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Problem specific heuristics for group scheduling problems in cellular manufacturing

Dissertation

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by

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Whatever is found in my life was done by grace
Whatever is missed in my life is compensated by grace.

H. Bezzel

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Janis Neufeld, Dresden, July 2016

Contents

List of Figures

List of Tables

List of Abbreviations

ANOVA	Analysis of variance
APT	Average processing time rule
CM	Cellular manufacturing
CMS	Cellular manufacturing system
CMD	Constructive group scheduling heuristic by Schaller
DK	Dynamic due dare based heuristic
EDD	Earliest due date rule
FCFS	First come first serve rule
FSP	Flowshop scheduling problem
GT	Group technology
IH'D	Constructive group scheduling heuristic
MJ	Most jobs rule
MS	Minimum setup time rule
MW	Most work rule
MWKR	Most work remaining rule
MIP	Mixed integer programming model
NEH	Constructive heuristic by Nawaz/Enscore/Ham
PCB	Printed circuit board
RER	Relative error rate
RPD	Relative percentage deviation
SDST	Sequence-dependent setups
SIST	Sequence-independent setups
SPT	Shortest processing time rule
SL	Slack rule
$\bar{\text{S}}$L	Mean slack rule
TSPT	Two class truncated shortest processing time rule
TWK	Total work content technique
VNS	Variable neighborhood search

List of Symbols

Chapter 6

C_j	Completion time of job j
d_j	Due date of job j
e	Index for part families
f	Index for part families
F_T	Testing value concerning influencing factor T
$\bar{F}$	Mean flow time
i	Index for machines
j	Index for jobs
K	Constant parameter
m	Number of machines
n	Number of jobs
n_{ei}	Number of jobs in waiting queue of family e before machine i
r_j	Release time of job j
s_{fei}	Setup time for a changeover from family f to family e on machine i
SL_{jei}	Slack of job j from family e on machine i
SS_T	Total spread concerning influencing factor T
SS_E	Spread of errors
$\bar{T}$	Mean tardiness
t_{ji}	Processing time of job j on machine i
u	Index for machines
WS_{fi}	Waiting queue of part family f in front of machine i

1 Introduction

1.1 Motivation

In the beginning of the 20th century, mass production was seen as ideal manufacturing philosophy to ensure long-term corporate success[1]. Nowadays, however, the prevalent demand for customized products has led to a paradigm shift towards flexible production systems.[2] In order to master the challenges of producing individual products and, at the same time, providing an increasing productivity, various manufacturing concepts have been developed and implemented within the last centuries. Among these, group technology (GT) as well as cellular manufacturing (CM) have had great influence on the effectiveness and efficiency of small batch size production systems.[3] The main idea of group technology and cellular manufacturing involves a subdivision of a production system into smaller groups of machines that produce certain sets of parts. In doing so the advantages of flow production, on the one hand, and job shop manufacturing, on the other hand, are intended to be attained. As in all production environments, a critical function for a cellular manufacturing system's operational efficiency is the scheduling task of assigning and sequencing jobs to limited resources. Despite its widespread practical relevance, however, scheduling problems in cellular manufacturing have been studied only since the 1990's extensively. Figure 1.1 displays the of development scheduling literature in flowshop manufacturing cells showing a still increasing number of publications since then. Research revealed that an integration of characteristic conditions in cellular manufacturing, such as part families and setup times, is of particularly high relevance for the applicability and effectiveness of scheduling approaches.[4] At the same time, the consideration of additional characteristics usually leads to more complex problems that cannot be solved optimally for realistic problem instances. Hence, the application of heuristic and metaheuristic algorithms is indispensable. This work in hand intends to provide novel algorithms for scheduling in manufacturing cells on the basis of a profound

[1] See Pine (1999): *Mass customization*, p. 5.
[2] See Duguay / Landry / Pasin (1997): *From mass production to flexible production*, p. 1188.
[3] See Gunasekaran et al. (2001): *Experiences in design and implementation of cells*, p. 222.
[4] See Allahverdi / Soroush (2008): *The significance of reducing setups*, p. 979.

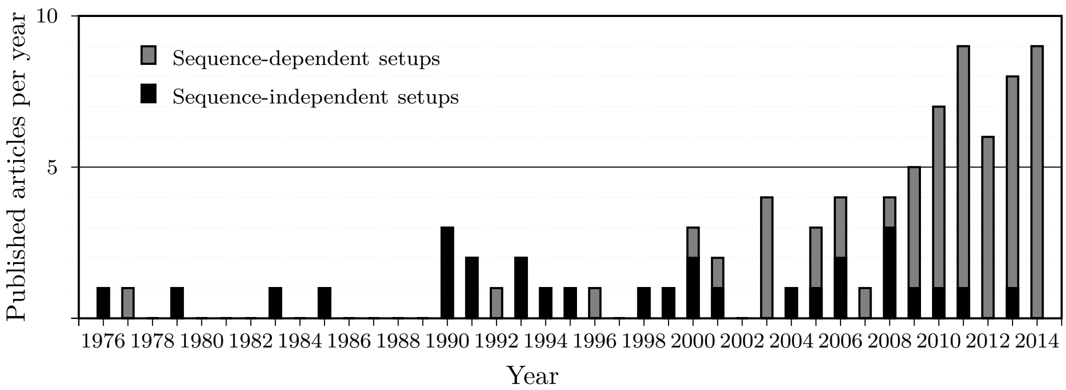

Figure 1.1: Publications on group scheduling problems in flowshop cells[5]

analysis and understanding of the considered problem. In doing so, the requirements on scheduling systems in these production environments are attempted to be met more appropriately.

1.2 Basics of scheduling in cellular manufacturing

Group technology is defined as "a manufacturing philosophy that identifies and exploits the underlying sameness of parts and manufacturing processes"[6], whereas cellular manufacturing is referred to as implementation of group technology in manufacturing environments[7], which is group technology's major application[8]. Following this idea, in cellular manufacturing systems (CMS) all resources are assigned to smaller organizational units referred to as manufacturing cells, each producing certain sets of products called part families. Since part families are mainly formed according to the required tools, machines and operations, the parts in each cell bear resemblance to each other, which leads to a minimization of setup costs. As each manufacturing cell is supposed to work autonomously a significant simplification of material flows can be gained. Through a team's responsibility for a limited set of parts, production control can be organized within each cell autonomously. As a result, an improved operator expertise is gained, which leads to more reliable production processes with lower rework costs and improved quality. Furthermore, by the application of group technology and cellular manufacturing

[5] Own figure based on Neufeld / Gupta / Buscher (2016): *A comprehensive review of group scheduling*, p. 6.
[6] See Ham / Hitomi / Yoshida (1985): *Group technology*, p. 7.
[7] See Wu / Chung / Chang (2009): *Hybrid simulated annealing algorithm to the cell formation problem*, p. 3652.
[8] See here and in the following Neufeld / Gupta / Buscher (2016): *A comprehensive review of group scheduling*, pp. 1–4.

lower stocks, shorter throughput times, decreased material handling and production costs can be achieved.[9] Thus, cellular manufacturing is especially advantageous for systems with complex material flows with a high level of automation like flexible manufacturing systems.

In order to ensure a successful implementation of cellular manufacturing systems three major planning steps are necessary, that differ from tasks in traditional production environments: cell formation, cell layout and scheduling.[10] The cell formation problem implies the grouping of machines to manufacturing cells as well as the formation of part families and their assignment to cells. This process is illustrated for a simplified example in Figure 1.2. Usually, part families are formed according to the required operations and machines. Additionally, due to varying setup configurations part families are often subdivided into sub-families or tooling families, each of which requiring a certain setup. Based on the results of cell formation, a layout problem has to be solved by positioning manufacturing cells in the shop floor and all machines within each cell. Both, cell formation as well as the cell layout problem have received abundant attention in literature.[11] Finally, despite its rather operational character, an effective scheduling system is crucial in order to gain the advantages of cellular manufacturing and is therefore the center of attention in this thesis.

The scheduling task in manufacturing cells is characterized by the allocation and sequencing of all necessary processes to limited resources in order to optimize a given objective function. By assigning part families as a whole to a certain cell, job shop environments, where jobs may follow different machine sequences, can often be transformed to flowshops, where all jobs require the same machine sequence. Despite this simplification of material flows, the scheduling task within each manufacturing cell still typically results in a complex sequencing task on two levels. On the first level, a sequence of parts within each part family has to be identified, which is called a job sequence. On the second level, a family sequence is determined, preferably an optimal sequence of part

[9] See Askin / Iyer (1993): *A comparison of scheduling philosophies*, p. 447; Snead (1989): *Group technology*, pp. 20–21.

[10] Notwithstanding, Franca et al. list cell loading instead of cell layout as a major planning task. However, the cell loading problem is most of the time included into the cell formation problem, as it comprises the assignment of part families to cells; cf. Franca et al. (2005): *Evolutionary algorithms for scheduling a flowshop manufacturing cell*, p. 492; see here and in the following Neufeld / Gupta / Buscher (2016): *A comprehensive review of group scheduling*, pp. 1–2.

[11] See Papaioannou / Wilson (2010): *The evolution of cell formation problem methodologies*; Wu / Chung / Chang (2009): *Hybrid simulated annealing algorithm to the cell formation problem*; Kia et al. (2012): *Solving a group layout design model of a dynamic cellular manufacturing system.*

[12] Own figure based on Neufeld / Horn / Buscher (2014): *Maschinenbelegungsplanung mit Teilebewegungen*, p. 60.

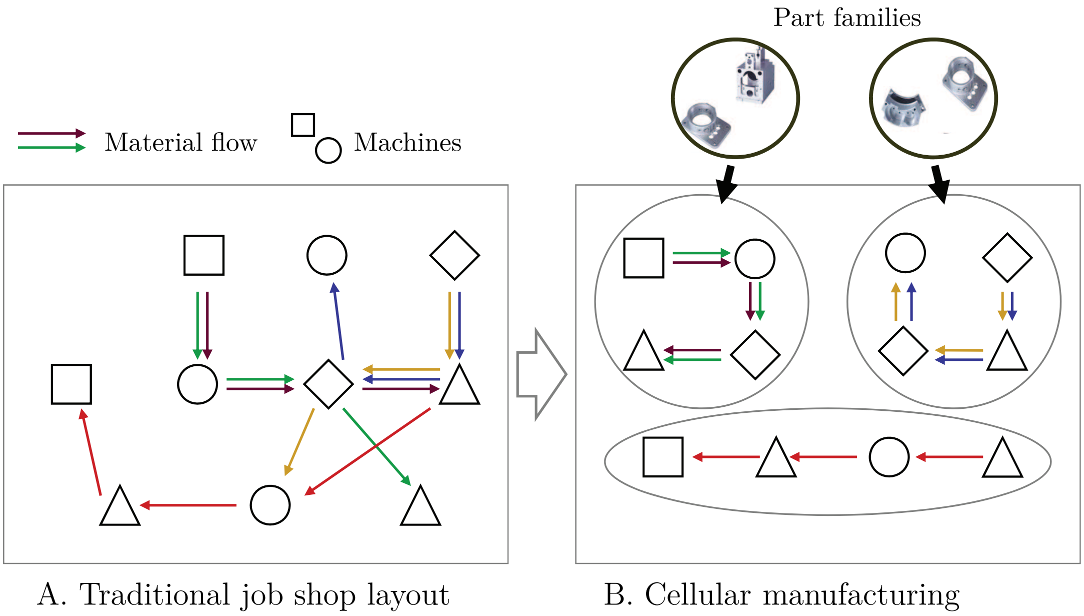

Figure 1.2: Simplified example for the basic idea of cell formation[12]

families or tooling families (sub-families) respectively.[13] Together all job sequences and the family sequence form a group schedule.

Usually, sequence-independent or negligible setup times occur for a changeover from one job to another within a part family. Hence, these can be included into the processing times. However, sequence-dependent or sequence-independent major family setup times, which arise from a changeover of part families and the involved change of tooling, have to be regarded separately from processing times.[14] In order to gain the advantages of a simplification of material flows and a minimization of setup times, the *group technology assumption* is commonly established, i.e. all parts of a part family (or sub-family respectively) are sequenced exhaustively on all machines without being interrupted by operations from jobs belonging to other families. This characteristic is a significant difference compared to classical scheduling problems. With this, the sequencing problem of jobs and part families on two levels in cellular manufacturing is referred to as *group scheduling problem*.

Since solving group scheduling problems requires specific solution algorithms, several approaches have been presented in literature. Except for the two-machine makespan group scheduling problem with sequence-independent setups, all basic static group scheduling problems with more than two machines considered in literature are known to be NP-hard in the strong sense regarding different optimality criteria.[15] Hence, nearly all group

[13] See Logendran (1998): *Group technology and cellular manufacturing*, p. 154.
[14] See Allahverdi / Soroush (2008): *The significance of reducing setups*, p. 979.
[15] See Gupta / Darrow (1986): *The two-machine sequence dependent flowshop scheduling problem*,

scheduling research focuses on methods solving this problem heuristically.

1.3 Purpose and research questions

The development of heuristic and metaheuristic approaches has recently been a very dynamic area of research in the field of operations research. Generic heuristics generally were shown to be incapable of attaining best performances regarding their effectiveness compared to individually adapted applications.[16] Group scheduling problems, however, have often been solved with slightly adjusted algorithms that had originally been developed for scheduling problems in traditional manufacturing systems.[17] Even though these approaches frequently led to promising results, it still remains an open question whether these algorithms adequately take the distinct characteristics of scheduling manufacturing cells into account. Hence, this thesis focuses on different aspects of scheduling in cellular manufacturing systems by presenting novel, problem specific solution approaches. However, for an appropriate development of procedures a thorough analysis of the considered problem is crucial. Thus, an extensive study of literature on the scheduling task arising in cellular manufacturing systems and the group scheduling problem in particular as well as its specific characteristics provides the basis for further considerations. In the course of this, some assumptions commonly adopted in manufacturing cells, namely the group technology assumption and the necessity of processing every job on each machine, are questioned. This facilitates a deeper understanding of the studied problem and allows additional insights into the scheduling task in cellular manufacturing.

Depending on a manufacturing system's general conditions and the allowed planning time the requirements for a scheduling system vary considerably. While in unstable and dynamic environments easy-to-implement dispatching rules are widely used, static constructive heuristics or metaheuristic approaches are applicable in more steady production systems. For a comprehensive discussion of the scheduling task in a certain environment it is, therefore, necessary, on the one hand, to consider constructive as well metaheuristics algorithms and, on the other hand, to evaluate state-of-the-art dispatching rules in simulation studies. The major purpose of this work is to point out the specific characteristics and requirements of the group scheduling problem in these different environments and to find ways to integrate this problem specific knowledge in the procedure of effective solution algorithms. With this, the purpose of this work can be summarized in the

p. 441; Kleinau (1993): *Two-machine shop scheduling problems with batch processing*, pp. 56–58.

[16] See Talbi (2009): *Metaheuristics*, p. 78.

[17] E.g. Schaller (2000): *A comparison of heuristics for family and job scheduling* and Schaller / Gupta / Vakharia (2000): *Scheduling a flowline manufacturing cell.*

following five research questions:

Q1: What is the current state of research for flowshop group scheduling problems?

Q2: How can constructive heuristics be improved by integrating problem specific enhancements, that take the characteristic structure of group schedules into account?

Q3: Can a relaxation of the group technology assumption lead to significant improvements of the solution quality for group scheduling problems?

Q4: Does the existence of missing operations in manufacturing cells require adjusted heuristic algorithms in order to gain good quality solutions?

Q5: Can state-of-the-art dispatching rules and heuristics be applied to dynamic cellular manufacturing systems and improve the performance of a scheduling system?

1.4 Structure of this work

In order to answer the proposed research questions five main chapters, each of which representing published or submitted manuscripts by the author and focusing on problem specific aspects of scheduling cellular manufacturing systems, are summarized to this thesis. The general structure and the connection between the different parts of this work is illustrated in Figure 1.3.

Forming a basis for the following chapters, the literature review in **Chapter 2** gives an overview of the current state of research on flowshop group scheduling problem answering research question **Q1**.[18] Despite a still growing number of publications[19], neither a consistent definition of flowshop group scheduling problems nor a comprehensive literature overview have been published so far. To close this gap a detailed problem definition, a differentiation from related problems and the commonly used solution representation are presented. In the following, the development of publications over the last years is analyzed. Relevant literature is classified into three categories based on the historical development of group scheduling publications: first, simulations studies, that have been prevalent in the early 1990's, second, static flowshop group scheduling problems in autonomous manufacturing cells, which the major part of publications focuses on, and finally, cell scheduling problems considering multiple cells. The analysis of literature is concluded with fruitful directions for future research.

[18] Chapter based on Neufeld / Gupta / Buscher (2016): *A comprehensive review of group scheduling*.
[19] Cf. Figure 1.1.

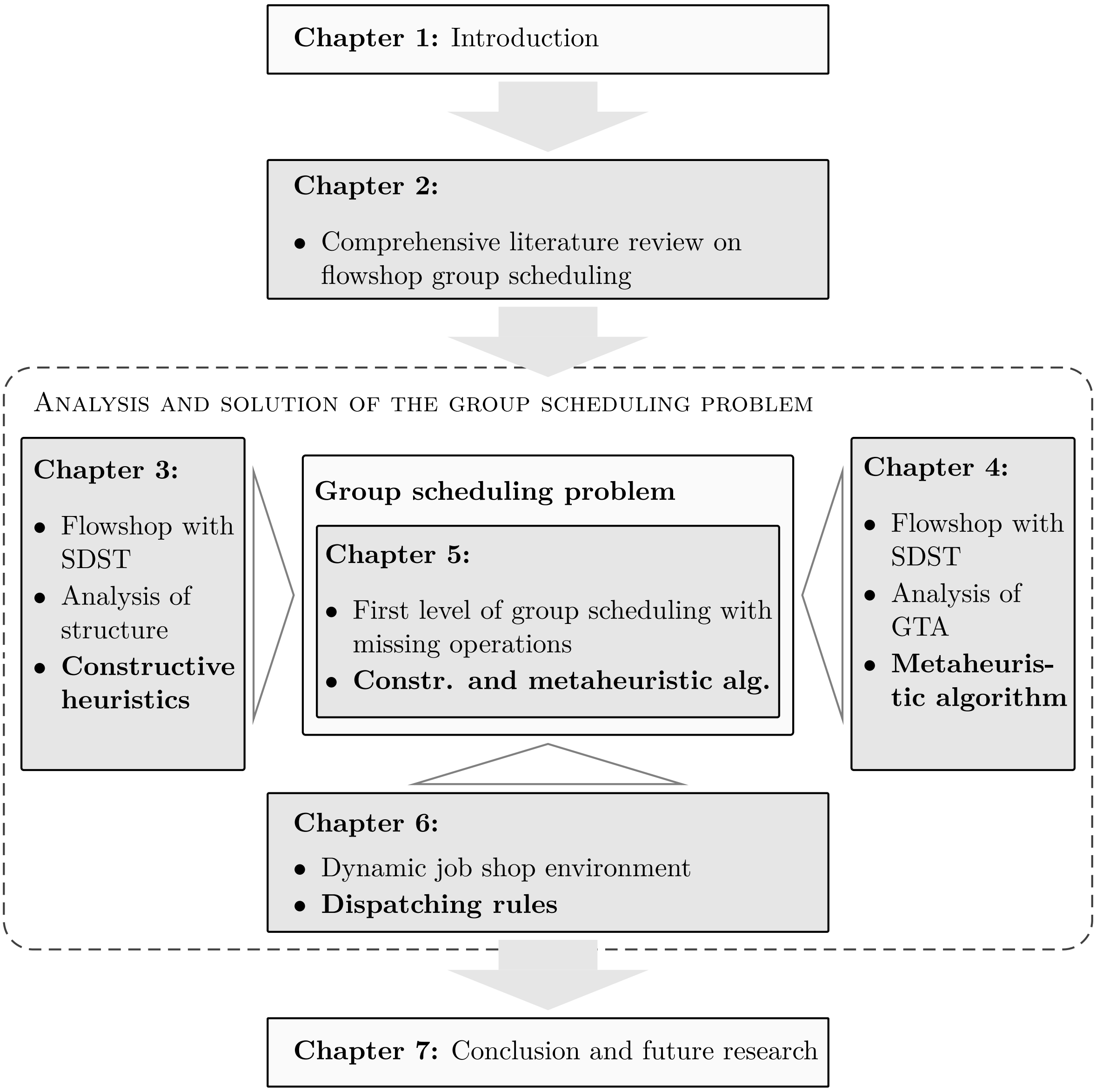

Figure 1.3: Structure of this thesis

Considering questions **Q2** to **Q5**, the following chapters discuss different methods to approach the scheduling task in cellular manufacturing systems: As it is shown in Chapter 2, the classical group scheduling problem with sequence-dependent setup times and makespan objective has been studied widely already. Nevertheless, only few heuristics have integrated problem specific characteristics into their procedures. Hence, based on the modeling of part families as jobs with times lags, the structure of group schedules with low makespan is analyzed and illustrated for an example in **Chapter 3**.[20] The idea of minimizing inserted idle time within each family is compared to a minimization of

[20] Chapter based on Neufeld / Gupta / Buscher (2015): *Minimizing makespan in flowshop group scheduling using inserted idle times.*

makespan for each family by integrating these findings in the procedure of several NEH based constructive algorithms. The influence of this problem specific modifications is tested for well known benchmark instances of the group scheduling problem and compared to the best performing constructive algorithms in literature so far. This provides an answer to research question **Q2**.

Chapter 4 presents variable neighborhood search (VNS) based algorithms for the group scheduling problem.[21] The metaheuristic of VNS has shown promising results for various scheduling problems but has not been applied to this problem before. The impact of the group technology assumption, which is a characteristic aspect of the group scheduling problem, is discussed and questioned using an illustrative example. In order to test the theoretical conclusions, a split processing of part families is enabled by using new definitions of neighborhood structures within the VNS algorithm, which is referred to as non-exhaustive group scheduling. Following research question **Q3** the exhaustive as well as non-exhaustive VNS metaheuristics are applied for several test instances and compared concerning their effectiveness and efficiency.

A typical characteristic emerging on the first level of flowshop group scheduling, the existence of missing operations, is discussed in **Chapter 5**.[22] Generally, in flowshop scheduling it is assumed that all jobs have to be processed on every machine. However, especially in manufacturing cells where several similar, but still differing, parts have been grouped to part families, it is common that individual jobs may not have to visit certain machines. Hence, flowshops with missing operations are examined in order to answer research question **Q4**. In literature, missing operations are often treated with processing times of zero, while at the same time solutions methods for traditional flowshops without missing operations are applied. The results of Pugazhendhi et al.[23], however, already indicated that an explicit consideration of missing operations for the development of algorithms can improve the performance of constructive heuristics in manufacturing cells. Based on the constructive NPS-set heuristic by Pugazhendhi et al. a constructive heuristic as well as two simulated annealing algorithms are developed that explicitly integrate the existence of missing operations in their procedure. The simulated annealing algorithms represent the first metaheuristic approaches in literature that consider flowshops with missing operations explicitly. For configuring the metaheuristic algorithms a full factorial design of experiments approach is used. A minimization of total flow time is considered as objective function. Since no benchmark instances exist for this specific

[21] Chapter based on Neufeld (2011): *Group scheduling in flow-line manufacturing cells.*

[22] Chapter based on Henneberg / Neufeld (2016): *A constructive and SA appraoch for flowshop problems with missing operations.*

[23] See Pugazhendhi et al. (2003): *Performance enhancement by using non-permutation schedules.*

problem so far, a large number of instances is generated in order to evaluate the novel algorithms. An thorough statistical analysis is conducted applying analysis of variance technique.

Considering research question **Q5**, **Chapter 6** includes two additional aspects of group scheduling in this thesis.[24] On the one hand, focus is put on a dynamic production environment modeled in a simulation study. In this environment, group scheduling problems are preferably solved by simple two-stage heuristics based on dispatching rules, that are widely used in practice. Despite the development of numerous dispatching rules for traditional job shop scheduling environments recently, nearly none of these has been applied to group scheduling within the last decade. On the other hand, a job shop manufacturing cell is considered. Since it is not always possible to form unidirectional material flows during the cell formation process, job shop cells are of high relevance for practical manufacturing systems. Hence, a detailed review of simulation studies on scheduling problems in manufacturing cells, including flowshop as well as job shop cells, is provided and research gaps are identified. Based on these results new two-stage heuristics are formed combining novel promising dispatching rules. In an extensive simulation study, implemented by using the discrete event simulator *simcron MODELLER*, these heuristics are tested and several influencing factors for the heuristics' performance are analyzed and statistically evaluated.

Finally, a summary and conclusion of the presented findings is given in **Chapter 7**. From these, interesting directions for future research are derived and delineated.

[24] Chapter based on Klausnitzer / Neufeld / Buscher (2015): *Two-stage heuristics for manufacturing cells.*

1.5 Declaration of authorship

The authorship for publications included in this cumulative thesis covers the following aspects: establishing of the research topic, literature review, conducting of research, appraisal and interpretation of results, development of a publication strategy, writing as well as preview and lectorship of the manuscript. Apart from the distinctions mentioned below all of this was conducted solely by the author of this thesis. The individual contributions of the denoted co-authors are as follows: Chapter 2 based on Neufeld et al. (2014), *A comprehensive review of flowshop group scheduling literature*, as well as Chapter 3 based on Neufeld et al. (2105), *Minimizing makespan in flowshop group scheduling with sequence-dependent family setup times using inserted idle times*, were co-authored by Jatinder N. D. Gupta and Udo Buscher. For both publications the establishing of research topic and the development of a publication strategy was conducted by all authors with equal shares. Jatinder N. D. Gupta and Udo Buscher solely contributed for these papers on pre-review and lectorship.
Chapter 5 based on Henneberg/Neufeld (2015), *A constructive algorithm and a simulated annealing approach for solving flowshop problems with missing operations* was written together with Max Henneberg. The research topic was established by both authors, with a major share of Janis S. Neufeld, while the literature review was solely conducted by Max Henneberg. The manuscript was written by both authors with equal shares. A major part of research was done by Max Henneberg with support of Janis S. Neufeld.
Finally, Chapter 6 based on Klausnitzer et al. (2015), *Two-stage heuristics for scheduling job shop manufacturing cells with family setup times: a simulation study* is a collaboration of the authors Armin Klausnitzer, Udo Buscher and Janis S. Neufeld. The research topic was established by Janis S. Neufeld and Armin Klausnitzer together, just as appraisal and interpretation of results (major share Armin Klausnitzer) and writing of manuscript (major share Janis S. Neufeld). While literature review and conducting of research was executed by Armin Klausnitzer alone, review and lectorship was done by Udo Buscher and Janis S. Neufeld. The publications strategy was developed by all authors with a main contribution of Udo Buscher.

2 A comprehensive review of flowshop group scheduling literature (reference only)

Reference

Title	A comprehensive review of flowshop group scheduling literature	
Authors	Janis S. Neufeld (JN), Jatinder N. D. Gupta (JG), Udo Buscher (UB)	
Published in	Computers & Operations Research, Vol. 70, 2016, pp. 56–74	
Link	`http://dx.doi.org/10.1016/j.cor.2015.12.00`	
Individual Contribution	Establishing of research topic	JN, JG, UB
	Literature review	JN
	Conducting of research	JN
	Appraisal and interpretation of results	JN
	Publication strategy	JN, JG, UB
	Writing of manuscript	JN
	Pre-review and lectorship	JG, UB

3 Minimizing makespan in flowshop group scheduling with sequence-dependent family setup times using inserted idle times (reference only)

Reference

Title	Minimizing makespan in flowshop group scheduling with sequence-dependent family set-up times using inserted idle times	
Authors	Janis S. Neufeld (JN), Jatinder N. D. Gupta (JG), Udo Buscher (UB)	
Published in	International Journal of Production Research, Vol. 53, No. 6, 2015, pp. 1791–1806	
Link	`http://dx.doi.org/10.1080/00207543.2014.961209`	
Individual Contribution	Establishing of research topic	JN, JG, UB
	Literature review	JN
	Conducting of research	JN
	Appraisal and interpretation of results	JN
	Publication strategy	JN, JG, UB
	Writing of manuscript	JN
	Pre-review and lectorship	JG, UB

4 Group scheduling in flow-line manufacturing cells with variable neighborhood search (reference only)

Reference

Title	Group scheduling in flow-line manufacturing cells with variable neighborhood search	
Authors	Janis S. Neufeld (JN)	
Published in	Dynamics and sustainability in international logistics and supply chain management, 1. Edition, 2011, Göttingen, Cuvillier, pp. 274–284	
Individual Contribution	Establishing of research topic	JN
	Literature review	JN
	Conducting of research	JN
	Appraisal and interpretation of results	JN
	Publication strategy	JN
	Writing of manuscript	JN
	Pre-review and lectorship	JN

5 A constructive algorithm and a simulated annealing approach for solving flowshop problems with missing operations (reference only)

Reference

Title	A constructive algorithm and a simulated annealing approach for solving flowshop problems with missing operations	
Authors	Max Henneberg (MH), Janis S. Neufeld (JN)	
Published in	International Journal of Production Research, Vol. 54, No. 12, 2016, pp. 3534–3550	
Link	`http://dx.doi.org/10.1080/00207543.2015.1082670`	
Individual Contribution	Establishing of research topic	MH, JN
	Literature review	MH
	Conducting of research	MH, JN
	Appraisal and interpretation of results	JN
	Publication strategy	JN
	Writing of manuscript	MH, JN
	Pre-review and lectorship	JN

6 Two-stage heuristics for scheduling job shop manufacturing cells with family setup times: a simulation study

Reference

Title	Two-stage heuristics for scheduling job shop manufacturing cells with family setup times: a simulation study	
Authors	Armin Klausnitzer (AK), Janis S. Neufeld (JN), Udo Buscher (UB)	
Published in	unpublished	
Individual Contribution	Establishing of research topic	AK, JN
	Literature review	AK
	Conducting of research	AK
	Appraisal and interpretation of results	AK, JN
	Publication strategy	AK, JN, UB
	Writing of manuscript	AK, JN
	Pre-review and lectorship	JN, UB

Abstract

Heuristics based on dispatching rules are still widely used in practice as methods for effective scheduling systems. Despite the successful development of various novel dispatching rules for traditional job shop scheduling environments, nearly none of these has been applied to cellular manufacturing within the last decade. In this paper, we close this gap by implementing novel dispatching rules into two-stage heuristics in order to solve group scheduling problems in a job shop manufacturing cell. By a comprehensive simulation study these heuristics are evaluated and compared to established effective dispatching rules. It is shown that some new heuristics are capable of leading to superior results compared to previous heuristics with respect to mean flow time and mean tardiness. Besides, several influencing factors for the heuristics' performance are analyzed and statistically evaluated.

Reference

Manuscript submitted to *The International Journal of Advanced Manufacturing Technology* together with Klausnitzer, A. and Buscher, U. on February 20th, 2015.

6.1 Introduction

For decades shorter product life cycles, foreign competition and growing product diversity have been forcing manufacturing industry to continually ensure an increasing productivity, while, at the same time, providing a high level of flexibility. Group technology and cellular manufacturing have evolved as successful possibilities to meet these requirements.[1] In the context of manufacturing *group technology* is defined as concept of grouping heterogeneous parts to part families in order to establish efficient production processes. The assignment of parts to part families is usually conducted according to similarities concerning the parts' geometry as well as required processes, machines and tools. As similar parts are processed together, particularly setup times can be reduced significantly.[2] Especially the integration of group technology into the concept of lean manufacturing gave impetus for a widespread application in practice.[3]

Based on group technology, *cellular manufacturing* defines the grouping of resources and machines to autonomous manufacturing cells on the shop floor.[4] The objective is to form independent cells that are capable of processing all necessary operations for a set of part families. Hence, intercellular material flow is avoided.[5] Beside the minimization of setup times, the main advantages of cellular manufacturing are lower throughput times, decreasing inventory, higher quality and fewer transport processes. With this, cellular manufacturing can constitute a basis for the successful implementation of just-in-time production.[6] Practical applications of cellular manufacturing have been reported in several areas of industry, such as automotive production[7], electronics manufacturing[8] and semiconductor industry[9].

However, in cellular manufacturing systems an effective scheduling system is crucial to gain these advantages. While manufacturing cells often constitute a job shop or a flow shop environment, the existence of part families leads to a scheduling task on two levels, usually referred to as group scheduling. On the one hand, a sequence of parts within each part or tooling family assigned to a certain cell has to be determined. On the

[1] See Kesen / Das / Güngör (2010): *A genetic algorithm based heuristic for virtual manufacturing cells*, p. 1148.
[2] See Stecke / Parker (1998): *Cells and Flexible Automation*, p. 391.
[3] See Carr / Groves (1998): *Teams and Cellular Manufacturing*, p. 391.
[4] See Curry / Feldman (2011): *Manufacturing Systems: Modeling and Analysis*, p. 177.
[5] See Stecke / Parker (1998): *Cells and Flexible Automation*, p. 391.
[6] See Wemmerlöv (1992): *Fundamental insights into part family scheduling*, p. 565.
[7] See Salmasi / Logendran / Skandari (2010): *Total flow time minimization in a flowshop sequence-dependent group scheduling problem*, p. 199.
[8] See Gelogullari / Logendran (2010): *Group-scheduling problems in electronics manufacturing*, pp. 177–179.
[9] See Celano / Costa / Fichera (2010): *Constrained scheduling of inspection activities*, p. 697.

other hand a preferably optimal order of processing families has to be found. While minor setup times within a part family can be integrated into processing times, for every changeover of jobs from different part families either sequence-independent (SIST) or sequence-dependent setup times (SDST) have to be taken into account. As an extension of classical scheduling, static group scheduling problems with sequence-dependent setup times are known to be NP-hard already even for single machine environments.[10] Thus, the development and application of heuristics is necessary. An effective scheduling system is characterized by its ability to reflect real production environments and especially its dynamic nature. Accordingly, it should be robust concerning diverse changes of shop conditions.[11] Simple heuristics based on dispatching rules are able to meet these requirements particularly since they are easy to implement in real-world manufacturing systems and, thus, they are of high relevance for practical applications. In this paper, the center of attention are two-stage heuristics that are characterized by three distinct major dispatching decisions[12]: First, the transition between two part families has to be defined. Exhaustive rules assume that all jobs of a family have to be processed before a job from a different family is taken into account. In contrast, non-exhaustive rules allow a switching of families even though parts of the current family are still queuing.[13] As for group scheduling problems exhaustive rules have shown superior performance compared to non-exhaustive rules[14], this study is limited to exhaustive rules. Second, a decision has to be made about which part family is processed. This *family rule* also determines the occurring setup times. Finally, a *job rule* determines the sequence of jobs within the current part family.

Even though many manufacturing cells are organized as job shops, few publications focus on this type of layout only.[15] While for scheduling static and deterministic job shop cells metaheuristic approaches have been proposed recently [16], to the best of our knowledge dynamic environments have not been considered since the last simulation study by Reddy / Narendran[17]. At the same time several novel dispatching rules and recom-

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[10] See Mahmoodi / Martin (1997): *A new shop-based and predictive scheduling heuristic for CM*, p. 314.
[11] See Mahmoodi / Tierney / Mosier (1992): *Dynamic group scheduling heuristics*, pp. 71–72.
[12] See Russell / Philipoom (1990): *Sequencing rules and due date setting procedures in flow line cells*, p. 525.
[13] See Mahmoodi / Dooley (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1924.
[14] See Frazier (1996): *An evaluation of group scheduling heuristics.*
[15] See Elmi et al. (2011): *A simulated annealing algorithm for the job shop cell scheduling problem*, p. 171.
[16] See Tang et al. (2010): *Optimization of parts scheduling in multiple cells considering intercell move*; Elmi et al. (2011): *A simulated annealing algorithm for the job shop cell scheduling problem*; Shen / Mönch / Buscher (2013): *An iterative approach for the serial batching problem.*
[17] See Reddy / Narendran (2003): *Heuristics and sequence-dependent set-up jobs.*

mendations for the design of rules have been proven to be efficient in job shop manufacturing systems without part families [18], but have never been applied to group scheduling problems. Especially for sequencing part families no combined dispatching rules have been applied and tested so far. In this paper, we attempt to close this gap by integrating new efficient rules originally developed for classical job shop environments in two-stage heuristics for solving dynamic group scheduling problems with sequence-dependent as well as sequence-independent family setup times. Thus, promising heuristics are tested and analyzed by an comprehensive simulation study, since simulation is known as a suitable method for analyzing complex problems with large amounts of data.[19] With this, the proposed study can give helpful insights for effective scheduling systems in practical cellular manufacturing environments.

The rest of the paper is organized as follows: Section 6.2 gives a detailed overview of previous simulation studies on group scheduling problems. Prior results and the significance of various influencing factors are summarized. Based on this, open questions are identified and the studied simulation model is described in Section 6.3. A well-founded selection of exhaustive two-stage heuristics and the chosen parameters is presented. Section 6.4 details the results of the conducted simulation study regarding the performance of the tested heuristics as well as influencing factors. Finally, in Section 6.5 essential findings are summarized and aims for future research are pointed out.

6.2 Literature review

Since the first study in 1960[20] until today[21] dispatching rules have been widely investigated in literature and are still of high relevance for research as well as practice. While in the beginning basic dispatching rules had been tested only, since the 1990's the capability of developing powerful heuristics by combining rules was exploited.[22] Moreover, various influencing factors for a shop's performance have been analyzed.

For group scheduling problems several two-stage heuristics were applied and tested in simulation studies since the 1980's [23]. An overview of popular and effective heuristics is

[18] See Sels / Gheysen / Vanhoucke (2012): *A comparison of priority rules*; Otto / Otto (2014): *How to design effective priority rules.*

[19] See Ponnambalam / Aravindan / Reddy (1999): *Analysis of group-scheduling heuristics*, p. 915.

[20] See Baker / Dzielinski (1960): *Simulation of a simplified job shop.*

[21] See Sels / Gheysen / Vanhoucke (2012): *A comparison of priority rules.*

[22] See Anderson / Nyirenda (1990): *Two new rules to minimize tardiness*, p. 2291.

[23] See Mosier / Elvers / Kelly (1984): *Analysis of group technology scheduling heuristics*; Ponnambalam / Aravindan / Reddy (1999): *Analysis of group-scheduling heuristics.*

given in Table 6.1. Since different shop types showed very similar results, all simulation studies on job shop, flow shop and single machine manufacturing cells are considered in the following. As the setup of a simulation study has a significant impact on the performance of certain rules, the basic characteristics and effective dispatching rules are listed for each study, too. Fundamental insights and the influencing factors identified in these studies are summarized in the following.

Two-stage heuristics vs. single-stage dispatching rules MOSIER / ELVERS / KELLY[24] were the first to prove the dominance of two-stage heuristics over single-stage dispatching rules concerning production flow oriented criteria in job shop cells. In their simulation study several variations of utilization and setup to processing time ratios were tested. Only for due date based criteria, the use of single-stage rules could partly lead to superior results. However, no due date oriented family rule was considered.[25] This gap was closed by MAHMOODI / DOOLEY / STARR[26], who studied several due date based family rules. Still, two-stage heuristics outperformed single-stage heuristics for all criteria. These results were also confirmed for flow shop manufacturing cells by WEMMERLÖV / VAKHARIA.[27] Besides, two-stage heuristics showed a significantly lower variance compared to single-stage dispatching rules, whose performance is greatly determined by the systems' parameters.[28] This proves a wide-ranging applicability of dispatching rules within two-stage heuristics.

Exhaustive vs. non-exhaustive heuristics MAHMOODI / DOOLEY observed that exhaustive family rules generally outperform non-exhaustive rules regarding production flow oriented criteria.[29] Only for mean tardiness non-exhaustive rules could improve a cells' performance in cells with low utilization and loose due-dates. Non-exhaustive rules show two contrary effects: a splitting of part families allows more jobs to be on time, while, at the same time, this results in additional setup operations and, hence, increasing total flow time. Furthermore, exhaustive heuristics were proven to be more robust regarding changes of influencing system parameters, in particular concerning the setting

[24] See MOSIER / ELVERS / KELLY (1984): *Analysis of group technology scheduling heuristics*.
[25] See RUBEN / MOSIER / MAHMOODI (1993): *A comprehensive analysis of group scheduling heuristics*, p. 1345.
[26] See MAHMOODI / DOOLEY / STARR (1990b): *An investigation of dynamic group scheduling heuristics*.
[27] See WEMMERLÖV / VAKHARIA (1991): *Job and family scheduling of a flow-line manufacturing cell*, p. 390.
[28] See MOSIER / ELVERS / KELLY (1984): *Analysis of group technology scheduling heuristics*, p. 872; RUBEN / MOSIER / MAHMOODI (1993): *A comprehensive analysis of group scheduling heuristics*, p. 1366.
[29] See MAHMOODI / DOOLEY (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1937.

#	Author	Year	Shop	superior rules: Mean flow time	superior rules: Mean tardiness	# tested heuristics	#families	$\frac{\#operations}{job}$	#routes	#machines	Setup
1	Wemmerlöv	1992	Single	SPT/SPT		3	4,8, 16,32	1	1	1	SIST
2	Mahmoodi/Martin	1997	Single	MS/SPT	FCFS/FCFS	6	3	1	1	1	SDST
3	Russell/Philipoom	1991	Flow Shop	APT/SPT	EDD/EDD,FCFS/EDD, FCFS/SL,FCFS/EDD	22	5	5	1	5	SDST
4	Wemmerlöv/Vakharia	1991	Flow Shop	FCFS/FCFS		4	3,6	5	1	5	SDST
5	Mahmoodi/Tierney/ Mosier	1992	Flow Shop	MS/SPT	EDD/TSPT	4	3	5	1	5	SDST
6	Frazier	1996	Flow Shop	MJ/SPT	EDD/TSPT	11	4,8	6	1	6	SDST
7	Reddy/Narandran	2003	Flow Shop	MJ/EDD,PH/SPT	MJ/SPT,PH/SPT	9	3	5	1	5	SIST
8	Mosier/Elvers/ Kelly	1984	Job Shop	MW/SPT	MW/SL	15	3	2-4	6	4	SDST
9	Flynn	1987	Job Shop	FCFS/FCFS		2	3	19,9	10	39	SIST
10	Mahmoodi/Dooley/ Starr	1990a	Job Shop	MS/SPT	EDD/TSPT,EDD/SPT	9	3	4-5	12	5	SDST
11	Mahmoodi/Dooley/ Starr	1990b	Job Shop	MS/SPT	EDD/TSPT	6	3	4-5	12	5	SDST
12	Mahmoodi/Dooley	1991	Job Shop	MS/SPT	DK/TSPT	12	3	4-5	12	5	SDST
13	Ruben/Mosier/ Mahmoodi	1993	Job Shop	MS/SPT	EDD/TSPT,FCFS/FCFS	5	3	3-5	12	5	SDST
14	Wirth/Mahmoodi Mosier	1993	Job Shop	MS/SPT	MS/SPT	5	3	4-5	12	5	SDST
15	Kannan/Lyman	1994	Job Shop	SL/SPT,SL/SL	MW/SL,SL/SL	12	3	3-5	16	5	SDST
16	Ponnambalam/Aravindan/ Reddy	1999	Job Shop	DK/EDD,DK/SPT DK/FCFS	DK/EDD,DK/FCFS	6	3	1	1	1	SDST

APT = average processing time, DK = dynamic due date based heuristic, EDD = earliest due date, FCFS = first come first serve, MJ = most jobs, MS = minimum setup time, MW = most work in queue, PH = predictive heuristic[a], SL = slack, SPT = shortest processing time, TSPT = two class truncated SPT

Table 6.1: Literature overview of simulation studies on group scheduling

[a] See Reddy / Narendran (2003): *Heuristics and sequence-dependent set-up jobs.*

of due dates. The superiority of exhaustive rules was also confirmed by FRAZIER[30]. Moreover, they are readily understandable and easy to implement in practice.

Number and size of part families Simulation studies conducted by WEMMERLÖV[31] and WIRTH / MAHMOODI / MOSIER[32] showed that the advantage of two-stage heuristics compared to single-stage dispatching rules decreases with an increasing number of part families. This becomes reasonable by considering an extreme example with each family consisting of a single job only. Understandably, in this case a family rule does not enhance the performance of a job rule. FRAZIER[33] confirms these results in his study for flow shop cells. Furthermore, he states that the number of part families does not impact the advantageousness of different two-stage heuristics compared to each other.
A dominating part family, with a significant higher number of jobs, generally leads to lower mean flow times, as fewer setup operations are necessary.[34] As a result, jobs belonging to this part family are less likely to be tardy. However, jobs from smaller part families tend toward a late date of completion as the machines are rarely set up for processing these part families. Particularly under mean tardiness criterion and a high cell utilization two-stage heuristics are often less robust, i. e. their performance differs widely dependent on variations of family size.[35] Hence, especially the proportion of the number of jobs in each family represents a significant influencing factor for the selection of dispatching rules.

Due date setting procedures RUSSELL / PHILIPOOM[36] investigated the effect of different types of due date setting procedures. They showed that a heuristics' performance can be influenced by due date setting procedures significantly, especially when minimizing mean tardiness. Nevertheless, superior two-stage heuristics remain favorable regardless of the chosen strategy. The mean flow time criterion was generally less influenced by due date setting procedures. Besides, MAHMOODI / DOOLEY report a case in which a non-exhaustive rule is superior compared to an exhaustive rule.[37] In a setting with loose due dates the non-exhaustive *dynamic due date based heuristic* (DK) rule led

[30] See FRAZIER (1996): *An evaluation of group scheduling heuristics*, p. 975.
[31] See WEMMERLÖV (1992): *Fundamental insights into part family scheduling*, p. 573.
[32] See WIRTH / MAHMOODI / MOSIER (1993): *An investigation of scheduling policies*, p. 775.
[33] See FRAZIER (1996): *An evaluation of group scheduling heuristics*, p. 975.
[34] See WEMMERLÖV (1992): *Fundamental insights into part family scheduling*, p. 577.
[35] See RUBEN / MOSIER / MAHMOODI (1993): *A comprehensive analysis of group scheduling heuristics*, pp. 1364–1366.
[36] See RUSSELL / PHILIPOOM (1990): *Sequencing rules and due date setting procedures in flow line cells*, pp. 533–535.
[37] See MAHMOODI / DOOLEY (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1934.

to slightly lower mean tardiness, while with tight due dates DK and *earliest due date* (EDD) performed similarly.

Setup times WEMMERLÖV showed that increasing setup times lead to larger flow times for both priority rules and two-stage heuristics.[38] The latter are less influenced by changes of setup times. In addition, a dominating part family as well as increasing setup times lead to a broader spread of the heuristics' performance concerning mean flow time. WIRTH / MAHMOODI / MOSIER come to the conclusion that the size of setup times has no significant impact on the performance of a cell but on the heuristics' ranking.[39]

Cell utilization Furthermore, WIRTH / MAHMOODI / MOSIER proved that a cell's utilization is crucial for its performance. Cells with a low workload generally result in low flow times and less tardy jobs.[40] However, the effectiveness of two-stage heuristics is less influenced by a varying cell utilization.[41]

Cell configuration MAHMOODI / DOOLEY[42] showed that generally flow shop cells lead to a similar ranking of heuristics compared to job shop cells as presented by MAHMOODI / DOOLEY / STARR[43]. Besides, only few dispatching rules have been tested in single machine cells as well as job shop cells. Thus, a profound analysis of cell configurations with a single machine is not possible. Nevertheless, concerning the influencing factors mentioned above similar conclusion were drawn in single machine environments.[44] Hence, a limited impact of the cell configuration on the selection of heuristics may be expected.

Distribution of inter-arrival and processing times The greatest impact on a shop's performance was ascertained for varying inter-arrival and processing times. Minor variances for these two values, in particular the inter-arrival time, lead to a significant decrease of mean flow time.[45] For an imbalanced arrival of jobs MAHMOODI / DOOLEY

[38] See WEMMERLÖV (1992): *Fundamental insights into part family scheduling*, p. 577-579.
[39] See WIRTH / MAHMOODI / MOSIER (1993): *An investigation of scheduling policies*, p. 777-778.
[40] See ibid., p. 777.
[41] See RUBEN / MOSIER / MAHMOODI (1993): *A comprehensive analysis of group scheduling heuristics*, pp. 1362–1363.
[42] See MAHMOODI / DOOLEY (1992): *Group scheduling and order releasing*, p. 75.
[43] See MAHMOODI / DOOLEY / STARR (1990b): *An investigation of dynamic group scheduling heuristics*, pp. 1708–1709.
[44] See WEMMERLÖV (1992): *Fundamental insights into part family scheduling*, p. 589.
[45] See ibid., p. 579.

detected strong differences in the heuristics' performance.[46] For less varying inter-arrival and processing times the attained results converge to each other.[47]

6.3 Model description

6.3.1 Manufacturing environment

The assumed model of a job shop manufacturing cell by MAHMOODI / DOOLEY[48] has been applied in several publications already.[49] Since it is our goal to analyze the influence of several factors on the shop's performance, the use of this model allows a direct comparison of the results to previous studies and eliminates the impact of the cell configuration on the heuristics' performance. Furthermore, based on various empirical studies the considered cell represents a typical size and configuration of real-life manufacturing cells.[50]

Figure 6.1 displays the considered cell consisting of five machines, representing limited resources. As soon as a job arrives in the system all relevant parameters are set and it is assigned to one of three part families as well as a certain route. All jobs consist of four to five operations with predetermined machines. Each route starts with an operation either on machine 1 or machine 2, one operation on machine 3 and ends either on machine 4 or machine 5. Hence, machine 3 constitutes a bottleneck that can be used as a measure for the utilization of the manufacturing cell.[51] Reentrant material flows are not considered. Every machine is able to treat one operation at a time and started jobs are not allowed to be disrupted. Furthermore, time for transportation is neglected and all buffers are of unlimited size.

In front of every machine three queues are established, one for each part family. For each part family 12 different routes exist, which results in the possibility of producing in total 36 distinct parts in this manufacturing cell. The job's characteristics are determined as described in the following.

[46] See MAHMOODI / DOOLEY (1992): *Group scheduling and order releasing*, p. 80.
[47] See WEMMERLÖV (1992): *Fundamental insights into part family scheduling*, p. 586.
[48] See MAHMOODI / DOOLEY (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1924.
[49] See KANNAN / LYMAN (1994): *Impact of family-based scheduling on transfer batches*; WIRTH / MAHMOODI / MOSIER (1993): *An investigation of scheduling policies.*
[50] See WEMMERLÖV / HYER (1989): *Cellular manufacturing in the US industry*; RUBEN / MOSIER / MAHMOODI (1993): *A comprehensive analysis of group scheduling heuristics.*
[51] See MOSIER / ELVERS / KELLY (1984): *Analysis of group technology scheduling heuristics*, p. 858.

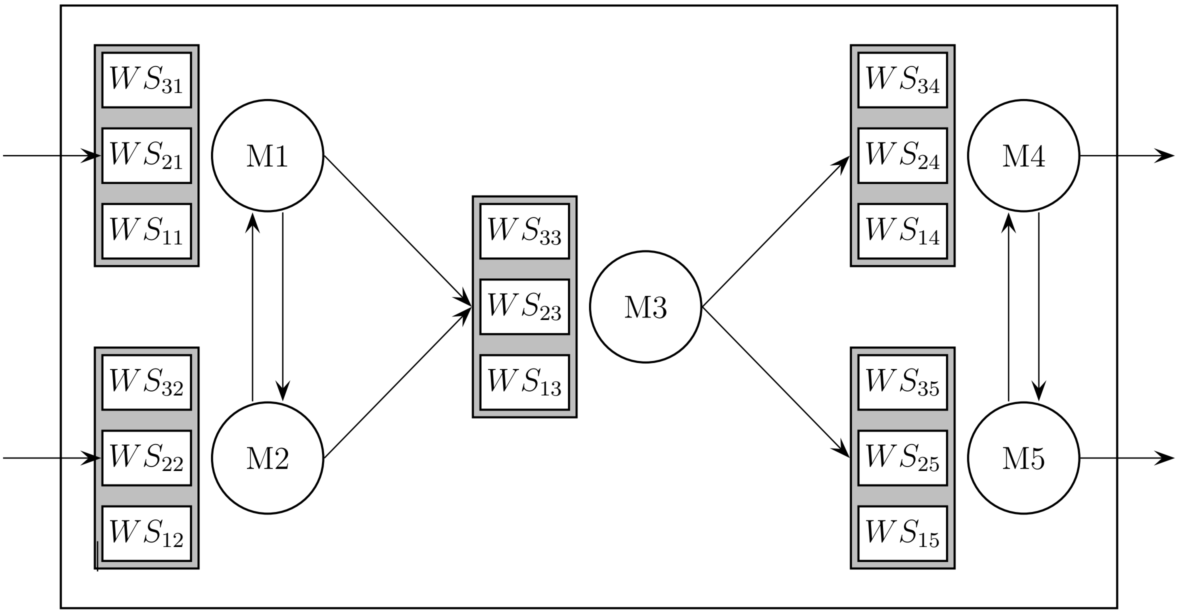

Figure 6.1: Considered model of a job shop manufacturing cell

Job arrival All jobs arrive at the system according to a POISSON distribution with exponential inter-arrival times and are released immediately. This guarantees a stochastic independence of two succeeding jobs.[52] The arrival time was determined by a pilot study using the basic two-stage heuristic FCFS/FCFS. With an inter-arrival time of 70 minutes a medium machine utilization of 85% could be ensured.[53]

Processing times Due to varying material quality and inconstant speed of operation through operation personnel, processing times in reality are often subject to considerable variation. Thus, a third-order ERLANG distribution with a mean value of 60 minutes was chosen.[54]

Setup times Minor setup times for a changeover between two parts of the same family are assumed to be part of the processing times.[55] In contrast, major family setup times have to be taken into account as soon as the part family is switched. Since the variation of setup times is usually higher compared to processing times, a second-order

[52] See THOMOPOULOS (2012): *Fundamentals of queuing systems*, pp. 11–13; BONALD / FEUILLET (2013): *Network Performance Analysis*, p. 12,27.
[53] See MAHMOODI / DOOLEY (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1929.
[54] See MAHMOODI / MARTIN (1997): *A new shop-based and predictive scheduling heuristic for CM*, p. 317.
[55] See MAHMOODI / DOOLEY (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1929.

[hh:mm:ss]		Family e 1	2	3
Family f	1	00:00:00	00:15:00	00:30:00
	2	00:15:00	00:00:00	00:45:00
	3	00:30:00	00:45:00	00:00:00

Table 6.2: Sequence-dependent setup times

Erlang distribution is used for generating these.[56] So far, the influence of different setup to processing time ratios has been analyzed for either sequence-independent setups[57] or sequence-dependent setups[58] only. However, the impact of the type of setup time on the performance of heuristic algorithms has not been studied, yet. Hence, we analyze the considered manufacturing cell with sequence-dependent as well as sequence-independent setup times.

- For the case of sequence-independent family setups, a mean value of 30 minutes was considered.
- Sequence-dependent setup times were determined according to the mean values for every changeover from a family f to e shown in Table 6.2.

With this the mean value of the setup to processing time ratio is 0.5, which is in accordance with previous studies that chose values between 0.1[59] and 1.27[60].

Due date Due dates for each jobs are determined by the Total Work Content (TWK) technique.[61] A constant parameter K is multiplied with the sum of processing times t_{ji} of a job j on all machines i. This value is added to the time of arrival r_j of job j:

$$d_j = r_j + K \cdot \sum_{i=1}^{m} t_{ji} \tag{6.1}$$

[56] See Mahmoodi / Martin (1997): *A new shop-based and predictive scheduling heuristic for CM*, p. 318.
[57] See Russell / Philipoom (1990): *Sequencing rules and due date setting procedures in flow line cells*, p. 532.
[58] See Wirth / Mahmoodi / Mosier (1993): *An investigation of scheduling policies*, p. 767.
[59] See Wemmerlöv (1992): *Fundamental insights into part family scheduling*, p. 572.
[60] See Mahmoodi / Martin (1997): *A new shop-based and predictive scheduling heuristic for CM*, pp. 317f.
[61] See Wemmerlöv / Vakharia (1991): *Job and family scheduling of a flow-line manufacturing cell*, p. 384.

On the basis of the FCFS/FCFS heuristic, several values for K have been tested. An average tardiness of about 35% was gained for $K = 4.11$, which was chosen in our simulation study.

Family dominance An influencing factor, that is analyzed in our study, is the dominance of a part family regarding its size. In nearly all previous publications arriving jobs are assigned to each part family with an identical probability. Nevertheless, as mentioned before, especially two-stage heuristics are affected by a family's dominance significantly. Hence, beside a uniform distribution of jobs to part families, a strong dominance of one part family is investigated. The latter is accomplished by assigning new jobs with a probability of 80% to the first part family, while 10% of the arriving jobs are assigned to each of the other families.[62]

6.3.2 Group scheduling heuristics

Based on the literature review in Section 6.2 as well as the results of recent studies on dispatching rules in classical job shop environments, promising novel combinations of family and job rules are proposed. The tested heuristics are described as follows:

[1] **FCFS/FCFS:** This simple heuristic selects the part family that contains the job that arrived first at this machine. All jobs from this part family are processed according to their arrival time in the queue.[63] As one of the first group scheduling heuristics that has widely been used in previous simulation studies, FCFS/FCFS provides a basis for evaluating other rules.

[2] **MS/SPT:** First, the part family requiring minimum setup time is selected. The jobs of this family are sequenced according to shortest processing time dispatching rule. MS/SPT is known as one of the best rules for minimizing mean flow time in group scheduling environments.

[3] $\mathbf{\frac{MS}{MJ}}$**/SPT:** Even though recent studies point out the effectiveness of combined dispatching rules[64], these have not been applied for scheduling part families, so far. The family rule $\frac{\text{MS}}{\text{MJ}}$ is a promising combination and is defined as quotient of minimum setup time s_{fei} for a changeover from family f to e on machine i and the

[62] See Ruben / Mosier / Mahmoodi (1993): *A comprehensive analysis of group scheduling heuristics*, p. 1348.
[63] See Mahmoodi / Dooley / Starr (1990a): *An evaluation of heuristics in a CMS*, p. 553.
[64] See Sels / Gheysen / Vanhoucke (2012): *A comparison of priority rules*, p. 4260.

number of jobs n_{ei} waiting in queue e belonging to machine i:

$$\frac{\text{MS}}{\text{MJ}} = \frac{s_{fei}}{n_{ei}} \quad \longrightarrow \min \tag{6.2}$$

Hence, the minimum setup time per job in a queue decides which family is processed first. The performance of this dispatching rule is investigated together with the SPT sequencing jobs within each family.

[4] $\mathbf{\frac{MS}{MJ}}$**/SPT+MWKR:** An additive combination of SPT rule and the *most work remaining rule* (MWKR) also led to good results for job shop scheduling.[65] Thus, the job rule chooses the job j that has the shortest sum of processing times from the current operation u up to the operation on the last subsequent machine m.

$$\text{SPT+MWKR} = t_{ji} + \sum_{i=u}^{m} t_{ji} \quad \longrightarrow \min \tag{6.3}$$

Compared with $\frac{\text{MS}}{\text{MJ}}$/SPT this newly combined heuristic serves as a basis for assessing the impact of the job rule on the performance of a heuristic.

[5] **EDD/TSPT:** The family rule dispatches first the family that contains the job with earliest due date.[66] All jobs of this family are sequenced according to TSPT rule. In contrast to the conventional SL rule, TSPT considers jobs with negative or no slack first. Remaining jobs are assigned to a non-priority queue:

$$\begin{aligned} \text{SL} &= d_j - \sum_{i=u}^{m} t_{ji} - r_j \leq 0, \quad \text{non-priority queue} \\ \text{SL} &= d_j - \sum_{i=u}^{m} t_{ji} - r_j > 0, \quad \text{priority queue.} \end{aligned} \tag{6.4}$$

Jobs in both priority queues are ordered according to SPT.[67] This rule is known to show a high performance concerning the minimization of average tardiness and serves as a benchmark for novel heuristics.

[6] $\mathbf{\bar{SL}}$**/TSPT:** The total slack of a family has been considered several times in a variety of ways, but always as non-exhaustive rule.[68] Since exhaustive rules generally showed superior results, here $\bar{\text{SL}}$ is used in an exhaustive manner. For the respec-

[65] See Dominic / Kaliyamoorthy / Kumar (2004): *Efficient dispatching rules*, pp. 71–72; Sels / Gheysen / Vanhoucke (2012): *A comparison of priority rules*, p. 4260.
[66] See Mahmoodi / Dooley / Starr (1990b): *An investigation of dynamic group scheduling heuristics*, p. 64.
[67] See ibid., p. 1698.
[68] See Mahmoodi / Dooley (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1927.

tive machine the total slack of all jobs assigned to a certain family is determined and divided by the number of jobs.

$$\bar{\mathrm{SL}} = \frac{\sum_{j=0}^{n} SL_{jei}}{n_{ei}} \tag{6.5}$$

The part family with minimum average slack is processed first, while all jobs are sequenced concerning TSPT rule. This heuristic serves for evaluating this novel family rule especially.

[7] **$\bar{\mathbf{SL}}$/SL:** The SL rule for sequencing jobs within each part family is considered, which is promising for due date based criteria. It is combined with the new exhaustive family slack rule.

[8] **$\bar{\mathbf{SL}}/\frac{\mathbf{SL}}{\mathbf{MWKR}}$:** Likewise, the novel combined $\frac{\mathrm{SL}}{\mathrm{MWKR}}$ job rule, that can be interpreted as expected waiting time, is used for sequencing the jobs within each part family.

$$\frac{\mathrm{SL}}{\mathrm{MWKR}} = \frac{d_j - \sum_{i=u}^{m} t_{ji} - r_j}{\sum_{i=u}^{m} t_{ji}} \tag{6.6}$$

Summing up, heuristics [3], [4], [6], [7], [8] have not been tested in the past.

6.3.3 Experimental setup

The described production environment was implemented with *simcron MODELLER*, a discrete event simulator, which has been developed specifically for modeling production processes. In the beginning of every simulation run, the production system is empty and undergoes a warm-up period. Similar to previous studies, the length of the warm-up period was predefined with 2,000 hours. Due to a high variance during this time span which decreases over time the dependent variables were not monitored in the beginning.[69] After the warm-up period for each run 8,000 hours of the manufacturing process were simulated.[70] Since reliable results can be realized by a long duration of a run rather than by frequent reiterations this procedure conforms the recommended setup for simulation studies.[71]

The variation of the examined influencing factors setup type and part family dominance

69 See HEDTSTÜCK (2013): *Simulation diskreter Prozesse*, pp. 65–66.
70 See MAHMOODI / DOOLEY / STARR (1990a): *An evaluation of heuristics in a CMS*, p. 555; MAHMOODI / DOOLEY (1991): *A comparison of exhaustive and non-exhaustive group scheduling heuristics*, p. 1929.
71 See LAW / KELTON (1984): *Confidence intervals for steady state simulation*, p. 1237.

leads to four scenarios:

1. sequence-dependent setup times with no dominating part family
2. sequence-independent setup times with no dominating part family
3. sequence-dependent setup times with dominance of one part family
4. sequence-independent setup times with dominance of one part family

In order to achieve statistically precise results 40 runs were performed for each configuration. Hence, the number of simulation runs in total is determined by

$$4\,\text{scenarios} \cdot 8\,\text{heuristics} \cdot 40\,\text{runs} = 1,280\,\text{simulation runs}$$

Statistical tests are necessary to prove the significance of different rules or experimental factors. In order to evaluate ascertained results for differences in heuristic performance, a two-sample t-test was performed for a confidence interval of 0.95. Also, a two-factor Analysis of Variance (ANOVA) was conducted to examine possible effects of experimental factors.

6.3.4 Performance measures

In order to evaluate the heuristics' performance and the impact of influencing factors a production flow oriented as well as due date based measure are monitored. While production flow oriented performance measures are used to minimize the total work in process and, therewith, capital commitment costs[72], due date oriented performance measures aspire a punctual completion of jobs in order to minimize contractual penalties and the customers' discontent.[73]

1. The minimization of **mean flow time** $\bar{F}$ represents the first objective and equals a job's time in the system. It is defined as the sum of completion times C_j less the release times r_j concerning all jobs j divided by the total number of jobs n:[74]

$$\bar{F} := \frac{1}{n}\sum_{j=1}^{n} F_j = \frac{1}{n}\sum_{j=1}^{n}(C_j - r_j) \rightarrow min! \tag{6.7}$$

[72] See Holthaus (1996): *Ablaufplanung bei Werkstattfertigung*, pp. 8–9.
[73] See Seelbach (1975): *Ablaufplanung*, p. 37.
[74] See Eiselt / Sandblom (2010): *Operations Research: A Model-Based Approach*, p. 289.

2. In this study, we consider **mean tardiness** $\bar{T}$ as due date based performance measure. It is defined as the average difference between the completion time C_j and due date d_j of all jobs j:[75]

$$\bar{T} := \frac{1}{n}\sum_{j=1}^{n}(max\,\{C_j - d_j; 0\}) \rightarrow min! \tag{6.8}$$

6.4 Results and discussion

6.4.1 Mean flow time

Table 6.3 summarizes the average values over all studied scenarios for both objectives, highlighting the best results. It can be seen that considerable divergences arise subject to the selected heuristic. Depending on the scenario the best performing heuristic leads to between 15.7% and 12.7% lower mean flow time compared to inferior heuristics. Furthermore, the data confirms the results of previous studies, sharing that the application of dispatching rules that are calculated similarly to the considered optimization criteria are usually promising. Due date based dispatching rules generally lead to higher flow times compared to production flow oriented rules. This relation can also be derived from Table 6.4, which ranks all investigated heuristics regarding to both introduced performance measures. A line between heuristics indicates differences that are statistically not significant according to two-sample t-test.

All four scenarios lead to similar results concerning the ranking of the heuristics, showing statistically insignificant differences only. Overall, either MS/SPT or the novel $\frac{\mathrm{MS}}{\mathrm{MJ}}$/SPT heuristic perform best. Only for the scenario with sequence-dependent setup times with no dominating part family, the $\frac{\mathrm{MS}}{\mathrm{MJ}}$ family dispatching rule shows a considerably superior performance compared to the MS rule.

[75] See DAUB (1994): *Ablaufplanung*, p. 72.

Scenario 1	Uniform families and SDST	
	Mean flow time	Mean tardiness
FCFS/FCFS	15:38:50	01:47:13
MS/SPT	13:24:59	01:08:47
$\frac{MS}{MJ}$/SPT	**13:21:14**	**01:06:05**
$\frac{MS}{MJ}$/MWKR+SPT	13:43:31	01:12:48
EDD/TSPT	14:35:58	01:22:11
$\bar{SL}$/TSPT	14:32:52	01:15:15
$\bar{SL}$/SL	15:23:56	01:26:28
$\bar{SL}/\frac{SL}{MWKR}$	15:39:50	01:39:01

Scenario 2	Uniform families and SIST	
	Mean flow time	Mean tardiness
FCFS/FCFS	15:23:29	01:39:19
MS/SPT	**13:28:27**	01:09:03
$\frac{MS}{MJ}$/SPT	13:29:07	01:10:23
$\frac{MS}{MJ}$/MWKR+SPT	13:51:09	01:16:00
EDD/TSPT	14:12:36	01:11:37
$\bar{SL}$/TSPT	14:16:24	**01:08:52**
$\bar{SL}$/SL	15:08:13	01:19:48
$\bar{SL}/\frac{SL}{MWKR}$	15:26:24	01:30:51

Scenario 3	Dominating family and SDST	
	Mean flow time	Mean tardiness
FCFS/FCFS	11:38:40	00:42:00
MS/SPT	10:10:10	00:37:24
$\frac{MS}{MJ}$/SPT	**10:08:49**	00:37:20
$\frac{MS}{MJ}$/MWKR+SPT	10:21:24	00:40:47
EDD/TSPT	10:27:04	00:33:42
$\bar{SL}$/TSPT	10:27:28	**00:32:59**
$\bar{SL}$/SL	11:12:58	00:36:41
$\bar{SL}/\frac{SL}{MWKR}$	12:02:08	00:51:48

Scenario 4	Dominating family and SIST	
	Mean flow time	Mean tardiness
FCFS/FCFS	12:12:55	00:49:39
MS/SPT	**10:40:50**	00:42:41
$\frac{MS}{MJ}$/SPT	10:43:09	00:43:40
$\frac{MS}{MJ}$/MWKR+SPT	10:56:43	00:47:36
EDD/TSPT	10:51:42	**00:37:10**
$\bar{SL}$/TSPT	10:54:38	00:37:41
$\bar{SL}$/SL	11:38:54	00:40:51
$\bar{SL}/\frac{SL}{MWKR}$	12:23:12	00:58:41

Table 6.3: Summary of simulation results for all scenarios

Ranking mean flow time	No dominating family/ SDST	No dominating family/ SIST	Family dominance/ SDST	Family dominance/ SIST
1	$\frac{\text{MS}}{\text{MJ}}$/SPT	MS/SPT	$\frac{\text{MS}}{\text{MJ}}$/SPT	MS/SPT
2	MS/SPT	$\frac{\text{MS}}{\text{MJ}}$/SPT	MS/SPT	$\frac{\text{MS}}{\text{MJ}}$/SPT
3	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	EDD/TSPT
4	$\bar{\text{SL}}$/TSPT	EDD/TSPT	EDD/TSPT	$\bar{\text{SL}}$/TSPT
5	EDD/TSPT	$\bar{\text{SL}}$/TSPT	$\bar{\text{SL}}$/TSPT	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT
6	$\bar{\text{SL}}$/SL	$\bar{\text{SL}}$/SL	$\bar{\text{SL}}$/SL	$\bar{\text{SL}}$/SL
7	FCFS/FCFS	FCFS/FCFS	FCFS/FCFS	FCFS/FCFS
8	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$

Ranking mean tardiness	No dominating family/ SDST	No dominating family/ SIST	Family dominance/ SDST	Family dominance/ SIST
1	$\frac{\text{MS}}{\text{MJ}}$/SPT	$\bar{\text{SL}}$/TSPT	$\bar{\text{SL}}$/TSPT	EDD/TSPT
2	MS/SPT	MS/SPT	EDD/TSPT	$\bar{\text{SL}}$/TSPT
3	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	$\frac{\text{MS}}{\text{MJ}}$/SPT	$\bar{\text{SL}}$/SL	$\bar{\text{SL}}$/SL
4	$\bar{\text{SL}}$/TSPT	EDD/TSPT	$\frac{\text{MS}}{\text{MJ}}$/SPT	MS/SPT
5	EDD/TSPT	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	MS/SPT	$\frac{\text{MS}}{\text{MJ}}$/SPT
6	$\bar{\text{SL}}$/SL	$\bar{\text{SL}}$/SL	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT
7	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$	FCFS/FCFS	FCFS/FCFS
8	FCFS/FCFS	FCFS/FCFS	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$	$\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$

Table 6.4: Ranking of heuristics and variance analysis

However, novel combined job rules cannot lead to an improvement of mean flow time in general. Out of all production flow based rules, MWKR+SPT as well as $\frac{\mathrm{SL}}{\mathrm{MWKR}}$ show the least performance among the due date based job rules. The latter is outperformed even by the simple FCFS/FCFS heuristic. Using $\frac{\mathrm{MS}}{\mathrm{MJ}}$ family rule, SPT job rule leads to 2.0% to 2.7% better results compared to the combined MWKR+SPT. Moreover, TSPT outperforms $\frac{\mathrm{SL}}{\mathrm{MWKR}}$ by 7,1% to 13,1%, both tested with the $\bar{\mathrm{SL}}$ family rule. In contrast to the results of previous studies, an overall improvement of up to 15,7% depending on the chosen job rule implies a strong impact of job rule on a heuristic's performance.

6.4.2 Mean tardiness

In comparison to the results with flow time objective, for mean tardiness the ranking of the heuristics varies considerably dependent on the regarded scenario. This implies a significant impact of the studied influencing factors. Due date based dispatching rules are not advantageous in all scenarios. Instead, for sequence-dependent setup times and part families of the same size the novel $\frac{\mathrm{MS}}{\mathrm{MJ}}$/SPT heuristic leads to the lowest average tardiness. MS/SPT, which is also an production flow oriented rule, follows with a statistically significant difference. Concerning the family rules, $\bar{\mathrm{SL}}$ outperformed EDD significantly. In general, in this scenario both analyzed optimization criteria lead to a similar ranking of heuristics.

No clear statement can be made about the advantageousness of production flow or due date based rules in the scenario of sequence-independent setup times and no dominating part family. Thus, the proposed $\frac{\mathrm{MS}}{\mathrm{MJ}}$/SPT and $\bar{\mathrm{SL}}$/TSPT heuristics are as efficient as the well known MS/SPT and EDD/TSPT heuristics.

Both scenarios with family dominance result in a similar ranking. Here, especially due date based family heuristics like $\bar{\mathrm{SL}}$/TSPT and EDD/TSPT perform best.

Concerning all scenarios, comparisons of the best and worst heuristics show differences between 30.7% and 38.4%. For the minimization of mean tardiness by using $\frac{\mathrm{MS}}{\mathrm{MJ}}$ family rule and replacing the MWKR+SPT job rule by SPT improvements of 7.4% to 9.2% can be aspired. Applying SL as job rule instead of $\frac{\mathrm{SL}}{\mathrm{MWKR}}$, results in a decrease of the average mean tardiness between 24.0% and 36.3% if at the same time the families are sequenced by $\bar{\mathrm{SL}}$. Finally, $\frac{\mathrm{SL}}{\mathrm{TSPT}}$ shows good results for all scenarios.

6.4.3 Analysis of influencing factors

Table 6.5 summarizes the substantial impact of the studied influencing factors, i.e. setup type and family dominance. In general, a dominating family leads to a lower mean flow time and less tardy jobs, while with families of the same size the type of setup times does not show any impact on the performance measures. This is reasonable since a dominating family results in fewer changeovers between jobs of different part families and therewith fewer setup operations are necessary. However, with a balanced family size SDST average to better results compared to SIST (see Figure 6.2 and 6.3). Again, this can be explained by lower total setup times. While for both types the average setup time is identical, SDST can show a higher variance and, hence, allow a minimization of total changeover times. Besides, this could imply an actual effect of the setup type on the performance of the proposed heuristics. However, Table 6.5 displays the results of the conducted analysis of variance. With a level of significance of 0.95 an influencing impact is indicated by a value $F \geq 3,9$. The total spread SS_T consists of several spreads caused by the influencing factors type of setup times ($SS_{SDST/SIST}$) as well as family

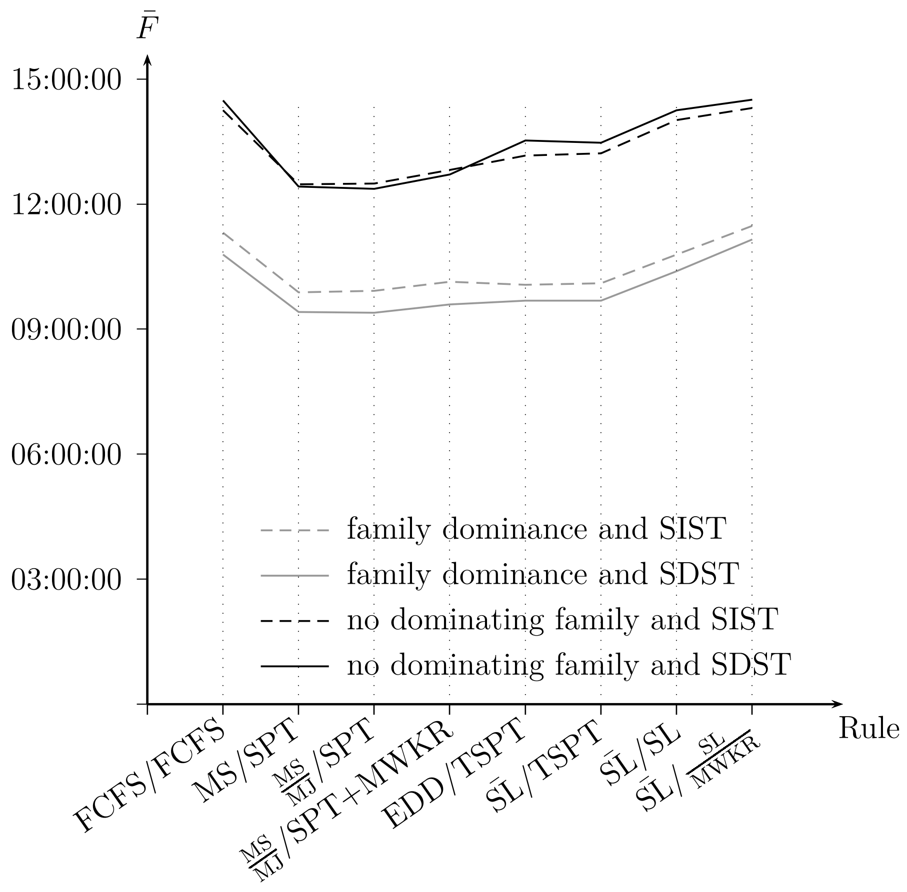

Figure 6.2: Results: mean flow time

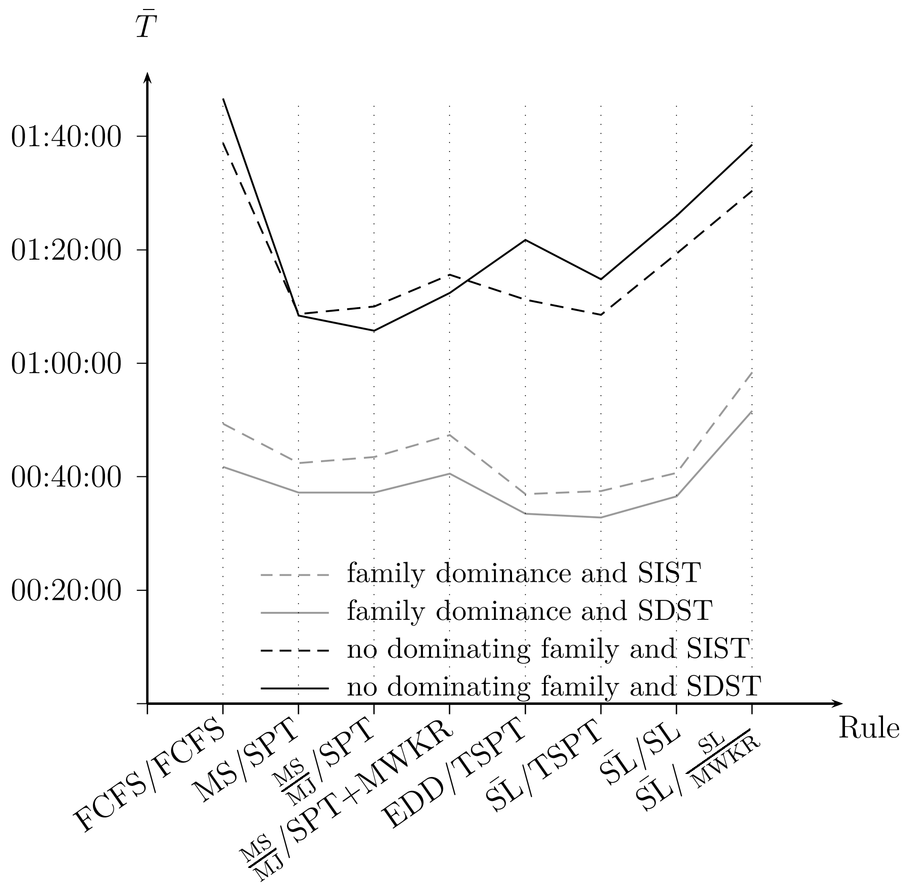

Figure 6.3: Results: mean tardiness

dominance ($SS_{eq/dom}$), their interaction ($SS_{interaction}$) and spread of errors SS_E. Caused by the special case of only two specifications per factor, the proportion of factor spread and error spread determines the testing value F. With this, the results show that the differences subject to the type of setup times are not statistically significant. Thus, there is no significant interaction effect as well.

In contrast, the effect size of dominating part families is pointed out in Table 6.6 and Figure 6.4. It is apparent that the dominance of a certain family has a strong impact on the performance of heuristics. Concerning mean flow time for all heuristics, except for $\bar{\text{SL}}/\frac{\text{SL}}{\text{MWKR}}$, over 96% of the total variance can be explained by the dominance of families, while this is the case for over 82% of the variance with tardiness criterion. This implies that the due date based objective is less influenced by changes of the family dominance compared to flow time. However, at the same time, tardiness is effected considerably by other influencing factors, such as variances of setup, processing or inter-arrival times. According to Table 6.4, for mean flow time the ranking of heuristics remains unchanged independently of the underlying scenario, while major differences

Mean flow time [s]	FCFS/FCFS	MS/SPT	$\frac{\text{MS}}{\text{MJ}}$/SPT	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	EDD/TSPT	$\bar{\text{S}}$L/TSPT	$\bar{\text{S}}$L/SL	$\bar{\text{S}}$L/$\frac{\text{SL}}{\text{MWKR}}$
$SS_{SDST/SIST}$	41,913,349	64,154,558	66,379,658	56,100	4,122,924	3,757,690	2,099,931	12,841,422
$SS_{eq/dom}$	4,728,548,103	4,623,671,824	5,104,786,688	7,283,413,488	7,198,623,151	7,627,014,507	5,786,141,594	6,679,278,425
$SS_{interaction}$	26,612,213	25,191,245	27,581,736	82,932,480	68,541,858	62,480,002	42,817,956	88,556,832
SS_T	4,896,921,221	4,772,388,609	5,305,974,100	7,481,279,432	7,377,113,078	7,808,684,335	6,344,163,714	6,946,082,868
SS_E	99,847,556	59,370,983	107,226,019	114,877,363	105,825,145	115,432,136	513,104,235	165,406,188
$F_{SDST/SIST}$	0.4198	1.0806	0.6191	0.0005	0.0390	0.0326	0.0041	0.0776
$F_{eq/dom}$	47.3577	77.8776	47.6077	63.4016	68.0237	66.0736	11.2767	40.3811
$F_{interaction}$	0.2665	0.4243	0.2572	0.7219	0.6477	0.5413	0.0834	0.5354

Mean tardiness [s]	FCFS/FCFS	MS/SPT	$\frac{\text{MS}}{\text{MJ}}$/SPT	$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	EDD/TSPT	$\bar{\text{S}}$L/TSPT	$\bar{\text{S}}$L/SL	$\bar{\text{S}}$L/$\frac{\text{SL}}{\text{MWKR}}$
$SS_{SDST/SIST}$	1,108,391	4,072,354	3,617,722	1,818,809	101,254	225,525	58,867	2,624
$SS_{eq/dom}$	120,067,448	110,832,397	131,346,444	247,638,105	194,218,694	283,553,588	226,845,020	475,189,636
$SS_{interaction}$	913,702	148,718	471,216	7,106,912	4,431,898	4,223,375	8,145,514	8,713,289
SS_T	137,508,530	133,626,062	159,707,689	279,305,062	218,291,473	309,794,066	290,266,870	516,887,462
SS_E	15,418,991	18,572,593	24,272,307	22,741,236	19,539,628	21,791,578	55,217,470	32,981,913
$F_{SDST/SIST}$	0.0719	0.2193	0.1490	0.0800	0.0052	0.0103	0.0011	0.0001
$F_{eq/dom}$	7.7870	5.9675	5.4114	10.8894	9.9397	13.0121	4.1082	14.4076
$F_{interaction}$	0.0593	0.0080	0.0194	0.3125	0.2268	0.1938	0.1475	0.2642

$SS_{SDST/SIST}$ = spread caused by setup dependency, $SS_{eq/dom}$ = spread caused by family proportion,
$SS_{interaction}$ = spread caused by interaction of both factors, SS_T = total spread,
SS_E = spread caused by unaccountable errors, $F_{SDST/SIST}$ = test value for setup dependency,
$F_{eq/dom}$ = test value for family proportion, $F_{interaction}$ = test value for interaction

Table 6.5: Results of variance analysis

η^2_{GD}	Mean flow time	Mean tardiness
FCFS/FCFS	0,9616	0,9193
MS/SPT	0,9656	0,8732
$\frac{\text{MS}}{\text{MJ}}$/SPT	0,9688	0,8294
$\frac{\text{MS}}{\text{MJ}}$/MWKR+SPT	0,9621	0,8224
EDD/TSPT	0,9736	0,8866
$\bar{\text{S}}\text{L}$/TSPT	0,9758	0,8897
$\bar{\text{S}}\text{L}$/SL	0,9767	0,9153
$\bar{\text{S}}\text{L}/\frac{\text{SL}}{\text{MWKR}}$	0,9120	0,7815

Table 6.6: Effect size concerning family dominance

can be identified for varying scenarios for mean tardiness. With a dominating family due date oriented dispatching rules lead to superior results, whereas production flow based rules performed best in settings with equally distributed family sizes.

Furthermore, Figure 6.2 and Figure 6.3 show a significantly higher variance concerning the achievement of objectives for mean tardiness subject to the chosen heuristic. This implies that especially for due date based criteria the selection of an effective heuristic is crucial. This confirms the results by Wemmerlöv.[76] In general, the novel $\frac{\text{MS}}{\text{MJ}}$/SPT heuristic shows the least varying performance subject to the chosen scenario. Concerning mean tardiness the proposed $\bar{\text{S}}\text{L}$/TSPT heuristic is more robust compared to EDD/TSPT, which is known as a preferable heuristic so far.

6.5 Conclusions

In this study we applied several novel heuristics for dispatching a dynamic job shop manufacturing cell. Based on a thorough analysis of previous simulation studies, some research gaps concerning the influencing factors of the type of setup time as well the dominance a single part family could be identified and closed. In summary, following conclusions can be drawn:

- The selection of an effective heuristic is crucial for a shop's performance, particularly concerning mean tardiness.
- The dominance of a part family has a significant impact on the achievement of objectives. This can be explained by fewer setup operations with a dominating family.

[76] See Wemmerlöv (1992): *Fundamental insights into part family scheduling*, pp. 577–579.

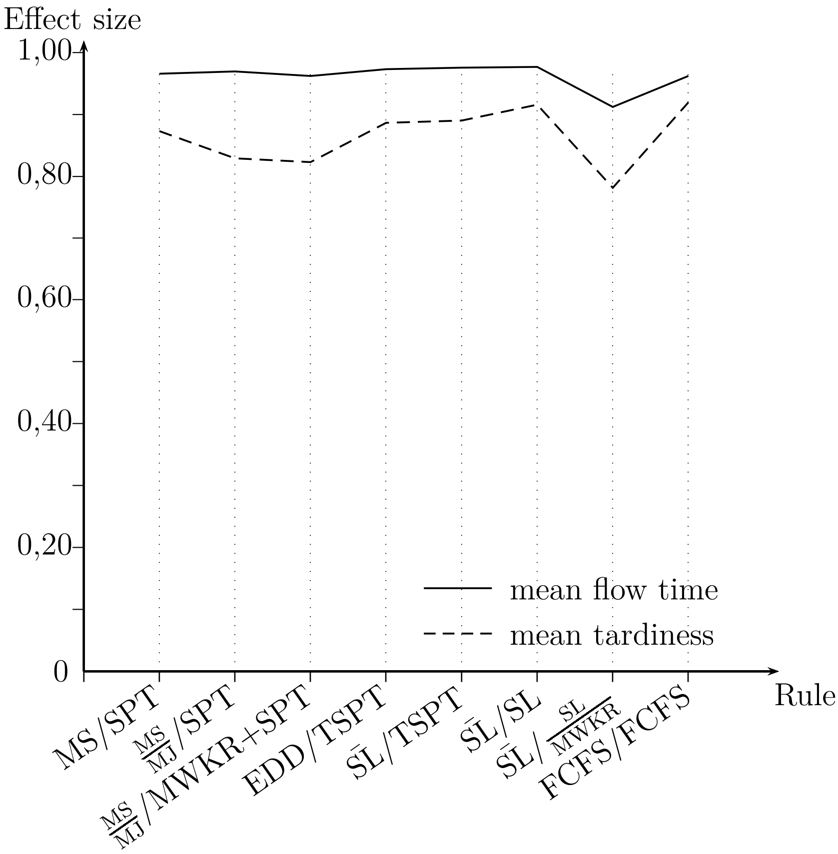

Figure 6.4: Illustration of the effect size concerning family dominance

- The influence of the type of setup times is low and cannot be proven to be significant.
- For mean flow time the ranking of heuristics proves to be very robust with respect to the considered scenarios. In contrast, for mean tardiness criterion the variance regarding the advantageousness of certain heuristics is considerably higher. As an exception, production flow oriented dispatching rules lead to the least tardiness for scenarios with families of equal size.
- For most simulation runs, combined job rules lead to inferior results compared to elementary dispatching rules.
- In general, no significant differences could be identified between the family rules MS- and $\frac{\text{MS}}{\text{MJ}}$ as well as between $\bar{\text{S}}\text{L}$ and EDD. However, for the scenario with no dominating family and SDST, the proposed novel rules lead to a substantial improvement.
- In contrast to previous studies, job rules are proven to have a great impact on the heuristics' performance.

- In total, $\frac{\text{MS}}{\text{MJ}}$/SPT for mean flow time and $\bar{\text{SL}}$/TSPT for mean tardiness are identified as preferable heuristics.

The presented results also point to interesting possible directions for future research. In particular, the interaction of other influencing factors and their effect on the heuristics' performance should be integrated in future simulation studies. Especially, the influence of varying cell configurations and layouts has not been analyzed in detail. The gained insights still have to be verified for flow shop manufacturing cells. Furthermore, additional performance measures should be considered in order to represent the wide range of practical goals more comprehensively. Besides, the consideration of workforce could enhance the model's applicability.

In this study we were able to show that combined family rules can improve the performance and particularly the robustness of two-stage heuristics. Future research should test further combinations of dispatching rules. Moreover, beside dispatching rules more sophisticated heuristics, e.g. based on constructive heuristics such as NEH, could be tested in dynamic environments. Generally, in addition to the various static scheduling models future research should focus on approaches that are able to meet the challenges of practical scheduling systems with changing and uncertain conditions.

7 Conclusions and future research

This work considered the scheduling task in manufacturing cells, which is a major planning activity in order to successfully implement cellular manufacturing. A comprehensive overview on group scheduling research as well as a detailed characterization of the studied problem were given. On this basis, novel problem specific solution methods have been developed, that are more suitable for scheduling jobs and part families efficiently. The proposed algorithms have in common that problem specific characteristics are exploited in order to gain a superior performance compared to existing heuristics. This general approach was applied for different aspects of scheduling in cellular manufacturing environments: For the classical flowshop group scheduling problem with sequence-dependent setup times and for the sequencing problem of a single part family with missing operations constructive heuristics as well as metaheuristic approaches based on variable neighborhood search and simulated annealing have been developed. Thereby, the relevance of the common group technology assumption and its impact on the scheduling task has been of particular interest. Eventually, dynamic cellular manufacturing environments have also been studied in order to evaluate the effectiveness of family based dispatching heuristics.

Within this work, the research questions posed above could successfully be answered. Considering question **Q1**[1] the conducted literature review in Chapter 2 revealed that the classical group scheduling problem with sequence-independent as well as sequence-dependent setup times has been studied widely already. Especially metaheuristic approaches are able to solve commonly used benchmark instances with relative error rates compared to a lower bound of on average less than 0.7 % within reasonable time. This shows that state-of-the-art algorithms are able to solve the flowshop group scheduling effectively and efficiently. Nevertheless, especially the inclusion of multiple manufacturing cells and the enhancement of existing algorithms by problem specific knowledge still unlock potential for further improvements and open areas for research.

Chapter 3 focused on the group scheduling problem with sequence-dependent setup times

[1] What is the current state of research for flowshop group scheduling problems?

in particular. Based on the characteristic structure of family schedules, consisting of head, body and tail, the significance of inserted idle times in family schedules was discussed. Interestingly, a minimization of inserted idle times within each part family can lead to a lower makespan of a group schedule compared to a minimization of makespan for each part family. This finding was integrated in the procedure of several NEH based constructive algorithms, that outperform the commonly used CMD heuristic significantly, which is known as best constructive heuristic. With this, research question **Q2**[2] could successfully be solved. For well-known benchmark instances of the group scheduling problem the proposed constructive heuristic IH'D showed the best results of all known constructive heuristics for the group scheduling problem with sequence-dependent setup times so far.

Research question **Q3**[3] scrutinizes the assumption fundamental for group scheduling whether it is reasonable to process all parts of a part family successively (*group technology assumption*). For this, a novel metaheuristic algorithm based on variable neighborhood search was developed in Chapter 4, which incorporates elements of simulated annealing within its local search phase. A variation of this algorithm appends new neighborhood structures, that allow a splitting of part families in multiple parts and, hence, generates non-exhaustive schedules. While an example showed that a significantly lower makespan can be achieved by this, the computational study indicated small improvements of makespan by non-exhaustive schedules only. Moreover, the splitting of part families led to an increasing complexity of the group scheduling problem and, therewith, the requirement of significantly higher computational effort. This again proves the advantageousness of the group technology assumption which reasonably decomposes the scheduling task in manufacturing cells into two levels that can be solved independently.

The following Chapter 5 concentrated on a different aspect of scheduling part families: due to the combining of unequal parts to one manufacturing cell, usually jobs do not need to be processed on all machines. The arising flowshop scheduling problem with missing operations was object of research question **Q4**[4]. The NPS-set algorithm by Pugazhendhi et al., which generates non-permutation schedules and has successfully been applied to this problem already, was analyzed and enhanced in order to minimize total flow time more effectively. Furthermore, two variations of simulated annealing algorithms were developed and configured using a full factorial design of experiments. In

[2] Can known constructive heuristics be improved by integrating problem specific enhancements, that take the characteristic structure of group schedules into account?

[3] Can a relaxation of the group technology assumption lead to significant improvements of the solution quality for group scheduling problems?

[4] Does the existence of missing operations in manufacturing cells require adjusted heuristic algorithms in order to gain good quality solutions?

order to prove the effectiveness of these novel algorithms extensive computational experiments had been carried out. Especially the modified NPS-set algorithm showed statistically significant improvements compared to the original algorithm for several problem sizes. The results indicate that non-permutation schedules and particularly algorithms that take missing operations into account explicitly should be used preferably to solve the flowshop scheduling problem of jobs in part families.

Finally, a dynamic environment was considered in Chapter 6. Even though several novel dispatching rules have been developed in the last centuries, none of these has been applied and tested in cellular manufacturing since the last simulation study published in 2003.[5] Answering question **Q5**[6] this gap is closed. Based on a detailed analysis of existing simulation studies in dynamic cellular manufacturing environments, the identification and implementation of eight heuristics, that incorporate job as well as family dispatching rules, constituted the core of this chapter. The conducted simulation study used the discrete event simulator *simcron MODELLER*. Evaluating the results revealed that novel combinations of dispatching rules indeed lead to superior results compared to the best performing rules so far. Furthermore, new insights concerning influencing factors, such as the size of part families or a high impact of the job scheduling rule, could be derived.

Despite these expedient insights, still some limitations of this work point to fruitful directions for future research. First, the development of efficient metaheuristic algorithms that incorporate problem specific procedures is worthwhile. Even though effective constructive heuristics, that meet the requirements of flowshop group scheduling problems more appropriately, could be presented in this work, especially the transfer of these ideas to metaheuristics only partly showed significant improvements of the algorithms. Nevertheless, metaheuristics constitute the state of the art for efficiently solving large size scheduling problems. Hence, further research should be conducted on how existing metaheuristic approaches can be enhanced more effectively by problem specific elements. Second, manufacturing systems with several cells as well as the interaction between these should be examined. The given literature review on flowshop group scheduling revealed that the classical group scheduling has been studied widely already, however, especially the consideration of multiple manufacturing cells, the so called cell scheduling problem, has attracted little attention only. Since most practical manufacturing environments consist of several cells, that are not independent from each other completely, material flows between cells (intercellular moves) have to be taken into account. The existence of several part families in each cell in particular, which is common in group scheduling

[5] See Reddy / Narendran (2003): *Heuristics and sequence-dependent set-up jobs.*

[6] Can state-of-the-art dispatching rules and heuristics be applied to dynamic cellular manufacturing systems and improve the performance of a scheduling system?

problems, has not been applied to the cell scheduling problem so far. Furthermore, the differences between the group scheduling problem and the cell scheduling problem have not been pointed out yet. Third, the findings concerning flowshop scheduling problems with missing operations have to be transfered to the classical group scheduling problem. In this work, missing operations have only been considered within a single part family, neglecting major setup times for every changeover of families. Obviously, missing operations are relevant for group scheduling problems with multiple families, too. Jobs with missing operations should be added to group scheduling benchmark instances, while the steps of the proposed modified NPS-set heuristic could be integrated in heuristics for solving both levels of group scheduling. Moreover, it can be ascertained that existing simulation studies in dynamic manufacturing environments still lack generality as they model very specific examples of manufacturing cells only. Due to its high practical relevance, the analysis and investigation of dispatching rules or other simple heuristics should be extended. Finally, other environments and restrictions, such as flexible flowshops or no-wait restrictions, should receive additional attention in order to model real-life manufacturing systems more accurately. With this, scheduling of manufacturing cells remains a promising field for future research.

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