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CHAPTER 5

Parallel machines

Virtual Cellular Manufacturing (VCM) creates groups of products and machines in the production planning and control system. Suchlike groupings may help to reduce set-up times. Starting from two industrial cases we study parallel machine shops assuming the implementation of VCM. We address the way mid-term investments in process planning, machines and secondary resources may improve shop performance. Here our prime focus is on an increase of routing flexibility in terms of the number and distribution of alternative machines available for a product family, and the number of secondary resources. An extensive simulation study makes clear that: (1) a small number of alternative routes will mostly suffice, (2) a chained distribution of routes is preferable, and (3) additional secondary resources are relevant only under specific conditions.

5.1 Introduction

In a globalising world manufacturers are under constant pressure to cut costs, while improving delivery speed, product quality, flexibility and delivery reliability at the same time (Richards, 1996). Cellular Manufacturing (CM) has been proposed as one of the possibilities to meet these challenges. CM is an application of Group Technology (GT), and assumes physical groupings of machines, each grouping or cell being dedicated to the manufacturing of a product family. The similarities in manufacturing requirements for members of a product family lead to reduced set-ups, less material handling, and more (Burbidge, 1975).

Virtual Cellular Manufacturing (VCM) has been proposed as an alternative to CM, for functional layout settings where a conversion to CM is not feasible from a technical or financial perspective. Instead of a physical re-allocation of machines—as in CM—VCM aims to reduce set-up times by grouping similar jobs in production planning and control. Hence, flow time performance of the shop may be improved (Kannan and Ghosh, 1996a). In this way, VCM achieves many of the benefits

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associated with CM, while retaining and building on the routing flexibility of a functional layout, i.e., the possibility to choose from alternative machines to execute an operation.

Basically, VCM assumes a trade-off between making use of pooling synergy—following from routing flexibility—and additional delays caused by machine set-ups (Jensen et al., 1998). In this article we address this trade-off by considering the way mid-term investments in routing flexibility, such as machine reconfiguration, additional tools, fixtures, or process planning, may improve shop performance. Our study is motivated by two industrial cases, concerning parallel machine shops. Shop managers lack insight in the potential of investments for flow time reduction. In this article we address their dilemma by studying the way the configuration of routing flexibility influences shop performance. Configurational choices concern:

1. The level of routing flexibility, i.e., the number of alternative routes (machines) available for a product family.
2. The distribution of routing flexibility, i.e., which product families have access to which machines.
3. The number of secondary resources (tools, fixtures, etc.) available to product families.

To study the above research issues, we conducted an extensive simulation study of a parallel machine shop for three VCM implementations, i.e., family-based control schemes. Shop characteristics, such as the number of product families, and the set-up to run-time ratio, are motivated by the aforementioned industrial cases and studies reported in the literature.

The paper is structured as follows. In Section 2 we discuss the two industrial cases that motivated this study. Next, in Section 3, we review relevant literature for basic insights on configuring routing flexibility in VCM environments. In Section 4 we discuss the design of the simulation study. Outcomes of this study are analysed in Section 5. Finally, we summarise our conclusions in Section 6.

5.2 Industrial motivation and shop model

Starting point for our research are two industrial case studies concerning in-house metalworking shops. Each shop concerns a number of machines in parallel. By discussing the case studies, we aim to identify relevant managerial dilemmas, and to motivate the configuration of our shop model. This model generalises shop characteristics as they are found in both cases, as well as in previous research, see for example Jensen et al. (1996) and Garavelli (2001). We conclude this section by stating our research questions.

5.2.1 Industrial context – two case studies

The first shop is found in a company producing high-tech defence products. The company performs in-house manufacturing of metal parts, prior to their assembly. Due to the low repeat frequency of end-items, parts manufacturing effectively boils down to one-of-a-kind production. Among its facilities are four rather similar machining centres. Around 20 product families can be identified by considering fixture type and the required operations. Typically, fixturing concerns family related set-up times, which may amount to twice the job processing time or even more. Further, tool changes may be realised in just a short time. To realise a good flow time performance for the shop, operators apply an informal VCM control policy. Accordingly, they try to reduce set-up time effects by grouping similar jobs for joint processing, as well as making good use of alternative machines. However, they are restricted in doing so as process plans are often machine specific due to choice of programming language, and the availability of fixtures. The shop manager considers the following investments for improving flow time performance:

- Increase process plans flexibility such that choice of programming language no longer determines the choice of machine. For example, part programs as they are available in the so-called “CL-language” can be handled by any of the four machines. However, process planners only implement new process plans in this language, concerning a very small share of the product portfolio. An alternative would be to renew the control systems of all machines, a costly upgrade.
- Increase the number of fixtures. Remark that fixtures tend to be expensive, due to the fact that they are family specific.

The second company manufactures metal plate components and assemblies for cars, power tools and household appliances. One of its shops concerns a number of hydraulic presses of a similar type. Many of the parts produced in the shop have a high repeat frequency (i.e. weekly), while other products are only manufactured a few a times per year. Lot-sizes range from 160 to 3300, and are determined by the customers. Parts manufacturing requires the presence of a part-specific die. Set-ups consist of attaching a die to the machine, changing the lubrication, and adjustments of the machine settings, like stroke and force. Each set-up takes up to a job processing time. It is possible to combine jobs requiring the same die into a larger process batch, to save set-up time.

To gain a competitive advantage, the company considers the possibility of reducing product delivery times. A first option to do so concerns the use of dies. In principle, most dies can be attached to multiple presses, thereby providing potential for routing flexibility. However, as a general rule, the production engineering department uniquely assigns each die to a specific press. The reason for this is the traceability of product quality problems. Also, adding an alternative route would require adjustments in the ERP-system—to be carried out by the production engineering department. Another option would be to increase the number of dies or to introduce modular dies. So far, only one die is available for each product. This choice is motivated by dies' high costs. Modular dies assume the presence of a basic die which may be extended by product specific inserts to meet product specific requirements.

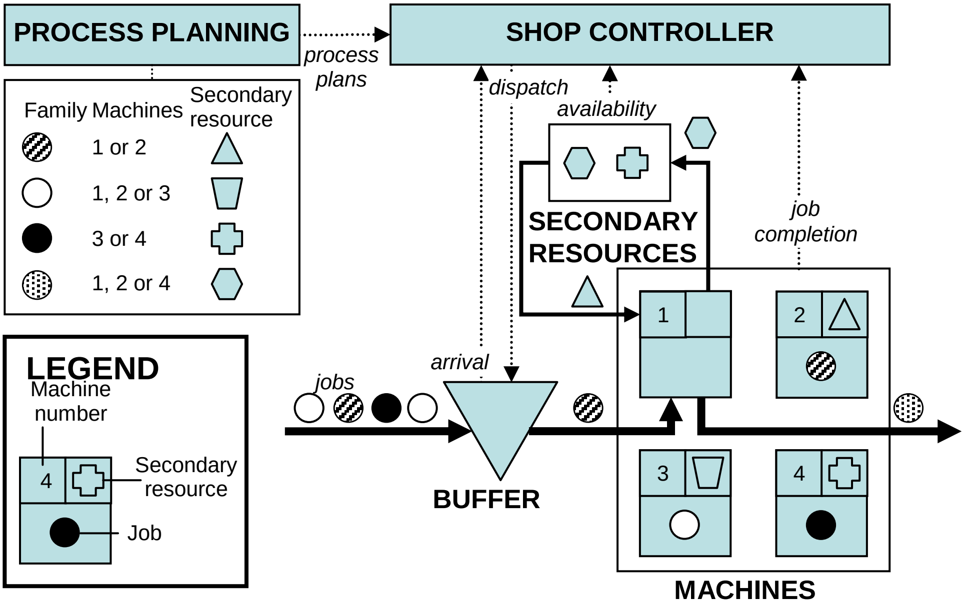


Figure 5.1: Shop model

5.2.2 Shop model

Essential elements that are distinguished in the shop model are a set of machines, a buffer for storing incoming jobs, a buffer for secondary resources, shop control, and process planning (see Figure 5.1). The machines address similar types of operations. However, differences may exist with respect to their capabilities, being expressed in terms of operations' characteristics, making machines fit or unfit for processing specific jobs. Jobs arrive at the shop and are stored in a buffer until their dispatch. This buffer is assumed to have an unlimited storage capacity. Storage of secondary resources that are not in use is modelled by a separate buffer. Process planning is assumed to be an off-line activity. A product's process plan specifies the operations' characteristics, set-up activities, the set of associated machines, and the required secondary resources. Process plans may be dedicated to specific machines. This may follow from, for example, machine capabilities or software characteristics, i.e., the CNC language being applied.

Let us now consider shop elements and their control in somewhat more detail. Each job refers to a product being part of a product family $j \in J$, i.e., a group of products sharing similar manufacturing requirements. Total number of jobs in queue for each family j equals q_j. Machines $m \in M$ are characterized by their capability (r_{jm}=1) or incapability (r_{jm}=0) of handling jobs from a specific product family j. Each product family requires a specific machine set-up. This so-called major set-up is associated with a set-up time $s_{j0,j}$. Length of the set-up time is not influenced by the choice of machine $m \in M$, but is solely determined by the current set-up – for family j_0 – and the required set-up for family j. Obviously, $s_{j0,j} = 0$ for $j = j_0$. Product related, so-called minor set-ups, are assumed to be included in job processing times $(p_{i,j})$, with i identifying individual jobs being available within a family. VCM logic for shop control may be characterized as follows:

- Criterion: As an objective we consider the minimisation of average flow time per job in the long run, so for a large number of jobs (N). Average flow time per job (MFT) is defined as:

$$MFT = \frac{\sum_{j \in J} \sum_{i=1,2,\ldots} ft_{i,j}}{N} \qquad (1)$$

$$\text{with } ft_{i,j} = w_{i,j} + p_{i,j}$$

  In computing flow time for a job i belonging to family j ($fl_{i,j}$) we distinguish between waiting time ($w_{i,j}$) and job processing time ($p_{i,j}$).

- Triggers: Two types of events govern shop dynamics: job arrivals and job completion at one of the machines. Both may trigger a planner for making a decision on job release.
- Decision options: Essentially a few decision options are open for the planner:
  - Switch a machine set-up to meet requirements of another family, and release jobs available for this family following a conventional dispatching rule.

  - Do nothing – wait for a next arrival – in case no jobs are present in the queue, i.e., $q_{j\cdot} = 0$ for all $j \in J$.

Note how the first decision option foresees in the possibility that multiple machines $m \in M$ are set up for the same product family j.

- Decision structure: Rules for family-based dispatching foresee in a two phase approach for decision making. In the first phase the need for changing system set-up is addressed. Important issues to be considered in formulating a dispatching strategy are, whether:
  - An exhaustive strategy should be followed, i.e. postpone decision-making on the choice of family until all jobs available for a family are processed, i.e. until q_j=0. Prior research showed that in most cases an exhaustive strategy is most beneficial for flow time performance (Frazier, 1996; Mahmoodi and Dooley, 1991).
  - Multiple machines $m \in M$ may be set-up for the same job family j simultaneously. Obviously, relevance of this choice is dependent on the availability of alternative machines being able to process the respective job family (r_{jm}=1), and the availability of the required secondary resources.

In case a decision has to be made on the next family for which the system should be set-up, the use of a priority rule is assumed. For example, the well-known First-Come FAMily rule (FCFAM), prioritizes the job family corresponding with the job indicating the largest time in queue (Wemmerlöv, 1992). See Nomden et al. (2006) for an overview of family based dispatching rules.

In the second phase, a job is chosen for release among those jobs available for the family. For this phase conventional dispatching rules are employed, like for example the First Come First Serve rule (FCFS), and Shortest Processing Time rule (SPT). Note how products arriving during processing may force a reordering of the queue – depending on the characteristics of the dispatching rule.

Above we defined essential elements of VCM control logic. Implementation of this logic in terms of a specific choice of rules is discussed in Section 4, where we consider the design of the simulation study.

5.2.3 Research issues

In both case examples discussed above, managers consider possibilities for improving flow time performance of their shop by means of a mid-term upgrade of the production system. They consider investments in process planning, machine upgrades, and secondary resources. Basically, they strive to improve shop performance by increasing pooling synergy of the system by extending the number of alternative machines and secondary resources available for job processing. Their dilemma is their lack of insight into the influence of such investments on system performance—as gains from pooling synergy may be counterbalanced by set-up time effects. We relate the managers' dilemma to three key decisions in configuring routing flexibility:

1. The number of alternative machines available per product family.
2. The distribution of alternatives machines over product families.
3. The number of secondary resources per product family.

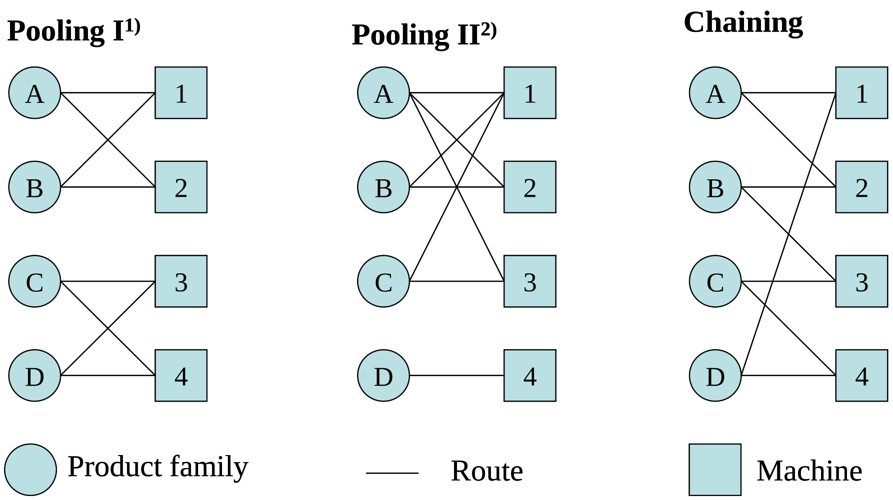
Clearly, these choices are related. For example, the extension of the number of secondary resources (3) only makes sense if the number of alternative machines available per product family is large enough.

5.3 Literature review

The adoption of CM is often not feasible in practice, for financial and technical reasons (Choi, 1996; Johnson and Wemmerlöv, 2004; Waterson et al., 1999). Virtual Cellular Manufacturing (VCM) is often considered a viable alternative for improving shop performance (Hyer and Wemmerlöv, 2002). A widespread implementation of VCM concerns the application of (in)formal family-based dispatching rules in a functional layout (Nomden et al., 2006). Here, jobs from the same product family are grouped for joint processing. Much research focuses on the single machine shop; see Nomden et al. (2007) for an overview. Parallel machine shops—as in our case examples—are considered by Kannan and Ghosh (1996a) and Jensen et al. (1998). They start from the idea of non-hierarchical control, i.e., jobs are stored in a central queue up to the moment of their dispatch. To exploit availability of similar machines they provide control mechanisms that foresee in the possibility of multiple simultaneous set-ups for the same product family. Such a control mechanism involves a trade-off between making use of routing flexibility, and delays caused by additional set-ups. An alternative approach implements the concept of hierarchical control; here job-to-machine allocations are realised at an early stage (Koo et al., 1998). This boils down to a decoupling of machine assignment and job dispatching. Hierarchical control is assumed by, for example, Sheikzadeh et al. (1998), Garavelli (2001) and Tsubone and Horikawa (1999).

Let us now consider key decisions with respect to configuring routing flexibility in a VCM environment, as it is introduced above. A number of researchers address the relationship between the level of routing flexibility, as indicated by the number of alternative routes, and shop performance. Suresh (1991 and 1992) and Suresh and Meredith (1994) consider performance differences between "classical" cellular manufacturing, a functional layout and VCM. Using a combination of analytical approaches and simulation modeling they show that cellular manufacturing only outperforms the other shop environments in case additional measures are taken, such as set-up and lot-size reduction, regular flow, similarity of jobs, less handling etc. Note that this finding clearly stresses the relevance of routing flexibility for shop operation. This is confirmed by Tsubone and Horikawa (1999), who consider a network environment. In their study, increasing routing flexibility always improved performance, despite the presence of family set-ups. However, the respective authors only considered limited routing flexibility. Jensen et al. (1996) suggest that for a parallel shop full routing flexibility can be undesirable in case this results in extensive set-up efforts. Sheikhzadeh et al. (1998) and Garavelli (2001) find that this holds especially for high shop loads. The aforementioned authors seem to unite in that little investment in alternative routes already results in significant performance improvements. The effect of additional efforts may be less clear or dependent on the VCM implementation.

The second issue that is raised in the cases, is the distribution of alternative routes, i.e. the linking of product families to subsets of machines according to a specific pattern, see Section 2. We mention three alternative patterns, see Figure 5.2. It depicts alternative route distributions assuming an equivalent number of routes, i.e. product – machine links. A basic pattern is "pooling". This concept foresees in a subdivision of a set of machines into two or more pools, i.e., groups of machines, that each focus on a distinct subset of product families. Two alternative implementations of pooling are considered. Pooling I assumes subdivision of the available machines into equally sized groups, cf. Jensen et al. (1996) and Suresh (1992). An alternative pattern, Pooling II, is proposed by Suresh (1991). It foresees in the possibility of a number of single machines being dedicated to a distinct subset of product families, and a remainder shop. Such an approach is in line with practice, where conversions between a functional layout and a cellular layout tend to be incremental (Marsh et al., 1999). A third pattern concerns Chaining (Jordan and Graves, 1995). According to the chaining principle each product family is offered two or more alternative machines. Moreover, machines are linked directly or indirectly through product assignments to form a single closed loop. Chaining is studied by Sheikzadeh et al. (1998), Tsubone and Horikawa (1999), and Garavelli (2001). The basic difficulty in interpreting the findings of the aforementioned authors, is that the alternative distribution types have been studied in isolation from each other; this hinders a fair comparison.



$$\text{Level of routing flexibility} = \frac{\text{Realised links-Minimum links}}{\text{Possible links-Minimum links}} = \frac{8-4}{16-4} = \frac{4}{12} = 0.33$$

1) Jensen et al. (1996) 2) Suresh (1991)

Figure 5.2: Alternative distributions of routing flexibility

The relevance of additional secondary resources, such as fixtures, tools or dies, for improving shop performance, has—to the best of our knowledge—received little attention in the context of VCM. The issue has been addressed to some extent for the related field of Flexible Manufacturing Systems (Veeramani et al., 1992). Here the periodic "loading" decision concerns, among others, the grouping and tooling of similar machines, see Shanker and Agrawal (1991) and Tempelmeier and Kuhn (1993). Filling the respective tool magazines with equivalent tools may help to increase pooling synergy for some products, at the possible expense of other products which cannot be processed in the period. However, the effect of set-ups on the investment decision hardly received attention (Gargeya and Deane, 1996). An exception is the work of Melnyk et al. (1989) who observe that control policies that limit the number of set-ups resulted in increased flow times. Remark how this seems not to be in line with research on VCM, which suggests that a reduction of set-ups by product family grouping may result in better flow time performance. According to Ghosh et al. (1992) the difference may be explained by the relatively small set-up to run-time ratio in that study of 0.065. Note that the shop characteristics of both companies introduced in Section 2 may justify ratios that are significantly higher.

In this article we strive for a more comprehensive study on the relevance of routing configuration in VCM environments. This refers both to the gaps observed in literature—where it comes to the single issues of the level and distribution of routing flexibility, and the number of secondary resources—as well as their possible interaction effects on shop performance. Relevant shop characteristics like number of product families, shop load, and set-up-to-runtime ratio are included in the study. Our research vehicle is simulation, which is the dominant method for VCM analysis. This follows from VCM's role as a control concept which hinders queueing analysis, especially for parallel machines (Benjaafar and Gupta, 1999).

5.4 Design of the simulation study

A series of simulation experiments was carried out to study the configuration of routing flexibility within a VCM environment. In this section we discuss the experimental design, and the shop characteristics in terms of fixed, and experimental factors, see Table 5.1. The choice of shop characteristics is motivated by the industrial cases underlying this study, see Section 2, and previous research, see below. We conclude this section by addressing simulation details.

Fixed factors	
Number of machines	4
Family mix	Equal
Inter-arrival time distribution	Negative exponential
Set-up time distribution	2-Erlang
Processing time distribution	3-Erlang (Mean=1.0)
Job selection	SPT
Experimental factors	
Level of routing flexibility (R)	0; 0.33; 0.66; 1.0
Distribution of alternative routes (D)	Chaining; Pooling I; Pooling II
Number of secondary resources (T)	1; 2; 3; 4
VCM configuration (V)	VCM_1; VCM_2; VCM_3
Number of families (F)	4; 16
Set-up to runtime ratio (S)	0.25; 1.0
Mean job inter-arrival times (I)	0.33; 0.44

Table 5.1: Overview of shop configuration, experimental factors and levels

Our design foresees in two series of experiments. In the first series (I), we address the basic issues of configuring routing flexibility in a VCM environment, i.e., the number of alternative routings per job family, their distribution among product families, and the number of secondary resources available to job families.

Moreover, we foresee three distinct VCM implementations. In the second series of experiments (II) we study the way shop conditions, i.e. the set-up to run-time ratio, the number of product families, and the shop load, may influence configurational choices. Note how the separation of experiments in two series and the definition of a limited range for experimental factors—founded on earlier insights in literature, see below—is meant to support an efficient approach in answering the research questions.

For all experiments we consider a shop with four parallel machines, and an unlimited buffer capacity for storing incoming jobs. Differences between machines are restricted to their capabilities of processing specific families of jobs. Jobs arrive according to a negative exponential distribution. Each job belongs to a product family. All product families have an equal share in the product mix. Job processing times are drawn from a third-order Erlang distribution, with average 1. Assumptions with respect to family mix and arrival distribution are in line with most research in this field, see for example Jensen et al. (1996) and (Wemmerlöv, 1992). Secondary resources are dedicated to product families.

Let us now consider experimental factors. In this study we test four levels of routing flexibility (R=0; 0.33; 0.66, and 1.0). Choices of levels are related to our definition of R:

$$
\begin{aligned}
&R = \frac{\left(\sum_{j \in J} \sum_{m \in M} r_{jm} \right) - |J|}{|J| \cdot |M| \; - |J|} \\
&\text{with } r_{jm} = 0,1 \\
&\qquad \sum_{m \in M} r_{jm} \geq 1 \forall \; j \in J \\
&\qquad \sum_{j \in J} r_{jm} \geq 1 \forall \, m \in M
\end{aligned}
\qquad (2)
$$

R concerns the ratio of the existing number of extra links r_{jm}, i.e., those actually creating routing flexibility, to the possible number of extra links between product families and machines. A level of zero corresponds to a situation where each machine is dedicated to a distinct set of product families, i.e., no routing flexibility. The definition of R foresees in a slight adaptation of the definition given by Sethi and Sethi (1990), who consider the number of existing links relative to the possible number of links. Remark how Figure 5.2 illustrates shop layouts with a level of routing flexibility of 0.33. In line with practice we assume that every machine and product is somehow linked. Note how settings for r_{jm} may be used to characterize machine differences.

We consider three distributions of alternative routes (D), as illustrated in Figure 5.2. Distributions follow the concepts of Chaining, and Pooling I as proposed by Jensen et al. (1996), and Pooling II proposed by Suresh (1991), see Section 3. In cases where ambiguity occurred in the process of assigning alternative routes, we assumed the application of the Chaining principle.

The number of secondary resources (T) varies from 1 to 4 per product family. Hence, each product family can be manufactured on 1 to 4 machines simultaneously. We assume the same number of secondary resources being available to each product family.

Three VCM implementations are considered (V). The first VCM implementation adopts the principle of hierarchical control (VCM_1). Here, jobs are assigned to a machine queue upon their entry in the manufacturing system. This is realised by adopting the Work In Next Queue (WINQ) rule, which allocates an incoming job to the machine queue containing the minimum work load, i.e., the sum of the required job processing times (Haupt, 1989). Dispatching decisions are made according to the First-Come Family rule (FCFAM) (Wemmerlöv, 1992). Family priority is set by considering the job in queue with the longest time in queue. Next, we assume available jobs for this family to be released following a Shortest Processing Time (SPT) ordering (Haupt, 1989). If all respective jobs have been processed, a new dispatching decision is triggered. In the second implementation of VCM (VCM_2), jobs are kept in a central queue upon entry in the system. Job dispatching follows the logic of VCM_1. The FCFAM-logic may result in multiple machines being assigned to the same family, as far as the availability of secondary resources permits. Note how machine assignment and job dispatching are linked for VCM_2. The third implementation (VCM_3) is quite similar to VCM_2. However, a coordination mechanism is added which prioritises families for which fewer machines are set up. This rule is inspired by the work of Jensen et al. (1998). They suggest the coordination of machine use by giving priority to families for which no machine has been set up.

The shop load is varied by changing the mean inter-arrival time (I)— 0.33 and 0.44 (underlined values correspond to the first series of experiments). In our basic setting with no routing flexibility, this corresponds to a shop utilisation (including set-ups) of about 0.85 and 0.65 respectively. The set-up to run-time ratio (S)—set at 0.25 and 1.0—equals average set-up time divided by average job processing time.

Set-up times are determined using a 2-Erlang distribution. Many other authors adopt similar settings, see for example Andrés et al. (2005), Frazier (1996), and Russell and Philipoom (1991). The choice for the number of families (F)—4 and 16—is in conformity with many other studies, see for example Jensen et al. (1996) and Marsh et al. (1999).

The software package that was used to carry out the simulation experiments is EM-Plant (EM-Plant TM 7.5, Stuttgart: Tecnomatix). The performance for each heuristic was estimated using the replication deletion method (Law and Kelton, 2000). A total of 30 runs were considered for each experiment. Each run concerned 15 000 jobs. The length of the warm-up period was determined using the Welch procedure (Law and Kelton, 2000). In accordance with the outcomes of the procedure it was set at 500 jobs.

5.5 Analysis of simulation results

In this section we discuss the outcomes of our simulation experiments. In line with the design of our simulation study our analysis of results follows a two-phase approach. First we address the basic issues of configuring routing flexibility for a VCM environment, as we identified them in Section 2 (Series I). We use our findings from the first phase as an input to the second phase, where the influence of shop conditions, i.e., set-up to run-time ratio, the number of product families, and the shop load, on configurational choices is assessed (Series II).

The starting point of our discussion is a four-way Multivariate Analyses of Variance (MANOVA) of the mean flow times and the shop utilisation for Series I, see Table 5.2. The experimental factors concern the elementary decisions on configuring routing flexibility, i.e., the level of routing flexibility (R), the distribution of alternative routes (D), and the number of secondary resources (T). Alternative choices are evaluated for different VCM implementations (V). We checked if any assumption underpinning MANOVA was violated and found no serious problems. MANOVA is robust with respect to minor violations of the underlying assumptions, since we consider equal cell sizes (Hair Jr. et al., 2006). We assumed normality of outcomes since kurtosis and skewness were generally near zero (Lindman, 1974). We refrained from variance reduction techniques, to ensure sample independence; note that this can lead to minor differences in outcome between otherwise similar settings (Law and Kelton, 2000). Significance was tested using Pillai's criterion because this is the most robust one, and it can easily be approximated by an F-statistic (Hair Jr. et al., 2006).

	Multivariate tests				Univariate tests				
						Mean flow-time		Utilisation	
Source	**Pillai's trace**	**df**	**F-value**	**p-value**	**df**	**F-value**	**p-value**	**F-value**	**p-value**
Level of routing flexibility (R)	1.16	6	960.93	<0.01	3	15729.76	<0.01	3553.19	<0.01
Distribution of alternative routes (D)	0.23	4	136.92	<0.01	2	266.71	<0.01	172.14	<0.01
Number of secondary resources (T)	0.51	2	1.068.63	<0.01	1	26.44	<0.01	1450.02	<0.01
VCM configuration (V)	0.89	4	830.54	<0.01	2	6828.81	<0.01	306.83	<0.01
RxD	0.80	12	233.31	<0.01	6	181.02	<0.01	218.08	<0.01
RxT	0.27	6	106.73	<0.01	3	3.45	=0.02	178.76	<0.01
RxV	0.76	12	212.68	<0.01	6	943.35	<0.01	46.11	<0.01
DxT	0.00	4	1.62	=0.17	2	2.83	=0.06	0.95	=0.39
DxV	0.01	8	1.92	=0.05	4	1.94	=0.10	0.75	=0.56
TxV	0.35	4	220.98	<0.01	2	197.10	<0.01	125.27	<0.01
RxDxT	0.02	12	4.26	<0.01	6	4.38	<0.01	1.06	=0.38
RxDxV	0.03	24	2.19	<0.01	12	2.57	<0.01	1.36	=0.18
RxTxV	0.19	12	36.68	<0.01	6	39.07	<0.01	15.14	<0.01
DxTxV	0.01	8	1.29	=0.24	4	1.07	=0.37	2.20	=0.07
RxDxTxV	0.02	24	2.11	<0.01	12	0.65	=0.80	2.63	<0.01
S=0.25; I=0.33; F=16						R^2=0.97		R^2=0.88	

Table 5.2: MANOVA output for Series I (α=0.01)

	R:	0		0.33		0.66		1.0	
V	**D** **T:**	1	4	1	4	1	4	1	4
VCM_1	Chaining	4.115	4.104	3.209	3.010	3.349	3.156	3.589	3.256
	Pooling I	4.157	4.109	3.668	3.660	3.415	3.166	3.571	3.280
	Pooling II	4.097	4.126	3.569	3.512	3.412	3.173	3.582	3.289
VCM_2	Chaining	4.138	4.088	2.485	2.528	2.266	2.423	2.234	2.456
	Pooling I	4.162	4.152	2.887	3.102	2.335	2.490	2.230	2.448
	Pooling II	4.162	4.107	2.948	3.036	2.306	2.437	2.210	2.450
VCM_3	Chaining	4.130	4.128	2.488	2.408	2.252	2.192	2.204	2.176
	Pooling I	4.112	4.110	2.863	2.873	2.357	2.277	2.223	2.170
	Pooling II	4.167	4.121	2.921	2.882	2.325	2.262	2.225	2.173
S=0.25; I=0.33; F=16									

Table 5.3: Series I - Mean flow times

5.5.1 Basic issues in configuring routing flexibility for VCM

The outcomes for Series I are shown in Tables 5.3, and 5.4. They refer to shop performance, i.e., mean flow times, and shop utilisation. The shop is characterised by a set-up-to-runtime ratio (S) of 0.25, a mean inter-arrival time of 0.33 (I) and 16 product families (F). Given these fixed settings, simulation outcomes relate to alternative choices the VCM implementation (V), the level of routing flexibility (R), the distribution of alternative routes (D), and the levels of secondary resources (T). The MANOVA output (Table 5.2) supports analysis of the outcomes (Table 5.3, and 5.4) by identifying the relevant main-effects and interaction effects of experimental factors with respect to system performance.

	R:	0		0.33		0.66		1.0	
V	**D** **T:**	1	4	1	4	1	4	1	4
VCM_1	Chaining	0.85	0.85	0.88	0.90	0.88	0.92	0.89	0.92
	Pooling I	0.85	0.85	0.88	0.89	0.91	0.96	0.89	0.92
	Pooling II	0.85	0.86	0.89	0.92	0.90	0.94	0.89	0.92
VCM_2	Chaining	0.85	0.85	0.87	0.89	0.88	0.90	0.88	0.90
	Pooling I	0.85	0.85	0.86	0.88	0.91	0.93	0.88	0.90
	Pooling II	0.85	0.85	0.89	0.90	0.90	0.92	0.88	0.90
VCM_3	Chaining	0.85	0.85	0.87	0.88	0.88	0.89	0.88	0.89
	Pooling I	0.85	0.85	0.87	0.88	0.92	0.93	0.88	0.89
	Pooling II	0.85	0.85	0.88	0.89	0.90	0.91	0.88	0.89
S=0.25; I=0.33; F=16									

Table 5.4: Series I - Utilisation

The VCM implementation (V) has a large impact on shop performance. The adoption of hierarchical control (VCM_1) results in flow times being up to 40%

worse than for a non-hierarchical control setting (VCM_2, VCM_3). This seems a clear consequence of the decoupling of the assignment and dispatching decisions for VCM_1. VCM_1 “sacrifices” opportunities to reduce the number of set-ups, by assigning jobs to a specific machine without a clear picture on set-up time effects. Note how VCM_1 results in the highest shop utilisation. Obviously, for higher levels of routing flexibility, the effects of this policy may become more apparent (RxV interaction). Remark how Garavelli (2001) reports similar findings. We come back to this point below. Finally, the importance of a coordination mechanism for distributing product families among the machines is clearly expressed. Table 5.3 indicates performance differences of up to 10% for VCM_2 (no coordination) and VCM_3 (coordination).

The level of routing flexibility (R) has a major impact on system performance: higher levels may reduce flow times by about 10–45%. The increased pooling synergy creates opportunities to use otherwise idling machines for productive work. At the same time, this leads to smaller process batches, and therefore, more set-ups. This is clearly reflected in figures for shop utilisation—which increases from 85% up to 92%. Higher levels of routing flexibility clearly suffer from diminishing marginal returns. Most of the performance gains are already reached at a low level of routing flexibility (R=0.33). In some cases high levels of routing flexibility may even result worse system performance, i.e, higher flow times, see the results for VCM_1.

The distribution of alternative routes (D) appears to be particularly relevant for low levels of routing flexibility (RxD interaction). Here Chaining outperforms both Pooling I and Pooling II by 15-20%. For higher levels of flexibility (R=0.66 and above), the performance differences between the chained and pooled distributions diminish. The strength of Chaining lies in the fact that it does not foresee in distinct cells—as in Pooling I and II. Instead it allows for a distribution of the workload over the whole shop. Hence, high peaks in shop load may be spread over all machines.

The main effect of the number of secondary resources on shop performance (T) appears to be small. A likely explanation may be their relative low utilisation levels, up to about 20%. We come back to this point in the next section. Some, interaction effects are, however, noticeable. Clearly, investments in secondary resources only make sense if the level of routing flexibility is larger than zero (RxT interaction), i.e., the number of alternative machines available for a product family is greater than one. Further, the choice of VCM implementation is of relevance (TxV interaction). Relevance of investments in secondary resources is high for shops with a hierarchical control concept (VCM_1). Implementation of this control concept tends to result in additional set-ups following from smaller process batches—see above. Consequently, also the use of secondary resources is increased. Investments in additional secondary resources may answer to this need, and may therefore help to reduce flow times by up to 10%. Where additional resources are helpful in case of VCM_1, increasing the number of secondary resources for VCM_2 may deteriorate performance by up to 10%. A likely explanation may be its lack of a coordination mechanism for machine use by product families. Under these circumstances the number of secondary resources sets a boundary to the number of machines that may be used simultaneously for a single product family. Relaxation of this boundary may result in fragmentation of process batches for specific families, and hence significant set-up time effects. Finally, we found that for VCM_3, improvements from adding secondary resources do not exceed 5%.

	Hierarchical control		**Non-hierarchical control**
	VCM_1	VCM_2 (no coordination of set ups)	VCM_3 (coordination of set-ups)
Level of routing flexibility	- Low level required - Moderate or high levels worsen performance	- Most performance gains realised already for low levels - Gains diminish for higher levels	
Distribution of routing flexibility	Chaining outperforms other distribution types		
Number of secondary resources	Higher numbers result in moderate improvements in mean flow time (up to 10%)	Higher numbers result in worse performance (up to 10%)	Minor improvements for higher numbers (up to 5%)

Table 5.5: Summary of conclusion from Series I

The results make clear that a company may set different priorities for its investments. This depends on a company's current situation, i.e. its current routing flexibility configuration, and the performance gains relative to the associated investments. What is more, investing in routing flexibility also affects operational costs, as can be noticed from the increased shop utilisation. This presents a trade-off, that is not trivial, nor easily comprehended in practical situations (Das and Nagendra, 1997).

In Table 5.5 we summarise the main findings for Series I. The table shows how the configurational choices may influence system performance for alternative VCM implementations.

5.5.2 Shop conditions

Shop conditions vary widely in practice. This is confirmed in our two cases, and also in the literature, see Section 2. In this second series of experiments we study the effects of set-up to run-time ratio (S), the number of product families (F) and shop load (I) on the configuration of routing flexibility. Prior research indicates that these factors are of relevance in a VCM environment (Kannan and Ghosh, 1996a). The simulation results are shown in Table 5.6. Results are only presented for a chained distribution of alternative routes. This is motivated by the fact that this configuration showed superior overall performance in Series I, and our wish to condense the discussion of results.

				R:	0	0.33		1.0			
V	**S**	**F**	**I**	**T:**	1	1	2	1	2	3	4
VCM_1	0.25	4	0.33		2.376	2.354	2.355	2.394	2.366	2.362	2.356
	0.25	16	0.33		4.115	3.209	3.014	3.589	3.334	3.290	3.267
	0.25	16	0.44		2.400	2.029	1.859	2.041	1.765	1.727	1.736
	1.0	16	0.33		8.833	12.023	14.235	22.526	28.147	28.604	29.102
VCM_2	0.25	4	0.33		2.371	2.359	1.818	2.368	1.679	1.725	1.735
	0.25	16	0.33		4.082	2.484	2.519	2.218	2.454	2.413	2.477
	0.25	16	0.44		2.392	1.682	1.637	1.520	1.490	1.487	1.490
	1.0	16	0.33		8.786	7.170	10.077	7.089	12.426	16.989	20.388
VCM_3	0.25	4	0.33		2.368	2.352	1.820	2.392	1.664	1.663	1.659
	0.25	16	0.33		4.110	2.497	2.393	2.211	2.174	2.179	2.185
	0.25	16	0.44		2.387	1.680	1.625	1.511	1.470	1.467	1.463
	1.0	16	0.33		8.960	7.211	7.203	7.079	7.125	7.017	7.022
D=Chaining											

Table 5.6: Effects of shop conditions on mean flow times

The set-up to run-time ratio (S) has a significant influence on performance. This is what one would expect, as it shifts the balance between pooling synergy and set-up time effects for the system. In line with this thinking, higher set-up to run-time ratios would make routing flexibility somewhat less important for realising a good system performance. More concrete: for VCM_2 and VCM_3 the benefits become smaller. For VCM_1 increased routing flexibility can even deteriorate performance. Investments in secondary resources (T) tend to be less interesting for higher set-up to run-time ratios. As the results in Table 5.5 make clear, for VCM_1 and VCM_2, additional secondary resources will hardly contribute to system performance or may even result in worse performance. For VCM_3 no performance gains are found.

For a lower number of product families (F), the relative benefits of additional routing flexibility become smaller (VCM_1), or remain about the same (VCM_2 and VCM_3). However, under these circumstances, the positive effects of investments in secondary resources become notable, see results for VCM_1 and VCM_3. At the same time performance losses for VCM_2 becomes smaller. A likely explanation for these effects may be in the utilisation of secondary resources. Reducing the number of families increases the utilisation of secondary resources up to around 80%. Clearly, offering an alternative for heavily occupied resources may pay-off.

An increase of shop load (I) strengthens the relevance of routing flexibility in order to meet imbalances in the composition of the current shop load, i.e., the work loads per product family. This is clearly reflected in Table 5.6, which shows how the relative performance gains of increased routing flexibility get smaller for lower work loads. However, from a general perspective, this does not violate our findings in the previous section.

In this section we investigated the influence of shop conditions on the configuration of routing flexibility. We found that findings reported in the previous section can be detailed further in the following way:

- An increase of the set-up to run-time ratio reduces benefits of higher levels of routing flexibility. Higher ratios make investments in secondary resources less worthwhile.
- A smaller number of product families reduces the performance gains of higher levels of routing flexibility. However, they strengthen the importance of investments in secondary resources.

5.6 Concluding remarks

Motivated by two industrial cases we studied parallel machine shops that implemented the concept of Virtual Cellular Manufacturing for production control. More in particular, we considered the question how mid-term investments in process planning, upgrades of machinery and secondary resources may improve lead time performance of the shop, thereby building on the increase of routing flexibility. To this end we studied three alternative VCM implementations. The first implementation (VCM_1) assumes the adoption of a hierarchical control concept, according to which machine assignment is decoupled from the dispatching decision.

Alternatively, the second and third VCM implementations (VCM_2, VCM_3) foresee in a suchlike coupling. Typically, this non-hierarchical approach offers more opportunities for set-up time reduction. The distinction between VCM_2 and VCM_3 lies in the addition of a coordination principle for VCM_3 which regulates the number of machines that may be assigned to the same product family.

Our findings on the three VCM implementations indicate that investments should be directed towards:

- Low levels of routing flexibility, i.e., the number of alternative routes per product family. Under these circumstances most of the gains are already realised. Moderate or high levels of routing flexibility do not contribute too much to system performance. It may even result in worse performance, especially in case a hierarchical control concept is implemented. The size of the gains is significantly influenced by the set-up to run-time ratio.
- A chained distribution of routes. Linking all machines through product routings helps the system in dealing with peak loads, as the load may be spread all over the shop.
- The addition of secondary resources in case of a hierarchical control concept, a low number of product families and/or a small set-up to run-time ratio.

Although this research has answered some questions with respect to the configuration of routing flexibility for VCM environments, many interesting directions for further research remain. For example, while our research focused on flow time performance, from a practical perspective it is worthwhile to consider due date and cost related criteria (Van der Zee et al., 1997). Another interesting avenue concerns extensions of the industrial context towards network configurations (Van der Zee, 2002; Corti and Portioli-Staudacher, 2004).