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Virtual cellular manufacturing

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C H A P T E R 1

Introduction

This first chapter introduces the research objectives underlying this thesis on the application of Virtual Cellular Manufacturing within small-batch discrete parts manufacturing operations. Essentially, Virtual Cellular Manufacturing aims at improving shop floor performance by exploiting product similarities in production planning and control. Section 1.1 outlines the concept by relating it to traditional ways of manufacturing and indicating its performance benefits. Section 1.2 discusses existing research on Virtual Cellular Manufacturing and highlights the specific gaps addressed in this thesis. The research objectives are presented in Section 1.3, followed by an outline of the thesis in Section 1.4.

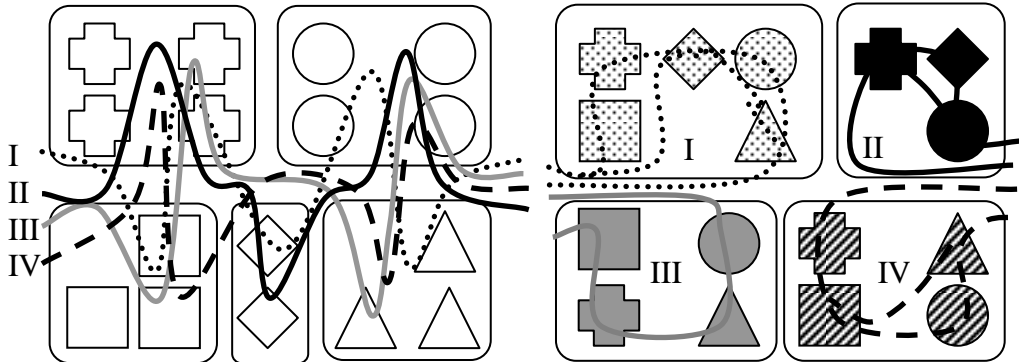
1.1 The trade-off between product and process orientations in manufacturing systems design

The manufacture of small batches of discrete parts can be found throughout industry. Examples include parts for centrifugal pumps, office equipment, power tools and military equipment (see Chapter 3). In all these situations, a large variety of parts is required, in fluctuating volumes, and with a low to medium annual demand. Designing and managing a competitive manufacturing system for such dynamic circumstances is an ongoing challenge for the companies involved.

An important decision in the design of small-batch discrete parts manufacturing systems is the extent to which the design should be driven by the products to be made, or by the processes used to manufacture them (Slack et al. 2007). A process-oriented organisation, also referred to as a Functional Layout, consists of separate departments, each equipped with resources (e.g. machines, workers) suited to a specific process¹ (e.g. turning, milling). Each product can undergo a distinct series

¹ A *process* is defined here as a particular treatment of a product, for example turning, milling, welding, heat treatment, inspection.

of operations² in the various specialist departments (see Figure 1.1). In contrast, a product-oriented organisation for small-batch discrete parts manufacturing usually takes the form of Cellular Manufacturing (see Figure 1.1). Here, products with similar routes³ are grouped into families, each of which is entirely processed in a co-located group of complementary resources: the manufacturing cell (Hyser and Brown 1999).



Functional layout:
each product may follow a distinct
route through specialist departments

Cellular Manufacturing:
products with similar routes
are processed in cells

Figure 1.1: Process- versus product-orientation

The purely process-oriented manufacturing organisation has been associated with long and uncontrolled throughput times (Gallagher and Knight 1986, Wiendahl 1995). Variations in job routings, processing times, demand volumes and so on complicate the coordination of successive operations in a process-oriented organisation, with long in-process waiting times as a result. Product-orientation (i.e. Cellular Manufacturing) can simplify the coordination of subsequent operations and so reduce waiting times. Set-up times will also probably be reduced if similar parts are processed in one cell; and the resulting efficiency improvements may further reduce in-process waiting times.

² An *operation* is defined here as the application of a process to change one or more product features according to pre-specified parameters, for example turning a specific shaft type to achieve a given diameter and surface roughness by using particular cutting tools.

³ A *route* or *routing* is defined here as the specification of the method to manufacture a particular product; it includes the operations a product has to undergo and in which sequence, which resources are involved, as well as time standards for the operations.

Cellular Manufacturing has indeed helped firms to realise significant improvements in throughput time performance (Isa and Tsuru 2002, Waterson et al. 1999, Wemmerlöv and Johnson 1997, Wemmerlöv and Hyer 1989). This approach gained popularity in the second half of the 20th century (see, for example, Burbidge 1975). Nevertheless, several researchers argue that Cellular Manufacturing could still be outperformed by a well-organised functional organisation (Rathmill and Leonard 1977, Flynn and Jacobs 1986, Suresh 1991).

The majority of small-batch parts manufacturing organisations remain process-oriented for two important reasons. The first concerns the loss of pooling synergy which results from assigning identical machines to specific manufacturing cells (see, for example, Morris and Tersine 1990). This can result in lengthened throughput times if there are short-term load variations, which cannot be accommodated by shifting work to similar machines in different cells. Cellular Manufacturing therefore needs to result in a range of additional benefits, such as reduced set-up times, lot-size reductions and a more regular flow, to counteract and overcome the loss of pooling synergy (Suresh and Meredith 1994). Moreover, longer term changes in the product mix may require a revision of cell layouts, whereas a functional organisation would not need to be reorganised in response to such demand changes.

The second reason for sticking with a process orientation is that initial layout changes may involve high costs, which discourages a change towards Cellular Manufacturing (Choi 1996, Johnson and Wemmerlöv 2004, Waterson et al. 1999). Such a situation particularly arises when machines are very difficult to move or are difficult to combine with other technologies. Good examples are large presses (heavy foundations, noise), welding operations (light and smoke), heat treatment and clean-room operations. Further, extensive investments may be needed to acquire additional machinery to facilitate the manufacturing cells to operate independently of one another. Under these circumstances, the costs of acquiring and moving equipment and their facilities may not outweigh the potentially short-lived benefits of a revised layout with shortened material handling distances.

Virtual Cellular Manufacturing has been proposed as a way to overcome the aforementioned shortcomings of both Cellular Manufacturing and Functional Layouts. With Virtual Cellular Manufacturing (Figure 1.2), groups of resources are again dedicated to the manufacturing of a part family, but these cells are not reflected in the layout of the manufacturing system. Machines remain in their original (functional) layout: the cells are instead formed in the planning and control system and have a temporary nature (Hyer and Brown 1999). As such, Virtual

Cellular Manufacturing combines the robustness and flexibility of process orientation with the advantages of product orientation, and this is expected to realise favourable throughput time performance. In so doing, it provides opportunities to improve performance in situations where a cellular layout is technically infeasible. It can also serve as a first step towards implementing full Cellular Manufacturing (Wemmerlöv and Hyer 1989).

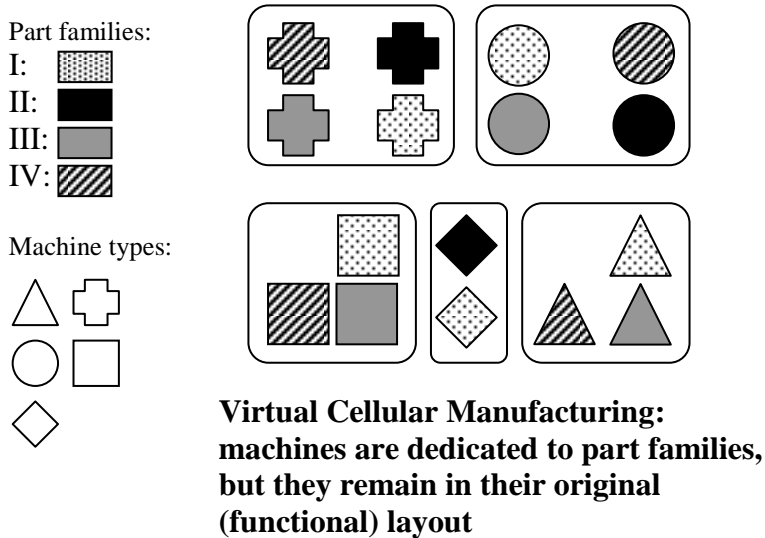


Figure 1.2: Virtual Cellular Manufacturing - combining product- and process-orientation

1.2 Research overview and research needs

Research on Virtual Cellular Manufacturing is relatively new. In this section, we first discuss the earliest references to Virtual Cellular Manufacturing and show how the principles of Group Technology underpin Virtual Cellular Manufacturing. Following this, we summarise the existing research and identify the specific gaps that will be addressed in this thesis.

One of the first implementations of Virtual Cellular Manufacturing was presented by Altom (1978), who describes the case of a large job shop where part families were distinguished and assigned to groups of machines. Although these machines remained in their original location, they were supervised by a group coordinator. In this way many of the claimed benefits of Cellular Manufacturing could be realised without cumbersome layout changes. McLean et al. (1982) associate the term “Virtual Manufacturing Cells” with such a logical grouping of

machines. Research gained momentum in the 1990s, and a full overview of the literature is contained in Chapter 2 (see also: Nomden et al. 2006).

The principles of Group Technology form the basis for Cellular Manufacturing (conventional and virtual). Group Technology has found most applications in industries where a variety of parts are required in low to medium volumes, which is also the context of this thesis. Such industries typically manufacture machine tools, agricultural equipment, medical equipment and a wide range of similar products (see, for example, Hyer and Wemmerlöv 2002). The application of Group Technology to manufacturing can be viewed as “exploiting similarities” within a manufacturing system. It builds on the notion that similar problems are likely to have similar solutions (Suresh and Kay 1998). Two types of similarities are particularly relevant, namely routing similarities (1) and processing similarities (2). Firstly, routing similarities (type 1 similarities) exist when parts have similar routings in terms of the required processes and the sequence in which they are needed. Cellular Manufacturing primarily builds on the identification of “routing families” for the selection of equipment for cells. Secondly, processing similarities (type 2 similarities) occur at individual processes when different parts require similar operations. These parts may share work holding devices, cutting tools, machine settings and so on. Information on processing similarities can be used to dispatch jobs to individual machines and, consequently, reduce the set-up times between these jobs (see, for example, Karvonen and Holmström 1996).

Routing and processing similarities may occur more or less independently of each other, i.e. parts that require a similar operation in one process do not necessarily share their complete routing. Several studies on Virtual Cellular Manufacturing, however, assume that jobs belonging to a routing family require similar operations as well. In fact, they combine processing similarities and routing similarities in their definition of a part family. Nevertheless, research on Virtual Cellular Manufacturing can be classified according to their focus on one of the above mentioned types of similarities (Nomden et al. 2006). Routing similarities are mainly addressed in design-oriented papers, whereas processing similarities are mainly addressed in operation-oriented studies.

Research on the design of Virtual Cells mainly involves mathematical models. For each part family, the required machines are clustered in a Virtual Cell, which can be changed in response to changing shop conditions. Consequently, benefits of conventional Cellular Manufacturing, such as more regular flows and reduced set-up times, and thus shorter throughput times, may be achieved. This research stream is

moving towards comprehensive decision-support models for Virtual Cell formation, with consideration given to machines, material handling aspects and sometimes even human resources (Ratchev 2001, Saad et al. 2002, Prince and Kay 2003, Slomp et al. 2004, 2005). Typically, Virtual Cells are formed as part of periodical planning routines, following changes in demand volumes and product mix, as new jobs accumulate during a planning period (see, for example, Slomp et al. 2005).

Other researchers focus on the exploitation of processing similarities (type 2 similarities) through family-based dispatching, which has also been referred to as Virtual Cellular Manufacturing (Jensen et al. 1996, Kannan and Ghosh 1996a, Suresh and Slomp 2005). By grouping similar jobs for joint processing, the time spent on setting up equipment is reduced and, as a consequence, throughput times are reduced as well. Accordingly, machines from various process departments become allocated to a particular family to form a Virtual Cell; the emerging Virtual Cells develop continuously in response to changing shop conditions. Typically, research in this stream (for example, Flynn 1987) compares the performance of Virtual Cellular Manufacturing (i.e. a Functional Layout operated with family-based dispatching rules) as against Cellular Manufacturing (i.e. permanent dedication of equipment to part families) and a Functional Layout operated with conventional dispatching rules (i.e. no dedication of equipment).

Virtual Cellular Manufacturing has been addressed in a limited number of empirical studies, i.e. industrial surveys and case studies (Wemmerlöv and Hyer 1989, Hyer and Brown 1999). These studies do show that a fair number of companies rely on dedicated equipment (referring to both routing and processing similarities) without adopting a cellular layout. As such, these companies apply a form of Virtual Cellular Manufacturing: in some cases as the only viable form of Cellular Manufacturing, in other cases as a step towards conventional Cellular Manufacturing. However, the studies mentioned above do not give a systematic overview of the applicability of Cellular Manufacturing, and Virtual Cellular Manufacturing in particular, in industrial practice. Additional empirical research is required to fill this gap.

The distinction between routing similarities and processing similarities aids in understanding the performance effects of virtual and conventional cells. Many improvements of throughput time performance that have been achieved through traditional cells, can in fact be attributed to the presence of processing similarities. Moreover, as mentioned before, the exploitation of routing similarities cannot always be realised in an economical way. Therefore the exploitation of processing

similarities provides a meaningful research theme for this thesis. Since family-based dispatching provides an important mechanism to exploit processing similarities, a considerable part of this thesis focuses on simulation studies of the mechanisms and effects of family-based dispatching.

The research into family-based dispatching, as an implementation of Virtual Cellular Manufacturing, offers several opportunities for further research. Many simulation studies in this area involve complex shop floor environments characterised by multiple manufacturing stages, extensive routing flexibility and an all-embracing application of family-based dispatching heuristics (Kannan and Ghosh 1996a, Jensen et al. 1998). Such complex environments create difficulties in understanding the precise effects of family-based dispatching on shop performance and the transfer of such insights to real shop environments. Future studies could therefore approach the complexity of shop environments in an incremental way, gradually building from a single machine environment towards more complex systems. In a similar vein, the study of family-based dispatching heuristics and their effect on shop performance is dispersed across research papers (compare for example Mahmoodi and Mosier 1998, Kannan and Ghosh 1996b). Moreover, many heuristics are restricted to use information on jobs readily available on the shop floor, such as queue lengths, set-up times and processing times. Alternative sources of information may be available and be used as well, such as information on jobs about to arrive at a machine. A more structured approach to the study of family-based dispatching could be used to expose the links between shop performance metrics, the available shop floor data and the construction of heuristics.

In the next section, we will discuss the research objectives and questions of this thesis in more detail.

1.3 Research objectives and approach

The research presented in this thesis is split into two parts that address two major objectives:

I) To explore the relevance of Virtual Cellular Manufacturing to small-batch discrete parts manufacturing, and identify opportunities for further research.

II) To develop heuristics for family-based dispatching and test them in basic shop configurations.

The shortcomings and limitations of the existing research, as identified in the previous section, lead to more specific research questions. The first research question reflects the need for an overview of the existing research:

RQ1: *What is the current state of research in the area of Virtual Cellular Manufacturing?*

Although there is now a mature stream of research into Virtual Cellular Manufacturing, no survey presenting an overview of the existing research has been made. After this introductory chapter, this thesis addresses the evolution of the concept, as well as what research has been done and what the findings are. From this, several research opportunities are identified, and these include the remaining research questions set for this thesis. The need for more empirical research gives rise to the second research question:

RQ2: *What is the applicability of Group Technology, and more specifically Virtual Cellular Manufacturing, in industrial practice?*

The thesis contains three industrial case studies. The central questions are how performance in terms of throughput time can be improved by applying Group Technology principles and which factors prevent the implementation of these principles. The cases confirm the applicability of family-based dispatching in industrial practice. As a by-product, these case studies form a valuable reference base and a source of inspiration for the study of quantitative models.

The need for a better understanding of the basic effects of family-based dispatching is addressed in an incremental way. The central performance measure throughout the entire thesis is throughput time. Although other performance measures (such as efficiency) are also relevant, throughput time is particularly so because it can serve as an aggregate measure of critical performance aspects of a manufacturing system (Schmenner 1988). The context of a single-machine shop forms a starting point to address some of the shortcomings and limitations of existing research discussed in the previous section. This approach is reflected in the following research questions:

RQ3a: *What alternative family-based dispatching heuristics can be developed, given the restricted use of shop floor data in existing heuristics?*

RQ3b: *What are the effects of family-based dispatching on throughput time performance in a single-machine shop?*

In the next step, the performance of family-based dispatching in a parallel machine shop will be addressed. This context introduces routing flexibility, which exists when a job can be assigned to a choice of alternative machines. As a consequence, family-based dispatching heuristics have to be adapted to handle the alternative assignments while also considering set-up effects at the same time. Further, a common assumption in the existing literature is that routing flexibility is either fully present or completely absent. The case studies in this thesis reveal that intermediate levels of flexibility are far more likely. Moreover, the extent of routing flexibility forms an important managerial decision, and this motivates us to ask the following research question:

RQ3c: *How do different levels of routing flexibility, combined with family-based dispatching, affect the throughput time performance of a parallel machine shop?*

The effects of family-based dispatching on the performance of subsequent operations are studied as the final step. Although family-based dispatching can have positive local effects, the resulting irregularity in the arrival of jobs at subsequent stations may negate these benefits in terms of the performance of the overall system. The eventual application of family-based dispatching should therefore be determined on a machine-by-machine basis, as the case studies in this thesis show. In contrast, existing research assumes that family-based dispatching is always applied at every machine throughout an entire shop. To gain a better understanding of the interactions between successive operations when family-based dispatching is applied, we have formulated the following final research question:

RQ3d: *How does the local application of family-based dispatching to a specific machine influence the overall performance of small manufacturing networks?*

The next section provides an outline of the thesis, where the research topics are linked to the individual chapters.

1.4 Thesis outline

This thesis is divided into two major parts, reflecting the major research objectives stated in the previous section. The first part of this thesis thus focuses on the exploration of relevant literature and industrial practice. The second part of the thesis presents three simulation studies of family-based dispatching. The chapters have been written as independent papers and have either been accepted (4) or

submitted (1) for publication in refereed journals. While the chapters can be read independently, together they also tell a coherent story. Inevitably, this structure will lead to some overlaps and repetition in the thesis although these are largely limited to the chapter introductions. Table 1.1 provides an overview of the chapters, the research topics and the methodology.

	Topic	Chapter	Approach	Scope
Part I: exploration	RQ1: What is the current state of research in the area of Virtual Cellular Manufacturing?	2	Literature survey	Literature until 2005
	RQ2: What is the applicability of Group Technology, and more specifically Virtual Cellular Manufacturing, in industrial practice?	3	Case research	Three manufacturing companies
Part II: development and testing	RQ3a: What alternative family-based dispatching heuristics can be developed, given the restricted use of shop floor data in existing heuristics?	4	Simulation	Single-machine shop
	RQ3b: What are the effects of family-based dispatching on throughput time performance in a single-machine shop?			
	RQ3c: How do different levels of routing flexibility, combined with family-based dispatching, affect the throughput time performance of a parallel machine shop?	5	Simulation	Parallel machine shop
	RQ3d: How does the local application of family-based dispatching to a specific machine influence the overall performance of small manufacturing networks?	6	Simulation	Small manufacturing network

Table 1.1: Overview of research topics, chapters, methodological approach and scope

Chapter 2 addresses the first research topic: a survey of the current state of research in the area of Virtual Cellular Manufacturing. Here, the evolution of the definition of Virtual Cellular Manufacturing is first presented. Following this, the various papers identified are classified and discussed, in particular addressing empirical research and approaches based on quantitative models. This discussion provides insights into conditions under which Virtual Cellular Manufacturing delivers a favourable performance. In addition, several directions for further research are identified from this review.

Chapter 3 addresses the second research topic by studying the existing and potential application of Group Technology, and more specifically Virtual Cellular Manufacturing, in three manufacturing firms. Two Group Technology principles are distinguished: exploiting routing similarities (type 1) and processing similarities (type 2). The three case studies show how the application of these principles can be hindered by contextual factors. In particular, Cellular Manufacturing (i.e. exploiting routing similarities) seems difficult to implement in practice, because it is often difficult to physically move and combine different technologies in manufacturing cells. Despite this, the cases show that a company can still successfully apply other Group Technology practices such as family-based dispatching (i.e. exploiting processing similarities).

The second part of this thesis starts with Chapter 4, which focuses on family-based dispatching. A framework is developed to classify and analyse existing family-based dispatching heuristics based on their decision logic. As a result, two new family-based dispatching rules are proposed. In addition, extensions to existing heuristics are suggested in order to accommodate information on forthcoming job arrivals. A simulation study is used to study the potential of the existing and new heuristics in a single-machine shop.

Chapter 5 investigates how different levels of routing flexibility, combined with family-based dispatching, affect the throughput time performance of a parallel machine shop. Routing flexibility exists when a job can be assigned to more than one machine. How much routing flexibility to implement is an important managerial decision because it comes at a cost, like investments needed to create alternative process plans and duplicate tooling. In this chapter, family-based dispatching heuristics are adapted to handle the assignment alternatives while simultaneously taking account of set-up effects. Simulation experiments are used to show the conditions under which increased routing flexibility is a benefit, and how the alternative routes are assigned to specific product families to maximise the performance benefits.

Chapter 6 presents a study of small manufacturing cells, with and without labour constraints. The study was inspired by one of the industrial case studies, and aims to understand how the application of family-based dispatching to a particular machine influences the performance of the entire cell. A simulation study is carried out to assess the impact of the specific machine to which family-based dispatching is applied, of load variations between machines, and of job routings on the throughput

time performance of the cell. The results indicate those conditions under which family-based dispatching is particularly beneficial.

Finally, Chapter 7 summarises the main findings of the thesis. Answers to the research questions are provided and briefly discussed. In the subsequent discussion, several issues for further research are identified.

The following papers, with their corresponding chapter numbers, are included in this thesis:

- 2: NOMDEN, G., SLOMP, J., SURESH, N.C. (2006), Virtual manufacturing cells: A taxonomy of past research and identification of future research issues, *International Journal of Flexible Manufacturing Systems*, Volume 17, Issue 2, Pages 71–92.
- 3: NOMDEN, G., SLOMP, J. (2010), The Application of Group Technology Principles in Manufacturing Practice, *Submitted for publication in Production Planning and Control*.
- 4: NOMDEN, G., ZEE, D.J. VAN DER, SLOMP, J. (2008), Family-based dispatching: anticipating future jobs, *International Journal of Production Research*, Volume 46, Issue 1, Pages 73–97.
- 5: NOMDEN, G., ZEE, D.J. VAN DER (2008), Virtual Cellular Manufacturing: Configuring Routing Flexibility, *International Journal of Production Economics*, Volume 112, Issue 1, Pages 439–451.
- 6: BOKHORST, J.A.C., NOMDEN, G., SLOMP, J. (2008), Performance evaluation of family-based dispatching in small manufacturing cells, *International Journal of Production Research*, Volume 46, Issue 22, Pages 6305–6321.

P A R T I :

Exploring the relevance
of Virtual Cellular
Manufacturing

