cross-training level for workers, LAB: labor assignment rules

Performance measures: FT: Flow time, WIP: Work-in-process inventory, U: Utilization, S: Set-up time, T: Tardiness, E: Earliness, W: Waiting time, Q: Queue length, L: Lot sizes, D: Material handling distances

Information source: C: Company data, L: Literature, E: Empirical research, H: Hypothetical data

Table 2.3: An overview of papers on the operational performance of Virtual Manufacturing Cells

2.5 Operational aspects of virtual manufacturing cells

In this section, we review the studies devoted to the operational aspects of VMCs. As in the above section, we first review the various studies, following which we identify areas for future research.

2.5.1 Research on operational issues of VMCs

This paragraph provides a further analysis of papers on the operational performance of VMCs. Several papers have appeared in this area, as can be seen from the first table. Table 2.3 summarizes the papers that are discussed in this section. The table subsequently lists the methodology, experimental factors, performance measures and the information source for the study.

Flynn and Jacobs (1986, 1987) performed simulation investigations of group technology (specifically, part family-oriented scheduling) in a shop layout that cannot be considered as a purely cellular layout (CL). Though these investigations were not intended as studies of virtual cellular systems, the findings of these studies are relevant to the area of virtual cellular manufacturing systems. Based on an actual case, they studied the effects of layout, product mix distribution and the dedication of equipment to part families. A general conclusion from these studies was that for this particular case, a functional layout provided the best alternative. Flynn (1987) continued research on this case comparing the effect of the repetitive lots sequencing procedure of Jacobs and Bragg (1988) in a functional and a cellular layout, as well as a functional layout with dedicated equipment. In this situation, a functional layout, in combination with sequencing rules that reduced set-up times, yielded superior performance over the cellular layout and functional layout with dedicated equipment. Persistent dedication of equipment itself would not reduce set-up times very much, so here a flexible way of exploiting job similarities had best performance. Subsequently, the queuing theory-based models of Suresh (1991, 1992) showed that these results are primarily due to the loss of routing flexibility (pooling synergy) when job shop work centers are partitioned when converting to CL.

Returning to the theme of virtual cells, Suresh and Meredith (1994) first explored the impact of using part family-oriented scheduling within a functional layout (FL), given the loss of routing flexibility in physical cells. This system was referred to as “FLP” systems, instead of as virtual cellular systems. It was shown that the FLP system performed better than traditional cells and functional layout under moderate setup time reduction and comparable lot sizes. However, it was also shown that traditional cellular systems performed better than functional layout and

FLP when setup time reductions were higher than a threshold level, and when traditional cells and FLP systems operate with lot sizes lower than in FL. It was also pointed out that cells lend themselves to other productivity benefits, which tilts the balance in favor of cells.

The above study utilized the first come, first serve (FCFS) scheduling rule. Kannan and Ghosh (1996a, 1996b) and Kannan (1997, 1998) explored the use of several other part-family oriented scheduling rules. They also referred to functional layouts with part-family-oriented scheduling as “virtual CM”. The factors explored in this stream are discussed at length in the recent work of Suresh and Slomp (2005).

Kannan and Ghosh (1996a) investigated the performance of functional, cellular and two virtual cell systems (VCM1 and VCM2). Among the two virtual cell systems, in VCM1, at any given work center, the next job to be processed belonged to a family with the most jobs in the current queue. In VCM2, the family requiring the fewest remaining machines in its routing was selected. Two levels of shop load (75% and 85%) and two levels of setup time were tested, in addition to four different demand patterns. The demand patterns included two levels of lot size, and balanced or unbalanced part mix. The performance of VCM was shown to be superior to FL, which in turn was superior to CL. VCM systems fared even better under high shop load, unbalanced demand patterns and low lot sizes.

In the above study, even though two levels of lot sizes were used, the lot sizes were the same in both functional and cellular layout. Given this setting, the superior performance of VCM1 and VCM2 in this study is consistent with the superior performance of “FLP” system in Suresh and Meredith (1994) in the common lot size region for functional, cellular and FLP systems. The findings can also be reconciled with the queuing results of Suresh (1992): CL systems tend to fare better than FL when lot sizes smaller than those used in FL are used in CL, and with setup reductions higher than a threshold value. When similar lot sizes are used in FL and CL, FL systems tend to fare better (Suresh 1992, p. 287).

In Kannan and Ghosh (1996b), the relative performance of five VCM systems was investigated, based on five different family selection rules. It was again shown that VCM generally outperforms cellular and functional layout. However, the point about not utilizing lower lot sizes and higher setup time reduction in CL applies to this study as well. Similar results are presented in Kannan (1997), where it was shown that VCM performed generally better than FL even with low setup times and when number of part families increases. In Kannan (1998), the impact of using transfer batch sizes lower than the lot sizes was investigated. Five levels of this

factor, along with two levels of shop load, batch size, setup time were used. This study showed that despite attempts to improve the flow performance in CL, CL outperformed VCM only under conditions of low shop load, small batch sizes and high setup times.

Jensen et al. (1998) considered a special case (a semi-conductor manufacturing system) consisting of a flowshop, with occasional skipping of work centers, and with each department consisting of multiple machines, as in a job shop. Three factors were explored: coordination of machine setups within a department, or otherwise; two family-based scheduling rules (EDD and SPT); and, setup time reductions ranging from 0% to 70% of processing times. With the first factor, namely, coordinated machine setups within a department, two or more machines of a department are allowed to have the setup for the same family only if the machines would be idle otherwise. This reduces the number of major setups at each work center. The utility of family-oriented scheduling was demonstrated when setup times are higher than a certain percentage of processing times. However, when family setup times were less than 15% of processing times, there was no advantage with family-based scheduling. An earlier study, Jensen et al. (1996), presented conclusions in a similar vein.

In the study of Shambu and Suresh (2000), the performance of hybrid cellular systems was investigated, and the issue of part family-oriented scheduling within functional and hybrid systems was investigated.

All the above studies on VMCs are based on single resource constrained (SRC) systems. This stream of research was extended to include the labor dimension in Suresh and Slomp (2005). Many of the benefits of cellular manufacturing systems arise from cross-training and worker mobility, and hence the flexibility associated with labor also need to be incorporated into the analysis. It was shown that in a DRC setting, VMCs can indeed outperform efficiently-operated functional and cellular layouts in certain parameter ranges, characterized by moderate setup reduction and cross-training, and when there is limited ability to reduce lot sizes in VMCs and traditional cells. However, it is also shown that traditional (physical) cells tends to outperform both VMCs and functional layouts in the parameter ranges customarily advocated in GT/CM, namely, low lot sizes, adequate levels of setup reduction, cross-training of workers, and worker mobility within cells.

2.5.2 A brief analysis of studies on operational issues

The studies devoted to operational performance of VMCs are summarized in Table 2.3. First, it is seen that operational issues have been investigated by a relatively

small set of researchers, and the use of simulation methodology dominates these investigations. Most authors have relied on hypothetical data, a few papers are based on a specific case, and one relies on empirical research for model inputs and parameters. Several performance measures are used, and flow time (FT) and work-in-process (WIP), utilization (U) and tardiness (T) are the most widespread. Some authors also measure the variability of, for example, flow time; this is closely related to earliness and tardiness measures. A measure of material handling efficiency is the distance traveled by jobs.

The studies can also be grouped on the basis of experimental factors. The major factor is the type of the manufacturing system, consisting of layout and cell formation procedure. Layout has been a topic in 9 out of the 13 studies reviewed. Several approaches have been assumed. Often, extremes are present in the form of a functional layout where each machine is accessible for every job, and a fully dedicated cellular layout where each part family is assigned to a subset of the equipment. Different methods of cell formation were also used to explain some performance differences.

Another critical aspect of the manufacturing system is its control structure, which is modelled in 10 out of 13 studies. Both the allocation of part families to machines as well sequencing of jobs can have an important effect on overall performance. Note that in case of a cellular layout the allocation of part families is fixed, i.e. it is inherent to the system, while in a functional layout this depends on the presence of some family allocation rule. The allocation of part families to machines is critical to achieve set-up time reductions; exploiting similarities in manufacturing requirements to prevent several set-up activities from occurring is central to group technology. Set-up reductions are a prerequisite for cellular manufacturing, although other measures like for example variance reduction are also necessary.

It has been suggested that VMCs are best suited to deal with a dynamic environment, i.e. where variations in the part mix and demand volume occur. An unstable part mix has been studied in several papers, demand volume variations have received much less attention. The structure of the part families, that is the size and number, has been studied once. The number and size of part families is related to the procedure used to create them. Several material handling aspects exist: the type of handling system and handling times, as well as lot sizes and the use of transfer batches which both have an impact on the load of the material handling equipment. Lot sizes have been taken into account quite often but transfer batches

have not. Using any of these two may require adjustments in the material handling system and its control.

2.5.3 Opportunities for future research in operational issues of VMCs

Several major opportunities exist in the area of operational issues of VMCs. Based on the above analysis, we suggest several directions for new investigations.

A prime area for research is the testing of more active forms of VMCs. Thus far, research has only addressed passive forms of VMC design, that is the application of family-based scheduling rules in non-cellular layouts. In such cases, VMCs emerge automatically as a result of operational decisions, but only at a local level. Information on jobs elsewhere in the factory is not used in such a case. A possible extension would be the use of look-ahead strategies, where knowledge of future job arrivals (thus jobs that are already somewhere else in the factory) is used to control the assignment of part families to machines. Such approaches have already been developed and tested for parallel batching systems (see for example Van der Zee, 2004). A step further would be to test VMC design methods developed for periodical configuration of VMCs. Such designs could be based on a set of jobs that are held in a pool in pre-manufacturing stage like master production planning.

In the context of changing environments, the quality of the design method becomes particularly important. While the adaptability of VMCs to a changing environment is an important characteristic, this has not been tested to a great extent. Shifts in the part mix may render a certain VMC configuration outdated, resulting in the need for a redesign. It would be interesting to know if VMCs can improve the performance of a manufacturing system even if the environment is very turbulent i.e., when changes in the part mix and/or volumes occur very often.

It may also be observed that, with the exception of the recent work of Suresh and Slomp (2005), all the studies in Table 2.3 are based on single resource constrained (SRC) systems, considering only machine resources. The inclusion of labor dimension is a critical need in future studies and this is a major avenue for future research. The effectiveness of VMCs can be improved by cross-training of workers, having the right mix of proficiency among workers, right labor assignment rules, etc. Learning effects would decrease the time needed to perform various manufacturing tasks as well. The impact of labor-related factors on the performance of VMCs needs to be investigated systematically in DRC-settings, and this appears to be a very interesting and necessary direction for future research.

2.6 Empirical research

As seen in Table 2.1, empirical research forms a small part, compared to the number of studies on design issues and operational investigations of VMCs. We review three empirical studies below, among the few empirical studies that have been conducted in cellular manufacturing in general, in order to draw some practitioner-oriented insights.

2.6.1 Empirical research dealing with VMCs

The early study of Wemmerlöv and Hyer (1989) was based on a survey of users and likely user of cellular manufacturing in US industry. The survey was conducted by means of a questionnaire. It was found that a fair number of firms that returned the questionnaire stated using the principle of dedicated equipment to achieve group technology-related benefits. Machine dedication was practiced in these firms without rearranging them into manufacturing cells. Some relied solely on dedicated equipment, others used a combination of both dedicated equipment and manufacturing cells (a hybrid arrangement). Generally, dedicated equipment alone would yield most benefits of a complete cellular rearrangement though often not to its full extent. The cost of relocating equipment was mentioned by most companies as a major expense and formed a major deterrent to creating physical cells. In addition, temporary load variations were pointed out as a problematic issue with cells, which could “dry out”, and shifting work between cells was not always easy.

In a more recent work, Hyer and Brown (1999) presented the results from fifteen case studies in industry. They also proposed a framework for the classification of manufacturing cells, wherein a virtual cell consists of people and equipment that are dedicated to a part/product family, and where the workflow is closely connected in time and information, but the resources are not clustered spatially. The authors stressed the importance of organizational aspects, next to the factors that are usually investigated in the design and operation papers. These aspects included the availability of information to workers, their ability to act on this information, cross-trained workers with teamwork skills, etc.

Wemmerlöv and Johnson (2000) investigated how cell design takes place in practice. The paper investigated the motives to implement manufacturing cells and the methods and organization employed to do so. They also considered constraints that hinder the implementation of manufacturing cells. Among these are the inability or huge costs of moving equipment and insufficient demand volume and stability. These factors were found to form major impediments to the introduction of cellular manufacturing.

2.6.2 Empirical research: Future research issues

Based on the above discussion of empirical papers, several observations can be made, and there also exists several possibilities for future research in this area. The combination of empirical research with other research types remains a fruitful possibility.

Most of the empirical research in the cellular manufacturing area has been carried out by a limited set of authors. Both survey method as well as case study research have been used. The empirical research studies have tended to be rather descriptive, and with much room for improvements in research rigor, overall. Nevertheless, these papers have provided useful explanatory power and guidance of analytical and simulation studies in the past. Further empirical research is clearly needed to provide realistic inputs for choice of experimental factors, and to validate analytical and simulation models. Descriptive statistics could be used to set parameter ranges in such studies. An interesting example is the study by Shafer and Meredith (1992) which is a comparative operational evaluation driven by empirical data from three firms.

From empirical research surveys, it has become clear that the adoption of cellular manufacturing has been lower than anticipated. Most respondents of these surveys have stated that they do not use traditional cellular manufacturing, for the most part and, if one or more cells were present within a company, the degree of cellularization has also been low. Apparently, the pure form of cellular manufacturing has been difficult to adopt in practice, within most industries. Empirical research has not fully provided answers relating to why firms have not adopted cellular manufacturing that extensively.

The samples of respondents in survey research has been somewhat selective as they have been aimed primarily at high-probability cell user plants. As prior research shows that the adoption of cellular manufacturing has been low, even among likely users, it would be interesting to know the reasons as to why manufacturing cells are not adopted. The work of Molleman et al. (2002) can be seen as an example for the directions into which empirical research should move.

Further empirical research is also needed to assess the real impact of cellular manufacturing in industry. In many of the firms that have implemented cellular systems, the real extent of success is still unclear. In some cases, the benefits seem to be marginal, at best. Whether this is due to improper implementation, improper planning systems, or due to underlying problems with cellular manufacturing, etc., is hard to say. But it does leave the impression in such cases that it may be beneficial

to merely resort to improvements in the erstwhile system through measures such as part-family-oriented scheduling, setup reduction, cross-training and better planning systems.

Empirical research is often constrained by the fact that it is possible to document the performance of cellular manufacturing only with what existed before; and, the *status quo ante* may not correspond to an efficiently-operated system. Research has also been confined to the cases where cellular manufacturing has been implemented, as stated earlier. It is necessary to include firms from the vast majority of low- and mid-volume situations where it has not been implemented, and the feasibility of implementing cellular manufacturing in such contexts should be explored.

In addition, in firms that have implemented cellular manufacturing, a reduction in lead time is often reported. There is a need to develop reliable metrics for lead time, work-in-process (WIP) inventory, and other physical measures, and include provisions for cross-checking and validating reported impacts. For instance, if lead times did indeed reduce significantly, we should see commensurate improvements in inventory turnover ratio, across all part types and in overall performance of the factory.

Data gathering is also at times based on information elicited from project champions and/or other change agents within each firm. It is likely that a more realistic assessment of cellular manufacturing may emerge from studies based on a broader respondent base within each firm, and with more rigorous empirical research methods.

2.7 Conclusions

Thus, after more than two decades of research into virtual manufacturing cells, it seems to be the right time to provide a critical review of this field. This initial paper has attempted to provide answers to three major questions: what VMCs are, what research has been done, and what the findings are, and what seem to be promising topics for future research.

VMCs are a concept primarily for production planning and control, involving a separation with the layout problem. Second, the requirements of a changing environment and the resulting adaptation of the manufacturing system has been emphasized consistently in past research. The layout of the manufacturing system is considered to be too rigid to change partially or completely in accordance with the new requirements. A third issue is the consideration of part/product families and the

exploitation of similarities in manufacturing requirements. Finally, three different types of resources need to be considered comprehensively: machines, people and material handling equipment. In essence, VMCs can be defined as temporary manufacturing cells, dedicated to the production of one or multiple parts/products, whose resources may not be physically adjacent in the shop floor.

Most of the research has focused mainly on the design and the operation of VMCs while empirical research has not received much attention. Most opportunities for future research are in the extension of testing more proactive versions of VMCs, incorporation of material handling and human aspects, and stronger empirical links. The consideration of new layout types is also very promising.

The investigation of virtual manufacturing cells is seen to offer a wealth of opportunities for future research. Much analytical and simulation work remain to be done for this problem area, both for design, and investigation of operational issues. The models developed so far have undoubtedly led us towards a generalized range of parameters in which VMCs may be effectively and efficiently utilized. Finally, there is major need to understand industry reality surrounding cellular manufacturing, through additional, and more rigorous empirical research.

