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### Virtual cellular manufacturing

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## Conclusions and issues for future research

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The first section of this chapter summarises the conclusions drawn from this thesis. The second section discusses several issues that would benefit from further research.

### 7.1 Conclusions

Group Technology, and its application in Cellular Manufacturing, has received considerable attention from researchers and practitioners. Following the difficulties in implementing Cellular Manufacturing in practice, the interest in Virtual Cellular Manufacturing has increased. With Virtual Cellular Manufacturing, a group of resources is dedicated to manufacturing a part family, but the original functional shop floor layout is retained. The cells only exist in the planning and control system, and this retains flexibility under changing demand conditions. Virtual Cellular Manufacturing is a relatively new, but growing, field that offers numerous research opportunities. The research presented in this thesis addresses 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.*

These two objectives are worked out in six research questions related to Virtual Cellular Manufacturing (I: RQ1-2, II:RQ3a-d).

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

Chapter 2 contains the answers to this research question in a review of 25 years of research into Virtual Cellular Manufacturing. The survey distinguishes between three streams of research of which the first focuses on designing Virtual Cells on the basis of routing information. The second stream concerns Virtual Cellular Manufacturing realised through family-based dispatching heuristics. The third stream focuses on empirical research, i.e. case studies and industrial surveys. In

terms of the design and operation of Virtual Cells, the following conclusions can be drawn:

- Analytical and simulation models point towards there being a generalised range of parameters (e.g. set-up times, lot-sizes) for single-resource constrained systems, in which Virtual Cellular Manufacturing outperforms both Cellular Manufacturing and a Functional Layout, see Section 2.5.
- The impact of labour-related factors on the performance of Virtual Cellular Manufacturing has largely been ignored, therefore additional research of labour-constrained systems is needed.
- Material handling aspects and alternative layout types, such as fractal cells and holonic layouts, could be considered in combination with Virtual Cellular Manufacturing, see Section 2.3.2.
- More proactive forms of Virtual Cellular Manufacturing, such as the use of information on future job arrivals in family-based dispatching heuristics, could be developed and tested in simulation models, see Section 2.5.3.

Turning to previous empirical research (i.e. case studies and industrial surveys) into Virtual Cellular Manufacturing, the following conclusions can be drawn:

- The few industrial surveys and case studies do show that Virtual Cellular Manufacturing is successfully applied in practice.
- Additional and more rigorous empirical research is needed to better understand the industry reality surrounding Cellular Manufacturing (conventional and virtual), especially to expose reasons that prevent companies from adopting traditional Cellular Manufacturing, see Section 2.6.3.

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

Chapter 3 responds to the second research question. Two basic principles for the application of Group Technology are distinguished: (i) exploiting processing similarities and (ii) exploiting routing similarities. These principles are explored further by analysing three case studies based in small-batch discrete parts manufacturing companies. These case studies demonstrate the applicability of both Group Technology principles (see Sections 3.5.1 & 3.5.2):

- The principle of ‘exploiting processing similarities’ can successfully be

applied in process planning, lot-sizing decisions, order release and family-based dispatching.

- The principle of ‘exploiting routing similarities’ can be applied through the establishment of permanent physical cells, dynamic cells or virtual cells.

However, contextual factors may hinder the effective implementation of Group Technology principles (see Section 3.5.3). The most significant factors to consider are:

- The manufacturing equipment in use can represent the largest barrier to applying the ‘exploiting routing similarities’ principle, because often machines cannot sensibly be moved and co-located in manufacturing cells.
- The available information technology may not provide the necessary information for family-oriented planning and dispatching, e.g. a clear overview of tooling requirements to realise set-up time savings.
- Organisational constraints may hinder the creation of autonomous sub-units, i.e. (Virtual) Manufacturing Cells, because capacity (e.g. workers, machines) cannot be split and redistributed to various cells.

Both the literature review and the case studies have identified several opportunities for relevant research on Virtual Cellular Manufacturing. This thesis focuses on one of these opportunities: the development and use of heuristics for family-based dispatching. A strong motivation for this decision is the observation, made in the case studies, that family-based dispatching heuristics are used in industrial practice. However, until now the development of heuristics has not been approached in a very systematic way and, perhaps surprisingly, this situation is, to some extent, reflected in the research to date. This leads to our remaining research questions.

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

Chapter 4 addresses this research question. The analysis of existing studies has shown that:

- Most family-based dispatching rules are constructed according to a weighted shortest processing time scheme (WSPT) and variants thereof, using set-up and processing times to represent workloads, and queue lengths as a weighing factor.

- Family-based dispatching rules can be adapted according to the WSPT scheme to make use of information on near-future job arrivals.
- Two additional rules are proposed to fill the gaps that have been identified by our analysis, namely Minimum Average Set-up time (MAS) rule and the maximum Set-up time and WORK content (SWORK) rule, as explained in Section 4.4.2.

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

This research question is also treated Chapter 4, this time through a simulation study of a single-machine shop. The experimental factors considered in this simulation study include the family-based dispatching rules used and the use of forecast data on jobs about to arrive at the shop. The family-based dispatching rule has a significant effect on throughput time performance:

- The best results are obtained using the MAS rule (Minimum Average Set-up time) and the MASP rule (Minimum Average Set-up and Processing time), see Section 4.4.5.
- The favourable performance of these rules may be explained by their strong focus on reducing the total time spent on set-ups, as well as their similarity to the Shortest Processing Time rule (SPT).

The use of information on future job arrivals can improve shop performance significantly, see Section 4.5.5:

- Most of the benefits of using forecast data stem from the possibility of starting set-ups prior to the actual arrival of a job, in this way set-up delays on throughput times are reduced.
- A smaller number of benefits relate to more accurate family priority settings, as a accurate prediction of actual process batches is obtained in advance of dispatching.
- Most of the benefits of incorporating forecast data occur when shop loads are low to moderate; here, a relatively short forecast horizon suffices, and there is little impact from forecast errors, see Section 4.4.5.

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

Chapter 5 provides the answer to this research question through a simulation study of a shop that contains four parallel machines. Each arriving job requires processing at one of these machines. Routing flexibility determines which job families can be processed by which machines; more than one machine may be capable of processing jobs from a specific family. More precisely, routing flexibility in this shop concerns 1) the number of alternative routes for jobs, 2) the distribution of these alternative routes (i.e. which product families can be processed by which machines), and 3) the number of family-specific secondary resources (e.g. tools, dies) which can be shared among the machines. Control strategies of the shop are used to assign jobs to machines within the limits of routing flexibility. A hierarchical control strategy assigns a job to a suitable machine as soon as it arrives in the shop, regardless of existing job assignments from the same family. Family-based dispatching is used at the individual machines to reduce the number of major set-ups needed. With a non-hierarchical control strategy, jobs are only allocated to a suitable machine at the last possible moment, by applying family-based dispatching to each machine; a job remains available for all suitable machines until it is finally dispatched.

The alternative shop control strategies have a large impact on shop performance:

- A hierarchical control strategy results in throughput times being significantly worse than for a non-hierarchical control strategy. The assignment of jobs to machines, regardless of existing assignments of jobs from the same family, may result in many machines (simultaneously) requiring set-ups for the same product family.
- A non-hierarchical control strategy may be preferred, because it minimizes short-term load variations between machines, reduces the time spent on set-ups in the entire system and reduces the time jobs have to wait for secondary resources to become available.

The presence of routing flexibility affects performance significantly:

- Low levels of routing flexibility are sufficient to yield most of the potential gains; the smaller (larger) the set-up to run-time ratio, the larger (smaller) is the extent of the improvement.
- Distributing routes according to the principle of chaining is preferable to the creation of machine pools. Since all machines are linked directly or indirectly in a single closed loop of overlapping capabilities, chaining offers more

options in spreading peak loads over the entire shop (see Section 5.5.5). This effect is relevant under conditions of intermediate routing flexibility, i.e. when there is at least some, but not complete, routing flexibility.

- Duplicating secondary resources (e.g. tools, dies) is most beneficial when using a hierarchical control concept in conjunction with a small number of product families and/or a small set-up to run-time ratio (see Section 5.5.5).
- When a hierarchical control concept is applied in a situation with moderate to high levels of routing flexibility, performance may even deteriorate, because multiple machines may simultaneously require a set-up for the same product family. This increases the time spent on set-ups as well as the time jobs have to wait for the appropriate secondary resources to become available, see Section 5.5.5.

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

This question is answered through simulations of a small ‘machine-limited’ manufacturing cell and of a ‘dual resource constrained’ manufacturing cell. In the latter configuration, there are fewer workers than machines. The simulations are used to assess the impact on cell throughput time performance of the specific machine to which family-based dispatching is applied. Other experimental factors considered are load variations between machines and job routings. The outcomes for a three-machine job shop cell indicate that:

- The application of family-based dispatching (as against a conventional dispatching rule) to a machine results in better mean throughput times at that specific machine, especially when it concerns the machine with the highest load.
- Applying family-based dispatching to one specific machine in a machine-limited shop may result in increased waiting times at subsequent machines, if jobs processed within the same machine set-up also have the same remaining routing. This happens because the job arrival pattern at those subsequent machines becomes less regular compared to a situation where a conventional dispatching rule is used.
- In a dual resource constrained shop, the positive effects of applying family-based dispatching to a machine are both local (less set-ups required at that

machine) and global (increased worker availability for all machines), see Section 6.6.4.

- The results further indicate that applying family-based dispatching in a dual-resource constrained shop delivers larger time savings in terms of overall mean throughput than in a comparable machine limited shop. Hence, family-based dispatching is applicable to a dual-resource constrained shop without (most of) the drawbacks that occur in a machine-limited setting.

This thesis shows how Virtual Cellular Manufacturing, realised through family-based dispatching, can be used to improve the throughput time performance of a number of basic shop configurations. Based on the conclusion from the previous section, several more general conclusions can be drawn in relation to Virtual Cellular Manufacturing:

- Most benefits of Virtual Cellular Manufacturing are obtained with elaborate control strategies. However, good results are still attainable with relatively simple, locally applied family-based dispatching heuristics.
- Secondary resources, such as the tools and workers that are needed for machines to operate, play an important role in the performance of Virtual Cellular Manufacturing. Their availability influences the time spent on set-ups as well as the time jobs and machines have to wait for the appropriate secondary resources to become available.
- When Virtual Cellular Manufacturing is applied locally to realise set-up savings, the resulting local benefits do not necessarily turn into global benefits, if it leads to highly variable flows of jobs through a manufacturing system.
- The case studies of this thesis have formed an important reference for the simulation studies that followed, in an attempt to bring the theory and practice of Virtual Cellular Manufacturing together. The findings of this thesis, especially those relating to family-based dispatching, are therefore considered to be relevant to many small-batch discrete parts manufacturers.

## **7.2 Issues for future research**

In this section, we discuss several issues appropriate for further research. These issues concern some of the interesting and relevant topics that were identified during the literature review and case studies, but which have been left untouched, as well as ideas to extend or shift the research focus.



Virtual Cellular Manufacturing builds on the notion that a manufacturing system has a physical and a logical design (Nof 1982, Montreuil and Nof 1988). With Virtual Cellular Manufacturing, a process oriented physical design is operated according to a product oriented logical design. Other papers, that may well fit this broader notion of a physical and a logical design, have been excluded so far because they used a different terminology than our search terms. For example, Lee et al. (1994) reported on the implementation of a pull-system for a selection of high-volume products within an actual job shop where the associated resources were treated as a virtual flow shop. Future research on Virtual Cellular Manufacturing could be extended to include this and similar studies.

The chosen focus for all the simulation studies in this thesis is on throughput time performance (chapter 5 also includes resource utilisation). While important, this may be a limited interpretation of relevant performance aspects in a practical context. Although throughput time reduction can reasonably be considered as a strategic goal, at the operational level other time-related performance measures may also be relevant. For example, not only the mean but also the variation in throughput times, as well as resource utilisation, could be analysed in future simulation studies. These parameters may be used to reflect respectively due date performance and efficiency.

The role of the layout of manufacturing systems is likely to be relevant for the performance effects of Virtual Cellular Manufacturing, but it is not explored in this thesis. A particularly relevant layout aspect refers to the access to the information needed for the planning and execution of activities. A physical cellular layout may enable a better overview of the state of all activities (i.e. visual management) than when the cell is created virtually. This particularly refers to the timeliness, accuracy and completeness of the information. A physical cellular layout may allow for more favourable planning and control decisions because individual activities can be more easily geared to one another. This may ultimately lead to shorter throughput times through an improved synchronisation of related activities and reduced set-up times. For example, the anticipation of near-future job arrivals, which has been studied in Chapter 4, allowed set-up activities to be started prior to the actual job arrivals; such near-future job arrivals may be predicted with relative ease inside a physical cell. In contrast, the dispersed nature of resources in Virtual Cellular Manufacturing may create a need for extensive investments in information systems to achieve a similar overview of shop floor status (Hyer and Brown 1999). Future research could address these different information positions and might even propose specific information systems for Virtual Cellular Manufacturing.

This thesis has studied the role of set-up times in the context of manufacturing systems. The findings apply directly to small-batch discrete parts manufacturing and to other manufacturing systems involving set-ups as well. In this manufacturing context, set-ups are needed to physically prepare a machine for a new job that differs from the previously processed one. In intellectual work, also referred to as white-collar work, a similar set-up effect may be observed in the form of learning effects (Hopp et al. 2009). For example, the execution of a new type of task may require extensive study and preparation by a worker and much less so for a recurring task. The management of intellectual work therefore involves similar trade-offs as the ones that were studied in thesis. The insights and heuristics developed in this thesis may form a starting point to study the management of learning effects in white-collar work environments.

