

# **Job Sequencing and Tool Switching Problems with a Generalisation to Non-Identical Parallel Machines**

Classification, Mathematical Formulations and  
Heuristic Solution Approaches

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# Abstract

Manufacturing tools have been dominating the manufacturing process since the 1960s. The job sequencing and tool switching problem is an NP-hard combinatorial optimization that has first been introduced in the context of flexible manufacturing systems in the late 1980s. Since then, production systems have undisputedly changed and improved but manufacturing tools still dominate manufacturing processes. Production and system operation processes are continuously adjusted and optimised to changing customer requirements. If the product variety requires an increasing number of tools for processing that exceeds the local tool magazine capacity of the manufacturing system, tool switches become necessary. Although tool changing times within a manufacturing centre or cell may nowadays be very small due to the high degree of automation, tool switching within a dynamic production environment is still a time consuming process that must be avoided. In order to minimize the total tool setup time to enhance productivity, the objectives of the basic job sequencing and tool switching problem are to sequence a set of jobs and simultaneously to determine the best tool loading. Therefore, job sequencing and tool switching problems are gaining considerable attention.

Several solution approaches to the standard problem and related versions of the problem exist. The first part of this dissertation assesses the current state-of-the-art of the job sequencing and tool switching problem and provides a classification scheme for literature on the job sequencing and tool switching problem and its variations. Only few authors consider generalisations of the problem because the level of complexity of extended problems is high. A general approach of the job sequencing and tool switching problem with non-identical parallel machines and sequence-dependent setup times is described in this dissertation. A novel mathematical model based on time periods is presented and analysed which can be adapted to different objective functions. The last part of this dissertation is a quantitative evaluation of fast and effective construction heuristics as well as of an iterated local search algorithm tested on a new set of benchmark instances. As such this dissertation provides a broad basis for future evaluations of solution approaches to the job sequencing and tool switching problem with non-identical parallel machines and sequence-dependent setup times as well as a basis for further generalisations of the problem like for example tool availability constraints or tool-size dependent variations.

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# I

## Preface

In 2018, the German Machine Tool Builders' Association reported an increasing significance of the machine tool industry driven by automation and customer orientation (German Machine Tool Builders' Association (VDW) 2018); the industry has achieved new historic records in production, exports, and incoming orders and it recorded a 7% growth in production in 2018 (German Machine Tool Builders' Association (VDW) 2019). Machining centres, turning, grinding, milling, press technology, and sheet metal machining still dominate the manufacturing processes (German Machine Tool Builders' Association (VDW) 2019). Interlinked machining centres that offer a high degree of flexibility and re-configurability have become the focus of machine tool customers. The increasing flexibility has permitted machine tools to use and share different tool types for different operations so that an effective tool management is required. Tool management has been discussed since the 1980s when the first flexible manufacturing systems were introduced, and thereupon different combinatorial optimization problems were proposed (Stecke 1983, 1985, Suri and Whitney 1984, Suri 1985, Singhal et al. 1987, Kusiak 1985, 1986, Kiran and Krason 1988, Buzacott and Yao 1986, Gray et al. 1993).

In the context of flexible manufacturing systems, the NP-hard<sup>1</sup> (Crama et al. 2007) job sequencing and tool switching problem (SSP) was first mentioned by Tang and Denardo (1988). The problem environment of the job sequencing and tool switching problem is depicted in Figure 1. It shows that a set of jobs has to be processed on a set of machines or machining centres. The jobs are not identical, which means that they may require different operations and therefore different tools. However, the capacity of the tool magazine of each machine is limited. Tool switches may therefore be necessary between processing of two consecutive jobs. Applications of the problem exist mostly in the metal-working industry, for example for vehicle body parts and tooling components (Shirazi and Frizelle 2001, Crama et al. 2007). Analogies of the problem can be found in electronics industry for sequencing printed circuit boards (Ghrayeb et al. 2003, Tzur and Altmann 2004, Raduly-Baka et al. 2005, Hirvikorpi et al. 2006a, Van Hop and Nagarur 2004), in computer systems (Djellab et al. 2000, Privault and Finke 2000, Ghiani et al. 2007), or in pattern sequencing (Linhares and Yanasse 2002, Yanasse 1997).

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<sup>1</sup> Non-deterministic Polynomial-time (NP) hardness is per traditional definition the class of problem sets that can be decided in polynomial time by a non-deterministic Turing machine (see, e.g. Goldreich 2010)

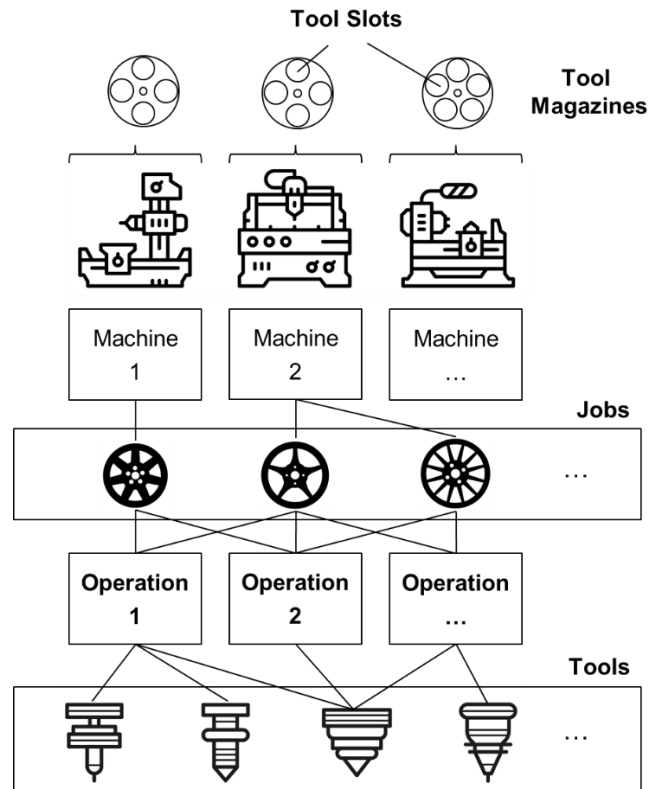


Figure 1. Schematic layout of the problem environment.

Due to the advances in production systems and machining centres, the job sequencing and tool switching problem and variations of it are intensively studied today (Calmels 2019). However, existing models do not represent the current requirements of the industries and should be adapted to larger magazines, many more tools or customized tools and more machines. Although generalized formulations of the classical uniform job sequencing and tool switching problem are required for practical applications, academic research has mainly focused on job sequencing and tool switching problems with a single machine and uniform tool switching times and lacks a common understanding of the job sequencing and tool switching problem as a whole.

This dissertation provides four studies in the field of job sequencing and tool switching. Figure 2 outlines the connection between the individual contributions. The systematic literature review identifies major research gaps and provides recommendations for future research. The literature on tool switching research is spread across several interdisciplinary areas and research gaps are hard to define. Therefore, this dissertation initially aims to define characteristics and attributes of job sequencing and tool switching problems in order to provide a conceptual foundation. Secondly, the generalisation of the uniform job sequencing and tool switching problem is addressed. New mathematical formulations are presented for a generalisation of the job sequencing and tool switching problem with multiple non-identical parallel machines. The evaluation of the formal representations shows the limitation of the mixed-integer linear models for problems of realistic size. Therefore, the efficient construction heuristics and an iterated local search scheme with different perturbation strategies intend to solve even large problem



instances within reasonable computation time. The purpose of the heuristics is to efficiently calculate near-optimal solutions even for large problems. The following paragraphs briefly introduce each paper and their major findings.

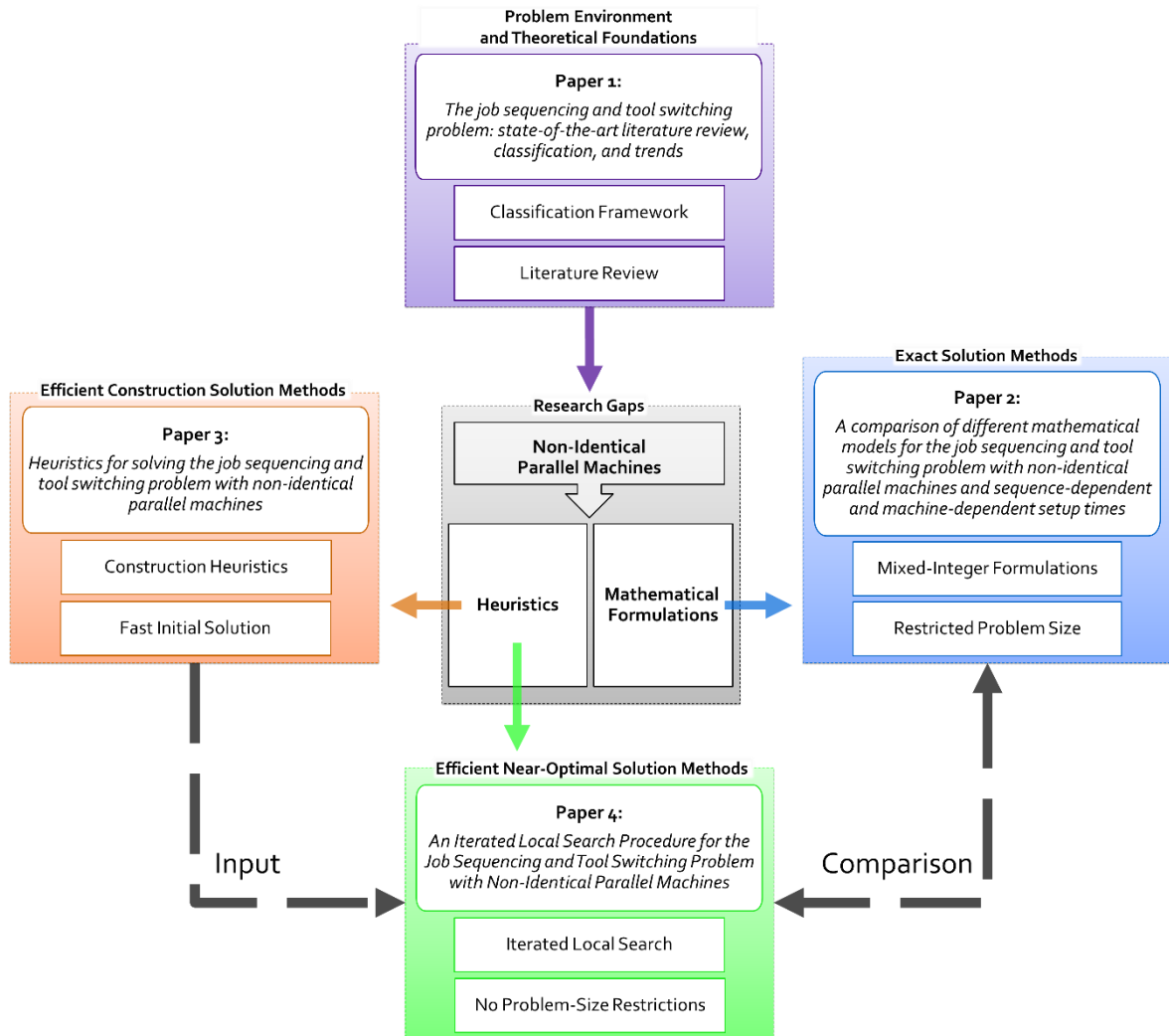


Figure 2. Outline and interrelation of the dissertation studies.

The first paper entitled “*The job sequencing and tool switching problem: state-of-the-art literature review, classification, and trends*” provides a classification framework for job sequencing and tool switching problems as well as a systematic literature review based on the presented classification scheme. Over the past years, different approaches and formulations for tool switching problems have emerged. Yet, existing literature reviews have focused on general concepts rather than specific sub-topics like the job sequencing and tool switching problem. In order to classify the research in this area, and to help identifying which aspects of the tool switching problem have been insufficiently explored, a classification structure for problem characteristics and solution approaches is proposed. The classification specifies two clearly distinct categories “problem perspective” and “solution approach”. In contrast to regular scheduling problems, the problem perspective requires additional categories, for example, “tool wear” and “tool size”. By applying the classification scheme to a structured literature review, the paper shows that the simple

uniform job sequencing and tool switching problem with uniform tool size and sequence-independent setup times has been widely studied. Generalisations of the problem with multiple machines, tool wear or different tool sizes present research gaps and lead to the motivation of the subsequent studies. The analysis of the applied solution approaches shows that only few exact approaches exist. The paper also highlights the lack of benchmark instances and the use of small instances far from realistic problem size. In summary, the first paper reveals the required categories and characteristics that define and classify job sequencing and tool switching problems and discusses the prevailing research gaps in the field of job sequencing and tool switching.

Building on the research gaps and the theoretical framework of the first paper, the second paper presents three different mathematical models for a generalisation of the single uniform job sequencing and tool switching problem. The paper is entitled “*A comparison of different mathematical models for the job sequencing and tool switching problem with non-identical parallel machines and sequence-dependent and machine-dependent setup times*”. The aim of this paper is to examine and compare the performance of three different mixed integer linear programs using a standardized solver, namely IBM ILOG CPLEX. In addition, a new set of publicly available benchmark instances is provided that can be used for further comparison of exact and heuristic approaches. In contrast to existing mathematical models for the job sequencing and tool switching problem, the models are tested for two different objective functions, minimizing total flowtime and makespan. The paper specifically investigates the impact of different problem instances on the solution quality and the computation time of the models. Thereby, it is concluded that the time-index-based formulation provides the worst performance and only very small problems can be solved to optimality. The precedence-based formulation is far more robust than the position-based formulation for minimizing the makespan as stated by Burger et al. (2015) for the single-machine problem. However, the statement of Burger et al. (2015) that the position-based formulation always provides faster results than the precedence-based formulation if the average required number of tools per job is far smaller than the size of tool magazine (i.e. so called *sparse* problems) could only be validated for minimizing makespan. It is shown, instead, that for the job sequencing and tool switching problem with non-identical parallel machines both formulations require significant longer computation times for sparse instances than for dense instances. For minimizing the total flowtime of most of the larger and *dense* problem instances (in contrast to *sparse* problem instances), the precedence-based formulation outperforms the position-based formulation if the computation time limit is high enough. Overall, the results show that only small problems can be solved to optimality within reasonable runtime. This restriction motivates the exploration of efficient heuristics provided by the following papers 3 and 4.

The third paper entitled “*Heuristics for Solving the Job Sequencing and Tool Switching Problem with Non-Identical Parallel Machines*” discusses different construction heuristics and provides a basis for future improvement heuristics. Motivated by the limitations of the mathematical models presented in the second study the third paper aims at providing fast yet effective heuristics for

different objective functions. It is the first paper to present and compare three different greedy strategies for the job sequencing and tool switching problem with non-identical parallel machines with the specific characteristics of machine-dependent processing times and machine- and sequence-dependent setup times. The computational study is based on the problem instances of Beezão et al. (2017) which were modified for non-identical parallel machines. It is shown that for different objectives different strategies should be applied. This study considers the three conflicting objectives: minimizing total flowtime, minimizing makespan and minimizing the total number of tool switches. The greedy heuristic based on the shortest processing time yields the best results for minimizing total flowtime and makespan while the heuristic based on the tool intersection performs best for minimizing the total number of tool switches. It can be concluded from this study that different heuristic strategies have to be applied when dealing with different objective functions. Yet, the greedy heuristics generate only fast initial solutions that require further improvement through improvement heuristics or meta-heuristics. Future research may introduce other construction heuristics and compare them to the presented results.

The fourth paper is entitled “*An Iterated Local Search Procedure for the Job Sequencing and Tool Switching Problem with Non-Identical Parallel Machines*”. The presented algorithm is motivated by the promising results of iterated local search (ILS) algorithms for the single-machine job sequencing and tool switching problem and scheduling problems in general. The new and publicly available sets of benchmark instances cover small and large problems as well as different switching times and tool requirements. The ILS builds on the findings of the construction heuristics of the third article which have been further improved. First of all, the advantages of the construction heuristics with respect to runtime and solution quality are examined. Secondly, the paper contributes three new perturbation methods, each yielding different results for different objective functions. The extensive computational experiments show the merit of the local search phase and the perturbation phase but also their computation limits for large problem instances. The two proposed perturbation methods outperform the popular random perturbation strategy. Another merit of the paper is the analysis of the problem structure. No significant difference was noted for the results with different tool switching times but a significant difference for sparse and dense matrices. In conclusion, this research reveals that the ILS is an efficient method for solving large job sequencing and tool switching problems instances. It is further shown that not only the processing and switching times but especially the structure of the job-tool-requirements may affect the outcome of the computational experiments.

This dissertation is limited to the investigation of an important generalisation aspect of the job sequencing and tool switching problem and additionally to specific solution approaches. Therefore, the following recommendations for further research are provided. The mathematical formulations presented in Section III extend existing formulations by adding sequence-dependent setup times and non-identical parallel machines with different tool switching times and tool capacities. Three further extensions to the model could include, amongst others,

different tool sizes, tool wear and a limited tool availability. Tools are subject to natural wear and, consequently, will break after a certain time or require regrinding. Therefore, a broader model could integrate either deterministic or stochastic tool lifetimes which have received a growing attention in the last years (Dadashi et al. 2016, Farughi et al. 2017, Mauergauz 2017). In this context, different tool lifetime models could be tested and compared. Not least because tools and especially special tools are expensive and require special handling, the tool availability is in reality rarely unlimited so that all tools are never available on all machines at any time. Amongst further extensions of the tool availability, two shall be mentioned. First, available tools can be allocated to machines prior to the processing. This option requires only few change to the existing model; however, it is important to ensure that allocation and the tool capacity of the model allow for feasible solutions. As a second option, tools can be allocated to machines from a shared tool storage. This would mean that it must be known at any time if a tool is in use or available, thus increasing the complexity of the model and requiring newly defined problem instances. Besides the adaptations to the model formulations different solution techniques could be implemented and tested. The literature review shows that among the most promising techniques for the uniform tool switching problem only few have been implemented for multi-machine problems. For example, different meta-heuristic concepts like ant colony algorithms or machine learning techniques may be implemented and compared to the ILS methods proposed in Section V. Last, further research based on the presented ILS strategies could investigate different local search operators or provide combinations of tight heuristic bounds and the presented mathematical models in order to solve even large problem instances to optimality. In summary, the job sequencing and tool switching problem is significant for both research and practice, and with the characterisation and solution of the generalised problem a decisive progress for future research contributions has been accomplished.

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## II

# The Job Sequencing and Tool Switching Problem: State-of-the-Art Literature Review, Classification, and Trends

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### Abstract

*The job sequencing and tool switching problem is a combinatorial optimisation problem that appears in various industries, mainly in the manufacturing sector. Although tool switching is only part of a much larger decision-making process in manufacturing systems, it has a major impact on the overall performance of the system by affecting the total set-up time as well as the machine and tool utilisation. Over the past few decades, various approaches have been applied to tool switching problems. This study provides a comprehensive review of the literature on the job sequencing and tool switching problem. Studies are identified and compared through a structured literature review and classified according to a new framework which allows the identification of problem perspectives and solution methods. The results show that current research does not fully exploit real-world situations and studies are often limited to a single-machine and uniform tool size and set-up time. Finally, this literature review summarises the current research results and provides directions for future research.*

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## **1. Introduction**

Manufacturing companies are facing multiple challenges since the transformation of market requirements towards buyer markets, including high product differentiation and mass customisation (Fogliatto et al. 2012). To overcome the trade-off between economies of scale and economies of scope, one has to review existing manufacturing concepts to cope with the emerging era of ‘industry 4.0’ and ‘smart factories’ (Bi et al. 2008, Brettel et al. 2014). Characteristics of smart factories include high flexibility and automated production operations supported by real-time data collection and analysis (Shrouf et al. 2014). Since the 1980s, manufacturing companies have made use of flexible manufacturing machines (FMM), or even flexible manufacturing systems (FMS) to handle larger product variety, changing customer requirements as well as complex and changing production requirements. An FMS is characterised by a number of numerically controlled machines linked by an automated material flow system. Each machine is equipped with a tool magazine of limited capacity that should hold at least the number of tools needed for processing a single job. Although reconfigurable manufacturing systems (RMS) are an emerging trend in smart factories because they allow the quick integration of new process technology and functionality (Bi et al. 2008, Brettel et al. 2014), FMS still seems promising for future production system purchasing plans (Mehrabi et al. 2002). Whether speaking of RMS or FMS, flexibility and process automation without generating high set-up times are crucial for manufacturing companies to keep up with the market requirements. Whatever system is used, it must provide flexible and different module functions, such as milling, drilling and turning, or tool and work-piece handling operations (Abele et al. 2007). When product variety becomes so large that the number of tools needed for processing a sequence of jobs exceeds the magazine capacity of the flexible manufacturing machine, tool changes will become necessary. In general, to produce different jobs on an FMM, the number of tools required for all jobs is greater than the tool magazine capacity. An automated tool changing device, therefore, is required to interchange the tools needed for the next job in line. In this context, the job sequencing and tool switching problem (SSP) or, for short, the tool switching problem arises. It generally consists of the following two sub-problems: (1) finding the sequence of jobs and (2) the tools to switch on the machine (i.e. the tool loading) before a new job is processed, with the objective of minimising the number of tool switches (a more detailed description can be found in section 2).

Various classification schemes mainly for FMS design, planning, scheduling and control problems exist (see, e.g. Suri and Whitney 1984, Kusiak 1985, 1986, Stecke 1985, Suri 1985, Buzacott and Yao 1986, Looveren et al. 1986, Singhal et al. 1987, MacCarthy and Liu 1993), rather than for classifying specific subtopics, like tool management as in Gray et al. (1993). Different optimisation models and approaches for the tool switching problem have been proposed in the literature. However, no paper summarises the research done in this area. Therefore, the objectives of this study are to:

- comparatively review, in an organised fashion, the existing unclassified tool switching literature with respect to problem formulation development and applied solution methods,
- develop a classification scheme that may help to identify aspects of the tool switching problem that have been insufficiently explored and show how far the existing modelling efforts have progressed towards real-world needs,
- synthesise the past trends of tool switching studies, and
- offer some suggestions and directions for future research.

The remainder of this paper is structured as follows. Section 2 introduces the generic tool switching problem, its sub-problems, and related optimisation problems. Subsequently, the research approach is described in section 3, and the classification framework is described in section 4. The literature review is presented in section 5. Section 6 outlines the research gaps and implications for future research. Section 7 concludes the paper with a short summary.

## 2. The job sequencing and tool switching problem

The SSP is a job scheduling problem where a set of jobs  $J = \{1, 2, \dots, n\}$ , each requiring a predefined set of tools  $T = \{1, 2, \dots, m\}$ , is to be processed on a single flexible machine. The basic or uniform SSP, as first stated in Tang and Denardo (1988a), consists of processing a sequence of  $n$  jobs on a single flexible machine. Each job  $j$  requires a subset of tools  $T_j$  that is to be loaded into the magazine before processing the job. The magazine can hold at most  $C$  tools. Often, the magazine cannot hold all tools at once, so tool switches become necessary for two successive jobs. A tool switch means removing a tool from its slot and inserting another tool in the free slot. The problem, therefore, consists of finding the processing sequence, and simultaneously, the tool loading that minimises the total number of tool switches. The uniform tool switching problem can be characterised by the following major assumptions and problem specifications (see, e.g. Bard 1988, Crama et al. 1994a, Shirazi and Frizelle 2001, Solimanpur and Rastgordani 2012): (i) the objective is to find the job sequence that minimises the number of tool switches, (ii) the set of jobs is to be processed on a single FMM, (iii) the tool sockets are identical and each tool requires only one slot, (iv) only one tool can be changed at a time and tool changing times are constant and are the same for all tools, (v) the set of jobs and the subset of tools required for each job is known in advance, (vi) the number of tools needed for any job is less than or equal to the capacity of the tool magazine, and (vii) the tools do not break or wear out.

The SSP appears in numerous industries (see, e.g. Shirazi and Frizelle 2001, Crama et al. 2007), and related problems exist in different fields. An analogy to the SSP in manufacturing industries can be found in the electronics industry for sequencing printed circuit boards (PCB) (see, e.g. Ghrayeb et al. 2003, Tzur and Altmann 2004, Raduly-Baka et al. 2005, Hirvikorpi et al. 2006b) when different electronic components are to be mounted by component assembly

machines on the PCBs. The machines hold a limited capacity of component feeders so that component switches become necessary between assembling different types of PCBs. In this context, the predominant objective is to minimise the number of component switches. Some authors present problems in computer systems, such as caching and paging problems or k-server problems, that are similar to the tooling problem (see, e.g. Djellab et al. 2000, Privault and Finke 2000, Ghiani et al. 2007). For the latter problem, a set of  $k$  servers and handle requests are represented as vertices in a complete graph. For a sequence of requests, which server to move to the requested vertices must be decided. As moving a server from one vertex to another implies costs, the objective for this problem is generally to minimise the total cost in response to a sequence of requests, as described by Privault and Finke (2000). The minimisation of the tool switching instants, also known as the ‘machine stop minimisation problem’, is a distantly related problem to the SSP, and is discussed by, among others, Tang and Denardo (1988b); Konak and Kulturel-Konak (2007); Konak et al. (2008); Adjashvili et al. (2015) and Furrer and Mütze (2017). It is mentioned here because some authors consider the SSP and the machine stop problem simultaneously. For the machine stop problem, a tool switch is counted any time a machine has to be stopped to remove or insert a tool, regardless of how many tools need to be changed. Notice that, this paper’s attention is restricted to the SSP, therefore, other combinatorial problems in connection with tool management are not considered. Similar problems as mentioned above have only been included if they are directly linked to the SSP. For further details, the interested reader is referred to Gray et al. (1993), as well as Crama and van de Klundert (1996). The next section presents the research approach and conditions of the literature search.

### **3. Research approach**

The study’s focus lies primarily on providing a common ground for future research by presenting a general classification framework with a special focus on applied approaches and solution methods for the tool switching problem. A structured literature review is implemented to conduct the classification process. With FMS and tool switching being an interdisciplinary topic in the fields of production, operations research, manufacturing and engineering, no specific journal search had been applied, but the focus is on general databases. The first idea was to search within the most relevant and high-ranking productions and operations management journals; however, the small number of hits indicated that the research field of tool switching research might be too narrow or more interdisciplinary. Therefore, the review was conducted in the following steps following the guidelines of Bandara et al. (2011):

- (1) Online search: an online computerised search was conducted of various scientific databases using keywords related to tool switching, resulting in the first hit list.
- (2) Removal of duplicates: identical articles were removed by means of title and abstract.
- (3) Relevance screening: subsequently, the second hit list was checked for relevance by reading the abstract and selecting papers that deal with tool switching.

- (4) Backward search: a backward search was performed by examining the literature discussions and references of all relevant papers found, resulting in the final selection.

It should be mentioned that only those articles which have appeared in the English language were included, and non-academic research and book chapters were excluded (Crama et al. 1994b, 1996). To ensure data consistency and relevance across the collection, only publications that contained the keywords ‘tool switch’, ‘tool switches’, or ‘tool switching’ within their title, abstract or keywords were considered. Those search terms that are specific or closely related to the topic of interest were chosen to generate as many appropriate search results as possible. Note that some databases do not provide an abstract search; in those cases, a full-text search had been applied. Although the selection of articles was intended to be exhaustive, the overlooking of relevant articles cannot be excluded.

Table 1 shows the summary of the conducted search procedure. The first search resulted in 1597 hits. However, many duplicates were found because of the relatively broad search in multiple databases. During the search process, some papers appeared that are only distantly related to the tool switching problem, and were excluded in phase (3). These mostly deal with other tool management problems, such as tool selection, tool allocation or path-finding for hole-making processes. One article was selected based on a backward search. Some studies were listed in multiple resources so that, finally, 61 unique papers were selected forming a basis for the proposed classification and review. The next section will cover the features for developing a structured and comprehensive classification scheme.

Table 1. Summary of the literature search.

Data source	T	A	K	F	hits	r/hits <sup>a</sup>
EBSCOhost ( <a href="http://search.ebscohost.com">http://search.ebscohost.com</a> )	✓	✓	✓	–	48	23
Google Scholar ( <a href="https://scholar.google.com">https://scholar.google.com</a> )	–	–	–	✓	1,350	58
IEEE Xplore ( <a href="http://ieeexplore.org">http://ieeexplore.org</a> )	✓	✓	✓	–	4	1
JSTOR ( <a href="http://www.jstor.org">www.jstor.org</a> )	✓	✓	✓	–	2	1
ScienceDirect ( <a href="http://www.sciencedirect.com">www.sciencedirect.com</a> )	✓	✓	✓	–	25	15
Springer Link ( <a href="https://link.springer.com">https://link.springer.com</a> )	–	–	–	✓	94	16
Taylor&Francis Online ( <a href="https://tandfonline.com">https://tandfonline.com</a> )	–	–	–	✓	74	16
Backward search	–	–	–	–	–	1
Total					1,597	133
<b>Final selection</b>						<b>(61)<sup>b</sup></b>

Notes: T = Title Search, A = Abstract Search, K = Keyword Search, F = Full-text Search, r/hits = relevant hits.

<sup>a</sup>Duplicates within database already removed

<sup>b</sup>Duplicates between databases removed

## 4. Classification scheme dimensions for tool switching research

The proposed classification adopts the frameworks of FMS scheduling (see Liu and MacCarthy 1996) and similar problems (see Yenisey and Yagmahan 2014). The following subsections discuss each dimension in detail.

### 4.1. Tool switching problem perspective

The attempt to generalise the basic SSP allowed different problem types to evolve over the past decades. Many different formulations of the tool switching problem and its variants exist. The assumptions from the tool switching literature, as described in section 2 and as mentioned by Bard (1988); Crama et al. (1994a); Solimanpur and Rastgordani (2012), define a basis for the subsections of different problem perspectives by characterising the specifications of the basic SSP. Therefore, Table 2 presents the specifications derived from the assumptions (underlined) and the possible variations of the characteristics. Note that the notation is based on and extends the notation for scheduling problems introduced by Graham et al. (1979). The basic SSP will be classified, for instance, as  $[1/ST_{si}/SO/Tool_{hom}/L_{ks},Seq_u/|T_j| \leq C/TW_{no}]$ .

Table 2. Classification attributes regarding problem perspective.

Descriptor	Attribute	Potential value	Acronym
$\alpha$	Machine setting	<u>single machine</u>	1
		multiple machines	$M$
$\beta$	Set-up information	<u>uniform (sequence-independent) setup time</u>	$ST_{si}$
		non-uniform (sequence-dependent)	$ST_{sd}$
$\gamma$	Objective	<u>single objective</u>	$SO$
		multi-objective	$MO$
$\delta$	Tool size	<u>homogeneous</u>	$Tool_{hom}$
		heterogeneous	$Tool_{het}$
$\epsilon$	Job and sequence information	<u>job list known and sequence unknown</u>	$L_{ks}, Seq_u$
		list known and sequence known	$L_{ks}, Seq_k$
		job list unknown	$L_{no}, Seq_u$
$\zeta$	Tool magazine capacity	<u>number of tools per job <math>\leq</math> magazine capacity</u>	$ T_j  \leq C$
		number of tools per job $>$ magazine capacity	$ T_j  > C$
$\eta$	Tool wear	<u>not included</u>	$TW_{no}$
		included	$TW_{yes}$

The SSP is concerned with a single FMM, even though different configurations of machine layout and material handling devices exist for FMS (see Liu and MacCarthy 1996). Multi-machine FMS, as depicted, e.g. by Keung et al. (2001a), additionally have to share tool handling devices and tools.

Likewise, two variations regarding set-up times will be considered. For the uniform case, the time to change a tool is assumed to be equal for all tools in the uniform case. The exchange of a tool may also depend on the previous tool at a position. Imagine the change of ink cartridges where the time to clean a rechargeable cartridge between a switch from a light to a dark colour

is less time-consuming than a change from a dark to a light colour. In this case, the time to switch a tool may be sequence depended. The job properties are usually known beforehand.

If only the generic SSP is considered, the single optimisation criterion is minimising the number of tool switches. However, the popularity of multi-objective approaches has increased in recent years, and a single criterion might become insufficient for real-world applications or holistic perspectives on manufacturing systems. Possible objectives include, e.g. minimising the makespan or tardiness, or any other scheduling related objective.

The simplification of the problem is also reflected in terms of tool size. In this classification, it is assumed that only two characteristics exist, namely *homogenous tool size*, where each tool fits exactly in one slot, and *heterogeneous tool size*, where different tool sizes can exist so that some tools cover more than one slot (the differentiation is, e.g. mentioned in Stecke 1983).

The sequence of jobs, however, may be unknown or fixed. The jobs and even their properties sometimes follow a stochastic process in dynamic cases. Here, it may be assumed that the identity of the tool that is required at a certain time only becomes known at that time. A fixed sequence simplifies the tool switching problem to the tool replacement problem, or called the ‘tooling problem’, with the objective being to determine the set of tools to be placed on the machine at each instant to minimise the number of tool switches. Tang and Denardo (1988a) prove that the tooling problem is solvable to optimality in polynomial time for uniform tool size by the ‘Keep Tool Needed Soonest’ (KTNS) policy where: (i) no tool is inserted unless it is required by the next job, and (ii) if it is necessary to free some slots to accommodate new tools, the current tools that are kept (not removed) are those needed the soonest.

The tool magazine capacity, in turn, can generally hold at least all the tools necessary for each individual job. In contrast, a scenario where the tool magazine cannot hold all the tools needed for a job and, therefore, implies tool switches not only between different jobs but also during processing a job, may still remain plausible.

The case of tool wear often occurs in practice. The basic model does not include tool wear in its modelling approach, but tools are subject to natural wear and tear and, consequently, will break after a certain period of time.

These attributes and values deducted from the main assumptions for the generic SSP define a selective base for the problem type dimension of the classification scheme. The problem type can be specified using the seven descriptors and one of the values. In the following section, the second dimension is explained to categorise the articles according to underlying solution methods.

#### **4.2. *Tool switching solution methods***

Different mathematical modelling (Math. Model) and solution approaches for solving the SSP both exactly and heuristically exist. However, since the uniform SSP has already been proven to be NP-hard by Crama et al. (2007), solving the SSP becomes inefficient for larger problem

instances with more jobs and tools, as well as for complex problem structures. Thus, particular attention was given to meta-heuristics other than exact and classic heuristic strategies because they have been among the most promising techniques for the past three decades. Table 3 shows the acronyms associated with the different solution methods. The terminology based on Talbi (2009) has been adopted to further divide the exact and approximate methods into several categories. (Note: the table is not an illustration of all types of solution methods found, but roughly a holistic view of solution approaches to identify research gaps.) Exact methods strive for finding an optimal solution, but only a few studies have implemented exact approaches due to the complexity of the SSP. Therefore, exact solutions can only be obtained for small size problems, and a complete enumeration for finding all combinations of the job sequences is quickly becoming inefficient.

**Table 3. Classification attributes regarding the modelling approach or solution method.**

Attribute	Subcategory		Potential value	Acronym	
Math. Model	Integer Programming Model		Integer Linear Programming	ILP	
			Nonlinear Integer Programming	NLP	
	Mixed Integer Programming Model		Mixed Integer Programming	MILP	
			Mixed Integer Nonlinear Programming	MINLP	
Exact	Brach & X		Branch & Bound	BB	
			Branch & Cut	BC	
Heuristic	Construction Heuristics		Nearest Neighbour	NN	
			Best Insertion	BI	
			Farthest Insertion	FI	
			Shortest Edge	SE	
			Partitioning	PART	
	Improvement Heuristics	Classic Strategies		2-opt	2-opt
		Meta-heuristics	Single Solution Based	Simulated Annealing	SA
				Tabu Search	TS
				Local Search	LS
				Adaptive Large Neighbourhood Search	ALNS
			Population Based	Genetic Algorithm	GA
				Ant Colony Optimisation	ACO
			Hybrid	Memetic Algorithm	MA

The technological progress and tighter formulations of mathematical models for the tool switching problem resulted in constantly improving results for larger problem instances. Nevertheless, heuristics for the tool switching problem are able to produce good quality solutions more efficiently, as the following section will reveal. The exact and heuristic solution methods as well as the classification will be discussed in the following.

## 5. Literature review

Next, the reviewed papers are grouped and analysed, taking into account the aspects discussed in the previous section using the two dimensions, problem perspective and solution method, that describe the relevant characteristics of tool switching problems. The problem type attributes are used to specify distinct problem types; however, due to the interrelation of the attributes, some articles have been assigned to multiple problem groups. A table summarises, at each section, the papers sorted in sequence of their date of publication.

### 5.1. The uniform SSP

The first problem group is dedicated to the uniform SSP that was used as a basis for defining different problem types. The uniform SSP is the most popular problem in the tool switching research. It was introduced by Tang and Denardo (1988a) and has the longest history of research. This specific case of a tool switching problem deals with finding the sequence of jobs and the loading schedule for the tool magazine that minimises the number of tool switches, as already described in section 2. It is often called uniform because of the uniform and sequence-independent set-up times as well as the uniform tool size. The problem type of the uniform SSP can be classified as  $[1/ST_{si}/SO/Tool_{hom}/L_{ks,Seq_u}/|T_j \leq C/TW_{no}]$ . The presented uniform SSP models and approaches are summarised in Table 4.

Bard (1988) formulates the tool switching problem as an NLP and applies a Lagrangian relaxation approach to obtain a job sequence with feasible tool loading followed by a local search technique using KTNS to explore neighbouring sequences. Almost at the same time, Tang and Denardo (1988a) present a MILP formulation for the tool switching problem that provided poor results for even small problems. Therefore, they propose a greedy perturbation method that comprises a greedy procedure to generate good job schedules, applying KTNS to determine the total number of tool switches and a perturbation procedure to improve the job sequence.

Crama et al. (1994a) show that the uniform SSP can be formulated as a travelling salesman problem (TSP). They present several TSP-based construction and improvement strategies. The examined construction heuristics are SE, NN, FI and BB (FI yielding the best results). Thereafter, they apply block minimisation techniques based on NN and FI. In addition, a simple greedy technique and an interval heuristic are proposed. Within the classic improvement heuristics, they propose a global and a restricted 2-opt, and a load-and-optimize strategy. Lastly, Crama et al. (1994a) combine the best construction heuristics (FI; FI Block Minimisation; simple greedy; interval heuristic) with the global 2-opt method. It turns out that the nature of the problem instance, specifically the density of the job-tool-matrix, affects the performance of the heuristics. A job-tool-matrix is a matrix with a 1-entry if a job requires a tool, and a 0-entry if not. For sparse problems, the simple greedy heuristic performs well, whereas TSP-heuristics perform very poor. Hertz et al. (1998) propose several TSP-based heuristics as well, in particular,



insertion methods, and a variation of NN and 2-opt. The performances of the heuristics show that there is a big trade-off between solution quality and computation time.

**Table 4. Literature overview of the uniform SSP.**

References	Solution category	Mathematical formulation/solution approach
Bard (1988)	math. model, heuristic	NLP/lagrangian relaxation + LS
Tang and Denardo (1988a)	math. model, heuristic	MILP/greedy perturbation
Crama et al. (1994a)	heuristic	several TSP-based construction and improvement heuristics
Follonier (1994)	heuristic	TS
Privault and Finke (1995)	heuristic	BI, Next Best, Super Task
Hertz et al. (1998)	heuristic	several TSP-based construction and improvement heuristics
Djellab et al. (2000)	heuristic	hypergraph/IBI
Privault and Finke (2000)	heuristic	Partitioning
Shirazi and Frizelle (2001)	heuristic	comparison of heuristics proposed by Crama et al. (1994a), Follonier (1994), Privault and Finke (1995)
Yanasse and Pinto (2002)	exact	network flow problem
Al-Fawzan and Al-Sultan (2003)	heuristic	TS
Laporte et al. (2004)	math. model, exact	ILP / BB, BC
Zhou et al. (2005)	heuristic	BS
Karakayalı and Azizoğlu (2006)	exact	BB
Salonen et al. (2006)	heuristic	improvement heuristics (grouping and 2-opt)
Ghiani et al. (2007)	exact	BB
Amaya et al. (2008)	heuristic	GA, MA, HC
Senne and Yanasse (2009)	heuristic	BS
Amaya et al. (2010a)	heuristic	COOP, LS
Amaya et al. (2010b)	heuristic	COOP, MA
Ghiani et al. (2010)	exact	least-cost hamiltonian cycle/BC
Amaya et al. (2011)	heuristic	COOP, MA
Amaya et al. (2012)	heuristic	GA, MA, TS, HC, SA
Amaya et al. (2013)	heuristic	cross-entropy based MA
Burger et al. (2015)	heuristic	grouping
Catanzaro et al. (2015)	math. model, exact	ILP / BC
Chaves et al. (2016)	heuristic	CS + BRKGA
Paiva and Carvalho (2017)	heuristic	ILS
Schwerdfeger and Boysen (2017)	math. model, heuristic	MILP/decomposition
Ahmadi et al. (2018)	heuristic	dynamic Q-learning-based GA

Privault and Finke (1995) study four heuristics related to the TSP-heuristics previously presented by Crama et al. (1994a). The so-called ‘Super Task’ method repeatedly groups jobs that use identical tools into partial orders followed by a restricted 2-opt method. ‘Farthest Insertion’ selects jobs for rearrangement within the sequence based on an approximation of the number of tool switches. The ‘Next Best’ method is a greedy heuristic that successively generates a sequence by adding the job to the partial sequence that matches best to the current tool loading. The tool that is least needed by the remaining jobs is unloaded if a tool has to be switched. The fourth method, PART, an adaption of partitioning heuristics, generates the job sequence based on the ‘Next Best’ method. It considers the actual loading of the magazine and

replaces tools that are not needed or least needed by future jobs. The results indicate that ‘Super Task’ is able to quickly generate good solutions, whereas PART can obtain high-quality solutions even for large problems in an acceptable running time. Later, Privault and Finke (2000) show the analogy of the SSP in a computer-related environment of a k-server bulk request. They compare a partitioning algorithm to a grouping and the farthest insertion method. The TSP-based grouping and insertion heuristics give rather poor results. The partitioning algorithm performs well in terms of solution quality, whereas running times are relatively high.

Follonier (1994) applies TS for a number of problem instances with up to  $n = 60$  jobs and  $m = 90$  tools and four different tool magazine capacities. Two different initial solution strategies, a randomly generated job sequence and a job sequence using best position insertion (BPI), as well as a global-2-opt improvement strategy are considered. The TS that starts from the BPI sequence provided the best results in terms of objective function value, but in terms of CPU time, it was far slower than the greedy heuristics. The use of the improvement strategy considerably improved the solution quality, but it required a large amount of CPU time.

Djellab et al. (2000) consider the tool switching problem and present a hypergraph representation. An iterated best insertion (IBI) algorithm is developed and compared to a simple greedy, multi-start greedy (MSG), global and restricted 2-opt. The IBI yields better solutions than the algorithms compared.

Shirazi and Frizelle (2001) provide an empirical study showing that companies do not use optimisation algorithms proposed in the literature, and thus, have huge optimisation potential for their tool switching operations. They apply the methods proposed by Crama et al. (1994a); Privault and Finke (1995) and Follonier (1994) to large real-world cases with up to 62 different jobs and up to 302 tools. MSG, BPI, and FI are the techniques that consistently performed well.

Al-Fawzan and Al-Sultan (2003) present six versions of a TS heuristic consisting of a diversified search procedure using swap mutation and/or block insertion and tabu lists based on short-term and long-term memory structures. The tool loading of each job sequence is subsequently improved by the KTNS policy. The computational results show that long-term memory structures, like the applied frequency based memory structure that diversifies the neighbourhood search by penalising neighbours attainable through frequent moves, have a significant effect on the performance of the algorithm.

Two years after Yanasse and Pinto (2002) presented the tool switching problem as a network flow problem, Laporte et al. (2004) proposed an integer linear programming (ILP) formulation with tighter bounds than the MILP formulation of Tang and Denardo (1988a). Furthermore, Laporte et al. (2004) present two exact methods, BC and BB, for the uniform tool switching problem. Their BC algorithm can find optimal solutions for small size problems with up to  $n = 10$  jobs only, whereas the BB algorithm is able to solve problem instances with up to  $n = 25$  jobs and  $m = 25$  tools to optimality within the predetermined computing time of 3600 seconds. Karakayalı and Azizoglu (2006) propose a BB algorithm for the tool switching problem with a minimum total flowtime objective. They implement improved precedence relations and

several bounding techniques for moderate size instances of the tool switching problem. Ghiani et al. (2007) propose a further BB algorithm based on Laporte et al. (2004) with a different branching rule. They provide optimum solutions for testing instances with up to  $n = 10$  jobs and  $m = 10$  tools. Ghiani et al. (2010) formulate the tool switching problem as a nonlinear least cost Hamiltonian cycle problem and provide a BC algorithm that is able to solve problem instances with up to  $n = 45$  jobs and  $m = 30$  tools. Recently, Catanzaro et al. (2015) presented three ILP formulations for the tool switching problem with tighter lower bounds than Laporte et al. (2004). The results of their BC show faster running times than the existing formulations, and yet, none of the new formulations were able to solve instances with more than 10 jobs, 10 tools and a magazine capacity of six.

Zhou et al. (2005) propose a Beam Search (BS) heuristic to formulate a set of job sequences with only one node being selected for each level on a search tree. The beam search applied on the test instances of Bard (1988) shows promising results compared to the heuristic presented in Bard (1988) in terms of the average number of tool switches per problem set. Senne and Yanasse (2009) also propose three Beam Search heuristics. All three techniques are depth-first strategies and are applied to randomly generated data, as proposed by Laporte et al. (2004). The strategy where at each node only the best three branches are kept performs best.

Salonen et al. (2006) consider the basic tool switching problem and propose an iterative group minimisation heuristic GMSA3. Iteratively, jobs are grouped into a ‘super job,’ and are improved by KTNS and 2-opt without exceeding the magazine capacity, including the concept of the GENIUS heuristic by Hertz et al. (1998). GMSA3 is similar to the ‘super task’ method by Privault and Finke (1995) where, conversely, grouping is only performed once. They use randomly generated test instances as well as real-world production data in PCB assembly to compare their algorithm with a number of different construction and improvement methods. The GMSA3 algorithm shows fast running times even for large real-world problems but cannot compare to the GENIUS heuristic by Hertz et al. (1998) in terms of solution quality.

Amaya et al. (2008) present an MA for the basic SSP, combining GA with a local improvement scheme. Therefore, they propose a GA based on the alternating position crossover scheme, which selects alternating genes of parent solutions and a mutation operator based on swapping blocks of genes, called Random Block Insertion. The local search strategy comprises a neighbourhood structure, known as the all-pairs neighbourhood (solutions differ in two positions of the sequence), and a steepest-ascent hill climbing (HC) approach. The KTNS policy is used to further improve the fitness of the candidate solutions. Amaya et al. (2008) provide test datasets with up to 50 jobs, 60 tools and a machine capacity up to 30 tool slots. The computational results show that the MA significantly outperforms GA and HC when the number of jobs increases. Amaya et al. (2010a), Amaya et al. (2010b) and Amaya et al. (2011) address the area of parallel meta-heuristics, particularly cooperative search algorithms, which means that several running algorithms or so-called parallel cooperating agents search for a solution in the whole solution space. Amaya et al. (2010b) propose four cooperative methods,

three with a specific interaction structure endowed with LS, and one model with a specific search, diversification, and intensification (SDI) technique. Only the results from the cooperative SDI technique seemed promising, but they were still inferior to the MA plus HC proposed by Amaya et al. (2008). At about the same time, Amaya et al. (2010a) and Amaya et al. (2011) extend the above mentioned cooperative scheme and combine the features of memetic agent models supported by different LS mechanisms, namely HC and TS. The results show that especially heterogeneous memetic agents that exchange current best solutions outperform individual agents. Amaya et al. (2012) extend their previous research for the basic SSP on hybrid meta-heuristics by a variety of memetic algorithms. They propose a partial or full examination of the neighbourhood, as well as a uniform-cycle crossover method, plus various improvement strategies, namely TS, HC and SA with an arithmetic, geometric or adaptive cooling scheme. TS is found to be the most effective strategy compared to the other non-hybrid strategies. However, the memetic algorithms mostly outperform non-hybrid algorithms. Particularly, the MA combined with HC and a partial neighbourhood search shows the best results regarding solution quality and computational cost. Lastly, Amaya et al. (2013) present cross-entropy based memetic algorithms with different local search components. Other than classic memetic algorithms, they are based on the use of probability distributions by minimising the cross-entropy distance to a target distribution. Results show that cross-entropy based memetic algorithms perform well compared to classic MAs, especially with multiple probability mass functions.

Burger et al. (2015) present heuristics for the tool switching problem in the context of the printing industry. A tool switch corresponds to a wash of an ink cartridge that needs to be replaced for some other colour needed for the consecutive job. Burger et al. (2015) decompose the problem into two sub-problems, a job grouping, and a group sequencing problem, solving them successively. Randomly created problem instances, as well as real-life instances, are solved with the job grouping and group sequencing heuristic, as well as using a solver for the mathematical formulations of Tang and Denardo (1988a) and Laporte et al. (2004). The average number of washes is decreased by over 60% for the real-life case. As for the random instances, the heuristic performs well, especially in cases where the maximum number of tools for any job is only slightly smaller than the tool magazine capacity. Burger et al. (2015) remark that the difference in the number of tools per job and magazine size influences the performance of the solution method and that this should be further investigated.

Chaves et al. (2016) present a Clustering Search (CS) technique for the basic SSP that is able to identify promising regions of the search space by generating solutions with a Biased Random Key GA (BRKGA) and clustering the solutions for further intensification of the neighbourhood using the Variable Neighbourhood Search. The results of CS + BRKGA are compared to a generic iterated local search (ILS) method and a stand-alone BRKGA. Although CS + BRKGA shows high running times compared to BRKGA, the solution quality is slightly better than ILS and BRKGA. Paiva and Carvalho (2017) present an ILS metaheuristic that outperforms the CS + BRKGA algorithm of Chaves et al. (2016) for test instances of different studies. Their ILS

metaheuristic is based on a new graph representation for which they develop a graph search based heuristic that analyses the relationship between tools and a local search method based on block grouping. Overall, the metaheuristic shows robust and promising solution quality and running time performance.

Schwerdfeger and Boysen (2017) discuss the similarity between the uniform SSP and sequencing orders from a crane-supplied pick face, where the picking orders represent jobs and the stock keeping units indicate the tools. The pick face capacity symbolises the magazine capacity of an FMS. Schwerdfeger and Boysen (2017) elaborate that not minimising the number of tool switches, but minimising the maximum number of switches between successive jobs, is more suitable for this related problem. They present an adapted version of the MILP by Tang and Denardo (1988a) and propose a heuristic decomposition procedure as well as a BB method. Both methods yield satisfactory results.

Recently, Ahmadi et al. (2018) showed that the SSP can be formulated as a TSP of second order (2-TSP). They present a dynamic Q-learning-based GA that is seeded by the solutions obtained from solving the SSP as 2-TSP. The GA uses roulette wheel selection, partially mapped crossover and random swaps and, moreover, an adaption of the block minimisation heuristic by Paiva and Carvalho (2017). Additionally, feedback on the quality of the solutions is given through the Q-value which rewards the generation of off-springs of higher quality. The proposed algorithm is compared to GA heuristics without learning; its solution quality is significantly higher than the standard GA methods without showing a significant difference in the computation time.

## 5.2. Variations with multiple machines

This section considers the SSP with multiple machines. The machine type used is stated for each article. Research in this area focuses especially on parallel machines with uniform or non-uniform magazine capacities. The articles are chronologically sorted in Table 5. All articles are classified as  $[M/ST_{sd}/SO/Tool_{hom}/L_{ts},Seq_u/|T_j|\leq C/TW_{no}]$ .

A multi-stage problem with interlinked different machines is presented by Bard (1988). An NLP is given for the tool switching problem with multiple tandem machines that is solved to optimality for test problems with two machines and up to 20 jobs, 36 tools and a capacity of 24. Tandem machines are lined one behind another, and the job sequence remains fixed between machines. Each machine has its own capacity and tool set, so the objective is to find the sequence that minimises the number of tool switches for all machines.

**Table 5. Literature overview of approaches with multiple machines.**

References	Solution category	Math. model/ solution approach
Bard (1988)	math. model	NLP
Khan et al. (2000)	heuristic	Greedy
Fathi and Barnette (2002)	heuristic	construction and improvement heuristics, LPT
Ghrayeb et al. (2003)	math. model, heuristic	NLP/construction heuristics
Van Hop and Nagarur (2004)	math. model, heuristic	NLP/GA
Sarmadi and Gholami (2011)	math. model	MINLP
Özpeynirci et al. (2016)	math. model, heuristic	MILP/TS
Beezão et al. (2017)	math. model, heuristic	ILP/ALNS
Gökgür et al. (2018)	heuristic	constraint programming

Khan et al. (2000) present a greedy heuristic for the SSP with two identical parallel machines. Fathi and Barnette (2002) present three heuristics for multiple parallel machines; an improvement procedure tested for combinations of different local search strategies (insertion and exchange) was compared to a list processing heuristic (LPT) and a constructive heuristic that starts with an MSG heuristic for the corresponding single-machine problem and then generates a subsequence for each machine. The most promising results were obtained with the improvement procedure, although the CPU time was slightly higher. Beezão et al. (2017) present two ILPs for the tool switching problem with parallel machines and specified processing times. The ILPs are based on the formulations of Tang and Denardo (1988a) and Laporte et al. (2004), with the altered objective of minimising the makespan. The first formulation obtains better results, yet both formulations struggle with instances of 15 jobs. Therefore, they present an ALNS heuristic that they compare to the improvement heuristics of Follonier (1994) and Fathi and Barnette (2002). Even for very large generated problem instances with up to 200 jobs, 10 machines and 40 tools, the ALNS clearly outperforms the improvement heuristics.

Ghrayeb et al. (2003) and Van Hop and Nagarur (2004) consider the SSP in the environment of scheduling printed circuit packs (PCP) (jobs) on multiple parallel sequencers (machines), each equipped with a fixed but non-uniform number of dispensing heads (magazine) that can be loaded with the required different input tapes (tools). Ghrayeb et al. (2003) assume a demand greater zero for each PCP, therefore the assignment of the PCPs to a sequencer is limited to a maximum allowable load to balance the workload across all sequencers. They present an NLP as well as a fast construction heuristic, but the results are not as good compared to some of the TS heuristics presented by Al-Fawzan and Al-Sultan (2003). Van Hop and Nagarur (2004) present an NLP to find the optimum processing and loading sequences for each machine to minimise the total makespan. A Genetic Algorithm (GA) is tested on instances with up to 55 different PCBs, 3 machines and a magazine capacity of 250. The GA is found to be significantly efficient measured upon the INLP's lower and upper bounds.

Sarmadi and Gholami (2011) present a MINLP for a variation of the basic SSP with more than one flexible manufacturing machine. They assume identical machines with the same working conditions but different magazine capacities. The model that they present is basically

an assignment and sequencing model that, in the process, optimises tool loading. They solve small problems with up to 15 jobs, 10 tools, and 3 machines to optimality.

Özpeynirci et al. (2016) and Gökgür et al. (2018) investigate the SSP for unrelated parallel machines to minimise the makespan without considering capacity constraints or tool switching time but including a limited amount of tool copies. Özpeynirci et al. (2016) present two MILP models as well as a tabu search heuristic due to the weak performance of the mathematical models for this NP-hard problem. Gökgür et al. (2018) consider a constraint programming approach for the same problem.

### 5.3. Variations with sequence-dependent set-up times

This section suffers from the negligence of some authors to state the properties of set-up times. In most cases, set-up time is sequence-independent and uniform, in some cases, it is non-uniform but known beforehand, and as shown in section 5.5, sometimes it is tool-size dependent. This section presents the only article by Privault and Finke (1995) , noted as  $[1/ST_{sd}/SO/Tool_{hom}/L_{k_s},Seq_k/|T_j|\leq C/TW_{no}]$  that directly states its consideration of non-uniform set-up times, although many mathematical models or heuristics described in the present study can be adapted to sequence-dependent set-up times. They provide a max-flow-min-cost model for solving the tooling problem with non-uniform set-up times. This general version of the tooling problem considers that the exchange of a tool may depend on the previous tool at that position. This model can also be applied to the uniform tooling problem with equal set-up times as an alternative to the KTNS-method.

### 5.4. Multi-objective approaches

This section considers problems that do not use single objective optimisation. The articles are chronologically sorted in Table 6.

Table 6. Literature overview of multi-objective approaches.

References	$\alpha$	$\beta$	$\gamma$	$\delta$	$\varepsilon$	$\zeta$	$\eta$	Math. model/solution approach
Keung et al. (2001a)	M	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_u$	$ T_j \leq C$	$TW_{no}$	GA
Keung et al. (2001b)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_u$	$ T_j \leq C$	$TW_{no}$	GA
Solimanpur and Rastgordani (2012)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_u$	$ T_j \leq C$	$TW_{no}$	ACO
Adjashvili et al. (2015)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_u$	$ T_j \leq C$	$TW_{no}$	lex-minimisation
Baykasoglu and Ozsoydan (2017)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_k$	$ T_j \leq C$	$TW_{no}$	SA
Furrer and Mütze (2017)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_u$	$ T_j \leq C$	$TW_{no}$	BB-based framework
Mauergauz (2017)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_u$	$ T_j \leq C$	$TW_{yes}$	greedy
Baykasoglu and Ozsoydan (2018)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s},Seq_u$	$ T_j \leq C$	$TW_{no}$	SA, multi-start SA

Keung et al. (2001a) present a multi-objective approach to the tool switching problem with the objectives of simultaneously minimising the number of tool switches, as well as minimising the number of tool switching instants. Their GA provides good solutions within a reasonable computation time. The test problems, however, are relatively small, with  $n = 10$ ,  $m = 9$  and  $C = 4$ . In the same year, Keung et al. (2001b) proposed another GA for the before mentioned multi-objective tool switching problem. They include tool assignment to multiple parallel machines and extend the tandem machine formulation of Bard (1988) by integrating the objective of minimising the number of switching instants. The best results for the two-phased mixed-gene approach are achieved with 1-point crossover and inverse mutation, doubling the mutation rate when the algorithm starts to converge. They find that the GA is effective for their type of problem. However, they use only very small instances with  $n = 10$  jobs and  $m = 9$  tools. Adjashvili et al. (2015) study the problem of minimising the number of switching instants or stops, including a processing time for each job as well as a tool-specific set-up time and assuming that each stop is long enough to complete all set-ups during the stop. The article is listed in this review because it introduces the idea of lex-minimisation of switching instants and tool switches. They show that for a given stop plan, it is possible to find an optimal and feasible tool switching plan. Furrer and Mütze (2017) extend the work of Adjashvili et al. (2015) by introducing a BB-based algorithmic framework that they analyse on randomly generated as well as real-world problem instances.

The problem of minimising the number of tool switches as well as the rotation speed of the tool turret is addressed by Solimanpur and Rastgordani (2012). The objective function is to minimise the sum of tool switching time and indexing time. Solimanpur and Rastgordani (2012) apply an ant colony optimisation approach to randomly generated test data, and compare it to an adaption of the multi-start greedy heuristic provided by Shirazi and Frizelle (2001). The ACO consistently obtains better, i.e. lower, objective function values for all problem instances, with only slightly higher (less than 2 seconds) running times. However, compared to other studies, the problem size is kept relatively small, with up to 7 jobs and a maximum magazine capacity of 15. Further, the number of tools per job and the capacity are equal, i.e. the magazine is always fully loaded, and no empty slots have to be filled up (e.g. by using KTNS). Baykasoğlu and Ozsoydan (2017) and Baykasoğlu and Ozsoydan (2018) address the same problem for a given sequence and with tool duplications without referring to the prior study of Solimanpur and Rastgordani (2012). Baykasoğlu and Ozsoydan (2017) present an SA algorithm that they evaluate with a lower-bound measure on randomly generated problem instances. Baykasoğlu and Ozsoydan (2018) include a dynamic component by allowing tool switching time and lot size to change during an ongoing production schedule. They propose a conventional SA, as well as an SA with multiple starts for the objective of minimising the makespan. The SA with multiple starts outperforms the conventional SA at each generation.

Mauergauz (2017) presents a multi-objective approach for the tool switching problem with tool wear and different fixture types and job due dates. The article will be discussed in the following section due to its specific tool wear characteristic.



### 5.5. Tool size and capacity constraint variations

The tool magazine of the uniform SSP is able to hold all the tools necessary for processing all jobs, and each tool only requires one slot. This section analyses variations with non-uniform tool sizes as well as relaxed capacity constraints, the latter indicating that a single job may require more tools than the magazine can hold. Table 7 shows a summary of the articles discussed in this section.

**Table 7. Literature overview of tool size and capacity variations.**

References	$\alpha$	$\beta$	$\gamma$	$\delta$	$\varepsilon$	$\zeta$	$\eta$	Math. model/solution approach
Rupe and Kuo (1997)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_k$	$ T_j  \leq C$	$TW_{no}$	NLP/GTNS
Rupe and Kuo (1997)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{no}$	MSG
Matzliach and Tzur (1998)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{no}$	dynamic heuristics
Matzliach and Tzur (2000)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_k$	$ T_j  \leq C$	$TW_{no}$	ILP/construction heuristics
Tzur and Altmann (2004)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_k$	$ T_j  \leq C$	$TW_{no}$	KSTNS
Tzur and Altmann (2004)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{no}$	ILP/ALADDIN
Van Hop (2005)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_u$	$ T_j  > C$	$TW_{no}$	ILP/greedy heuristic
Raduly-Baka et al. (2005)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{no}$	TLSM-heuristic
Hirvikorpi et al. (2006b)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{no}$	ILP/greedy heuristics
Crama et al. (2007)	1	$ST_{ij}$	SO	$Tool_{het}$	$L_{k_s}, Seq_k$	$ T_j  \leq C$	$TW_{no}$	proof NP-complete

Rupe and Kuo (1997) present a GTNS-policy (*‘get tool needed soonest’*) for the SSP with a given job sequence when a job could require more tools than slots available in the magazine. The policy is similar to the KTNS-policy for the uniform SSP. They give a nonlinear model for this problem as well as a modified model for tool changes concurrent with the job changes. Moreover, they propose a heuristic approach similar to the MSG-heuristic by Crama et al. (1994a) if the job sequence is unknown. Only later, Crama et al. (2007) show that the SSP with a uniform tool size and a given job sequence with a heterogeneous tool size is NP-complete, and it is optimally solvable in polynomial time for a fixed tool magazine capacity value by treating it as a shortest path problem in a directed graph.

Matzliach and Tzur (1998) show that the tool switching problem with non-uniform tool sizes is NP-complete for the case where the physical location of the tools in the storage is ignored. They analyse this problem in the context of storage management of items in two different warehouses, where the capacity of the warehouse stands for the capacity of the tool magazine. An item request is made to the nearest warehouse, which is not capable of storing all items that may be required. The sequence of the requested items is known, and the cost of transferring an item is dependent on its size. The objective is to minimise the total transferring cost. They develop two different construction heuristics. For the first scenario, with only one item requested at a time, no heuristic performs best when compared to the optimal solutions computed through an IP model. Matzliach and Tzur (1998) also study the dynamic tool switching problem with non-uniform tool sizes. They introduce three heuristics to handle the

switching of non-uniform tools, considering stationary and non-stationary demand distributions of tools with respect to past information on tool requirements. Hirvikorpi et al. (2006b) extend the work of Matzliach and Tzur (1998) by introducing reorganisation costs for insertion, removal and moving of tools with different sizes. They present an integer programming model for this variation of the tool switching problem in the context of PCB assembly. They assume that, first, tools can have different sizes, and hence, their width can cover more than one slot, and second, that each job only requires one tool. During their research, they extend the problem to multiple tools required per job. However, due to the complexity of the problem and the inability to solve instances of this problem within reasonable time, they do not use a solver but use the exact solution method of Matzliach and Tzur (2000) to calculate optimal solutions for the problem sets. The problem sets' tool switching costs are either tool-size dependent or equal. Hirvikorpi et al. (2006b) further present three heuristics, one of which is based on the iterative greedy approach given by Matzliach and Tzur (2000) for the problem with only one tool per job, and two for the extended version. Hereby, the heuristic where tools are inserted step by step clearly outperforms the heuristic where tools will be removed, sorted, and reinserted as one 'super-tool'.

Whereas the KTNS-policy is mostly used to improve the tool loading of heuristically generated sequences for the uniform SSP, Tzur and Altmann (2004) propose a variation of this policy for the SSP with non-uniform tool sizes, which they call KSTNS ('keep smallest tool needed soonest'). The tools are kept in the magazine with respect to their soonest use, but also with respect to their size. Moreover, they present an ILP for the SSP with non-uniform tool sizes and a tool-size independent transfer cost. The CPLEX solver could only solve very small instances with 5 jobs and 5 tools. Therefore, Tzur and Altmann (2004) propose a heuristic approach ('ALADDIN') that they compare to an adapted version of the most promising previous approaches by Crama et al. (1994a) and Hertz et al. (1998) to the uniform SSP. An important feature of the SSP with non-uniform tool sizes is the physical placement of the tools within the magazine because even if enough slots are available, a bigger tool needs a continuous block of free slots, therefore, the tool arrangement within the magazine requires further optimisation. Tzur and Altmann (2004) propose a block breaking and merging procedure that they combine with the adapted heuristics. The ALADDIN-heuristic shows very good results for both solution quality and running time, especially for larger problem instances.

Van Hop (2005) considers non-uniform tool sizes and relaxed magazine capacity constraints. This means that one job might need more tools than the magazine can hold. In his research, he introduces partial and complete job splitting, as well as concurrent tool switches, i.e. tools can be switched simultaneously with jobs. He presents an ILP that considers the maximisation of concurrent tool changes and the minimisation of total tool changes in a single objective approach. The sub-problems are proven to be NP complete; therefore, Van Hop (2005) presents a construction heuristic solution procedure for the SSP with non-uniform tool sizes and relaxed capacity constraints for complete and partial job splitting, as well as tool changes

concurrently or not concurrently with job changes. The greedy heuristic yields good results compared to the exact solutions and fast computation time (less than 1 second).

Raduly-Baka et al. (2005) present a two-level storage management (TISM) heuristic that they combine with an existing job ordering algorithm by Djellab et al. (2000) for the tool switching problem with non-uniform tool sizes. Hereby, the tools can occupy 1, 2, 3, etc. slots. Test instances and the benchmark algorithm were taken from Tzur and Altmann (2004). The heuristic given by Raduly-Baka et al. (2005) shows higher quality and improved running time performance compared to the job ordering algorithm by Djellab et al. (2000).

### 5.6. Approaches with tool wear

The approaches with tool wear assume either deterministic (Hirvikorpi et al. 2006a, Dadashi et al. 2016, Mauergauz 2017) or stochastic tool lifetimes (Hirvikorpi et al. 2007, Farughi et al. 2017). The Weibull distribution is used for both studies with stochastic tool life. The articles are chronologically sorted in Table 8. It is particularly noticeable that GA is the dominant solution method for this problem group.

Table 8. Approaches with tool wear.

References	$\alpha$	$\beta$	$\gamma$	$\delta$	$\varepsilon$	$\zeta$	$\eta$	Math. model/solution approach
Hirvikorpi et al. (2006a)	1	$ST_{si}$	SO	$Tool_{hom}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{yes}$	MILP/GA, LS
Hirvikorpi et al. (2006a)	1	$ST_{si}$	SO	$Tool_{hom}$	$L_{k_s}, Seq_k$	$ T_j  \leq C$	$TW_{yes}$	KTWL-policy
Hirvikorpi et al. (2007)	1	$ST_{si}$	SO	$Tool_{hom}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{yes}$	GA
Hirvikorpi et al. (2007)	1	$ST_{si}$	SO	$Tool_{hom}$	$L_{k_s}, Seq_k$	$ T_j  \leq C$	$TW_{yes}$	SUM-policy
Dadashi et al. (2016)	1	$ST_{si}$	SO	$Tool_{hom}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{yes}$	MILP/GA
Farughi et al. (2017)	1	$ST_{si}$	SO	$Tool_{hom}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{yes}$	NLP/GA
Mauergauz (2017)	1	$ST_{si}$	MO	$Tool_{hom}$	$L_{k_s}, Seq_u$	$ T_j  \leq C$	$TW_{yes}$	greedy

Hirvikorpi et al. (2006a) and Hirvikorpi et al. (2007) study both, the SSP with tool wear as well as the tooling problem with tool wear. Hirvikorpi et al. (2006a) present a MILP that can only be solved for small-sized problems. Therefore, they propose a GA and study combinations with LS. The tool loading is obtained from a novel ‘keep tool which wears out last’ (KTWL) policy. Hirvikorpi et al. (2007) propose another GA for the same problem with stochastic tool life. In addition to existing rules for optimising the tool loading problem, they present a removal policy (SUM) which not only orders the tools based on their need in the near future but also based on their tool life.

Dadashi et al. (2016) consider the alternate objective of the minimising total cost of tool purchasing and cost of job tardiness. Tool life is assumed to be deterministic and specified in advance. A MILP model is presented and larger instances with up to 40 part types and 30 different tools are solved with a GA.

Farughi et al. (2017) propose an NLP formulation with the objective to minimise the tool switching and the machining cost. The GAMS solver was only able to solve small problems of

up to 4 jobs, 7 tools and a magazine capacity of 4 to optimality. Therefore, the authors present a basic GA that yields good results in terms of running time and solution quality but, as other studies of the SSP with tool life constraints do not exist, a comparison has only been made to the exact solver. Mauergauz (2017) takes a completely different approach. In his paper, the value of a tool's lifetime is known beforehand and is calculated as a spent resource percentage on a current operation. The tool is sent for maintenance once the tool wear limit is reached. Mauergauz (2017) also integrates different fixture types and job due dates. A multi-criteria dynamic grouping method is proposed based on the set-up expenditure and the average orders utility. The multi-objective greedy algorithm considers the grouping of jobs with identical fixtures and tool types. The user then has to choose a sequence out of the set of non-dominated schedules.

### 5.7. Other research

This section, summarised in Table 9, includes articles that cannot be sorted within the proposed framework because they either address different fields or different perspectives. Only articles considered to be important and closely related to the research of tool switching problems have been included.

**Table 9. Overview of research that cannot be classified.**

References	Problem	Solution category	Math. model/solution approach
Avci and Akturk (1996)	Magazine arrangement and Operations Sequencing	heuristic	Decision hierarchy
Song and Hwang (2002)	Tool transporter movements	math. model, heuristic	INLP/tooling policy
Raduly-Baka and Nevalainen (2015)	Modular tool switching	–	proof complexity

Avci and Akturk (1996) unlike most authors, address a holistic tool management problem in the context of flexible manufacturing systems. They developed a two-phase decision hierarchy system to minimise the total manufacturing cost by simultaneously solving magazine arrangement and operations sequencing problems on a CNC machine.

Song and Hwang (2002) consider the objective of minimising the number of tool transporter movements. Their variation is based on the fact that, in FMSs, required tools that are not in the magazine will be transferred from a tool crib to the magazine and back by an automatic tool transporter that can transport a certain number of tools. They present an INLP for this problem, and further a tooling policy for the tooling sub-problem. The tooling policy guarantees optimality for the studied objective, while the general KTNS-policy does not guarantee optimality.

Raduly-Baka and Nevalainen (2015) analyse the hardness of the modular tool switching problem, which is an extended version of the generic tool switching problem. This problem appears in assembly systems for PCBs. The problem here is that single component reels (i.e. tools in FMS) and/or whole reel modules can be switched. This would correspond to an SSP

that additionally allows the switching of tools in groups. They consider four cases with/without a fixed number or capacity of modules. They show that if both number and capacity are fixed, the problem can be solved optimally in polynomial time.

## 6. Research gaps and directions for future research

Research trends, as well as gaps in the field of job sequencing and tool switching, can be identified based on the review in section 5. Section 6.1 provides an analysis of attributes and characteristics using the classification scheme. Section 6.2 discusses trends regarding solution methods. Table 10 and Table 11 classify the articles discussed in the sections 5.1–5.6 with respect to the solution approach and problem perspective.

**Table 10. Mapping of articles regarding modelling approach and problem perspective.**

		Context of SSP			
		Uniform SSP	Multiple machines	Tool size & capacity constraints	Tool wear
<b>Math. Model</b>	<b>ILP</b>	Laporte et al. (2004), Catanzaro et al. (2015)	Beezão et al. (2017)	Matzliach and Tzur (2000); Tzur and Altmann (2004); Van Hop (2005); Hirvikorpi et al. (2006b)	–
	<b>NLP</b>	Bard (1988)	Bard (1988); Ghrayeb et al. (2003); Van Hop and Nagarur (2004)	Rupe and Kuo (1997)	Farughi et al. (2017)
	<b>MILP</b>	Tang and Denardo (1988a); Schwerdfeger and Boysen (2017)	Özpeynirci et al. (2016)	–	Hirvikorpi et al. (2006a); Dadashi et al. (2016)
	<b>MINLP</b>	–	Sarmadi and Gholami (2011)	–	–

The articles reviewed in this paper are published in 27 different journals. In addition, there are 7 conference publications or prints in proceedings. The diversity of the publication origins reflects the interdisciplinary nature of tool switching research, with the *European Journal of Operations Research* and the *International Journal of Production Research* being the major sources. The cumulated number of publications per year is given in Figure 1. It is seen that the number of studies has been increasing over time, and became more relevant than ever in the year 2017.

Table 11. Mapping of articles regarding solution method and problem perspective.

		Context of SSP					
		Uniform SSP	Sequence-dependent setup time	Multiple machines	Multi-objective	Tool size & capacity constraints	Tool wear
Exact	BB	Laporte et al. (2004); Karakayali and Azizoğlu (2006); Ghiani et al. (2007)	-	-	-	-	-
	BC	Laporte et al. (2004); Ghiani et al. (2010); Catanzaro et al. (2015)	-	-	-	-	-
	BS	Zhou et al. (2005)	-	-	-	-	-
Classical Heuristics		Tang and Denardo (1988a); Crama et al. (1994a); Privault and Finke (1995); Hertz et al. (1998); Djellab et al. (2000); Privault and Finke (2000); Shirazi and Frizelle (2001); Salonen et al. (2006); Senne and Yanasse (2009); Burger et al. (2015); Schwerdfeger and Boysen (2017)	Privault and Finke (1995)	Khan et al. (2000); Fathi and Barnette (2002); Ghrayeb et al. (2003)	Adjashvili et al. (2015); Furrer and Mütze (2017); Mauergauz (2017)	Rupe and Kuo (1997); Matzliach and Tzur (1998); Matzliach and Tzur (2000); Tzur and Altmann (2004); Raduly-Baka et al. (2005); Van Hop (2005); Hirvikorpi et al. (2006b)	Mauergauz (2017)
	ACO	-	-	-	Solimanpur and Rastgordani (2012)	-	-
Solution Approach / Method	ALNS	-	-	Beezão et al. (2017)	-	-	-
	GA	Amaya et al. (2008); Amaya et al. (2012); Chaves et al. (2016); Ahmadi et al. (2018)	-	Van Hop and Nagarur (2004)	Keung et al. (2001a); Keung et al. (2001b)	-	Hirvikorpi et al. (2006a); Hirvikorpi et al. (2007); Dadashi et al. (2016); Farughi et al. (2017)
	HC	Amaya et al. (2008); Amaya et al. (2012)	-	-	-	-	-
	ILS / LS	Bard (1988); Paiva and Carvalho (2017)	-	-	-	-	Hirvikorpi et al. (2006a)
	MA	Amaya et al. (2008); Amaya et al. (2010a); Amaya et al. (2010b); Amaya et al. (2011); Amaya et al. (2012); Amaya et al. (2013)	-	-	-	-	-
Meta-heuristics	SA	Amaya et al. (2012)	-	-	Baykasoğlu and Ozsoydan (2017); Baykasoğlu and Ozsoydan (2018)	-	-
	TS	Follonier (1994); Al-Fawzan and Al-Sultan (2003); Amaya et al. (2012)	-	Özpeynirci et al. (2016)	-	-	-

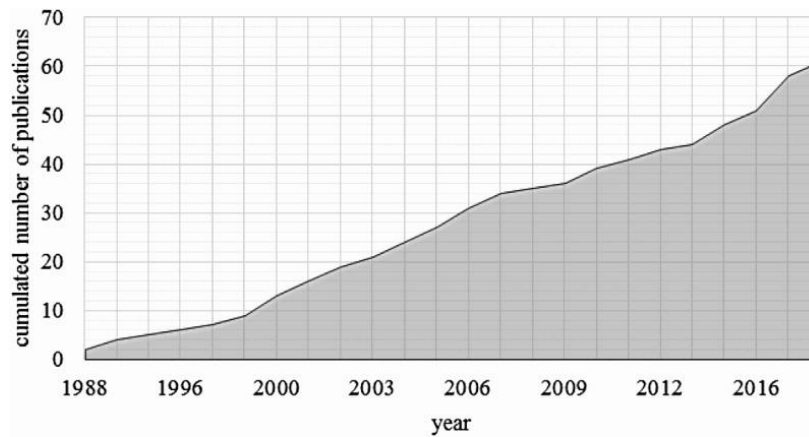


Figure 1. Cumulative trend of publications by year.

### 6.1. Trends and research gaps concerning problem perspective

Despite the many years of tool switching research, some key characteristics have not been fully incorporated. The specific areas of future research that may offer the highest potential include the following. Approaches with tool wear, multi-objective approaches, as well as tool switching for multiple machines represent the latest trends within the tool switching literature. Multiple machines offer a number of research opportunities because mostly basic problems have been studied until now. In practice, multi-machine systems require the sharing of resources, such as tools, switches, transport systems or replacement tools. Integrating those concepts may be as interesting as developing and solving multi-stage models, as proposed by Bard (1988).

Overall, most of the articles deal with the uniform SSP, probably because it is the simplest case of the SSP, and it provides a basis for more general formulations. Almost all models presented in section 5 consider sequence-independent and uniform set-up times. However, for some practical applications, this assumption would be too unrealistic. Moreover, the exact formulations for the SSP are not satisfactory in terms of efficient execution. Therefore, improving the existing exact methods and searching for tighter bounds is still necessary.

The problem adaptation to related problems seems to play an important factor in the tool switching research. Not only closely (like the production of PCBs), but also distantly related problems in other fields and industries exist which have not been considered within this work. The number of models of related variations of the SSP has increased in recent years. This is enabled by specific industrial applications, such as PCB sequencing and hole-making in the metal-working industry. The present models often consider a single machine and a sequence-independent set-up time, even though the underlying real-world application may be different, e.g. consisting of multiple machine systems.

A majority of the literature is dedicated to deterministic models. In practice, however, the demand, the tool lifespan or unexpected events, like machine failure, may not be known beforehand. Two recent studies that include stochasticity, Baykasoglu and Ozsoydan (2018)

with dynamic job arrival and Farughi et al. (2017) with tool wear, can be used as a good foundation for future studies with probabilistic dimensions.

Overall, even the latest research trends on tool wear and multiple machines provide sufficient research possibilities in terms of problem formulations and solution approaches to variations of the SSP.

**6.2. Trends and research gaps concerning solution methods and benchmarks**

Only a few articles on tool switching research developed exact algorithms (see Figure 2). Although search tree methods and integer programming techniques are used for solving tool switching problems, most of the exact methods are designed for the uniform SSP. Surprisingly, no exact solution method and only a few meta-heuristics have been applied to variations of the SSP. However, tool switching models can easily decompose into sub-problems. It is surprising that only a few authors propose decomposition methods to solve the SSP and more general models. In the future, exact algorithms, but also heuristics, need to be developed for more generic cases of the SSP. So far, the lower bounds of existing exact methods remain disappointing, and optimality can only be proven for small problem instances. An exact algorithm with powerful lower bounds and different search strategies can be developed to provide a meaningful benchmark for measuring the solution quality of tool switching heuristics, as well as to enable optimal solutions for larger problem instances. The recent research on tight formulations for small problems may, in addition, be reused as part of novel IP-based heuristics.

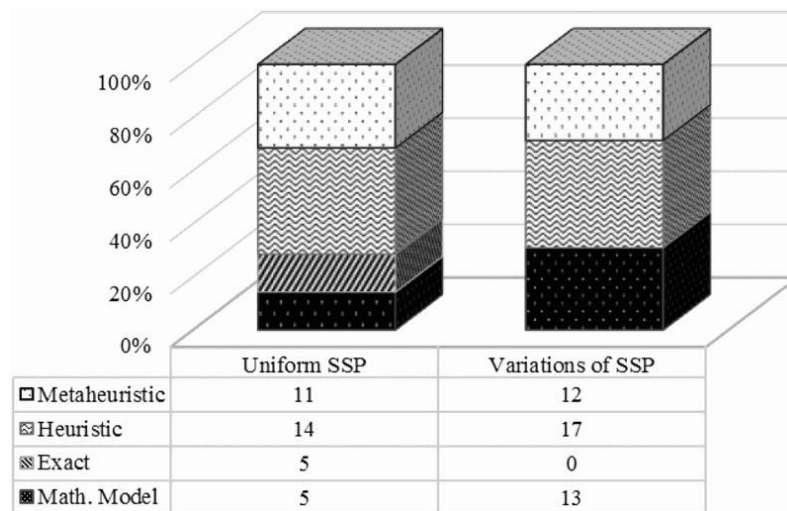


Figure 2. Frequency of solution approaches by problem group.

Until now, problems of industrial size have only been solved with heuristics. Classic heuristics have been the most studied methods in the past. The research trend in recent years has been the development of more efficient approximation algorithms in terms of solution quality and computation time. Classic heuristics, of which most are TSP-based heuristics, show fast performance for larger size problems. It still has to be shown if they perform equally well for problems with multiple machines, which have only applied IP and meta-heuristics so far. Other



research directions can be identified towards randomised meta-heuristics, e.g. shuffle methods, and new meta-heuristics that have emerged in recent years, e.g. bee colony, artificial immune or particle swarm algorithms.

The use of different problem instances makes the comparison of algorithmic performance difficult. Authors mostly generate their own test data with different instance sizes. Rarely, the same test data is used to compare the performances of different algorithms. The dissemination and acceptance of benchmark instances in SSP research is low, although some authors attempted to provide benchmark instances (see, e.g. Laporte et al. 2004, Amaya et al. 2008). The randomly generated problem sizes seem to be significantly smaller than the size of real-world problems, but recent empirical data is lacking. The acceptance and coherent use of benchmark instances would be desirable for tool switching problems like the similar flow shop scheduling has shown. But future research may also explore which algorithms allow the solving of larger realistic-sized problems.

## **7. Summary**

This article presented a classification scheme for tool switching problems to guide future research efforts and annotated 61 articles reflecting the interdisciplinary research effort and the ability of tool switching problems. The tool switching research is motivated by many industrial applications, mostly by the metal-working industry or scheduling of PCBs. The analysis shows that a variety of configurations can be considered and that the problem is still very present in operation, engineering and production research. Nevertheless, the prevailing problem type up to now is the uniform tool switching problem. Therefore, future research may focus on more holistic problems, with multiple machine systems or multiple objectives.

Diverse solution methods have been applied to the SSP. Nevertheless, research directions include hybrid meta-heuristics and powerful bounds for exact solution methods, as exact methods still interest researchers. However, the literature does not provide benchmark data to compare the performance of various solution methods. It would be extremely useful to test the relative advantageousness of the solution methods discussed in this paper on a benchmark system and to study how the performances of these methods vary with respect to systems characteristics.

Possible extensions to this review might include remotely related research areas, such as stop minimisation problems, machine loading and holistic FMS planning problems, which have not been considered within this paper.

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### III

# A Comparison of Different Mathematical Models for the Job Sequencing and Tool Switching Problem with non-identical Parallel Machines

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#### **Abstract**

*This paper addresses the generalisation of the NP-hard job sequencing and tool switching problem with non-identical parallel machines and sequence-dependent setup times where a set of jobs is to be scheduled on unrelated parallel machines with machine-dependent processing and tool switching times. Three different mathematical models for two different objectives are presented and applied to newly generated test instances. The instances are compared and analysed using a commercial solver and an iterated local search heuristic. Overall, it is shown that the solution quality obtained by the mathematical models depends on the size of the problem instance as well as the tool requirements. The precedence-based formulation is superior in general to the position-based and time-index-based formulation for dense problem instances while the position-based formulation works well for sparse problems. With an increasing problem size, the metaheuristic requires significantly less time to find near-optimal solutions than the mathematical models.*

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## 1. Introduction

This study presents three different mixed integer linear programs (MILP) for the job sequencing and tool switching problem (SSP) with non-identical parallel machines (SSP-NPM). The problem is a generalization of the uniform SSP, first presented by Bard (1988) and Tang and Denardo (1988) for a single flexible machine, and proven to be NP-hard by Crama et al. (1994). In this paper, multiple non-identical parallel machines and sequence- and machine-dependent setup times are considered. The SSP-NPM arises in a flexible manufacturing context when a given set of jobs is to be processed without pre-emption on a set of unrelated flexible machines. Each job requires a predefined set of tools that has to be loaded on the tool magazine of the machine. The magazine capacity, however, is limited so that tool switches become necessary between two consecutive jobs. Job-splitting is not allowed, i.e. no tool switches occur during the processing of a job. Non-identical machines imply in this case that the time to switch a tool and the capacity of the tool magazine may be different for different machines. In short, the SSP-NPM consists of the three interdependent problems (1) assigning a set of jobs to machines, (2) sequencing the allocated jobs on the machines, and (3) arranging the tool loading, in order to optimize a pursued objective, e.g. minimizing the number of tool switches, minimizing the makespan or minimizing the total flowtime.

A detailed review of all variations of tool switching problems and their solution approaches considered in literature are discussed by Calmels (2019). Among the most recent approaches to the uniform SSP, Paiva and Carvalho (2017) present an ILS metaheuristic based on a new graph representation. Their work is adapted by Ahmadi et al. (2018) who show that the standard SSP can be formulated as a Traveling Salesman Problem of second order and they present a dynamic Q-learning-based Genetic Algorithm. Schwerdfeger and Boysen (2017) present an adapted version of the MILP by Tang and Denardo (1988) and propose a heuristic decomposition procedure as well as a Branch and Bound method.

Apart from the above-mentioned approaches to the standard uniform SSP, several recent articles consider multiple machines. Özpeynirci et al. (2016) and Gökğür et al. (2018) investigate the SSP for unrelated parallel machines and the objective of minimising the makespan. They consider a limited amount of tool copies but do not include capacity constraints or tool switching times. Calmels et al. (2019) compare several construction heuristics for the SSP-NPM based on simple order policies. They show that the SSP-NPM requires different policies for different objectives functions.

Several integer linear programming (ILP) formulations have been proposed for scheduling problems (Pan 1997), and specifically for the SSP. The ILP formulations can be grouped according to different definitions for binary variables in precedence-based, position-based, and time-index based models, which were first proposed for job shop scheduling problems by Manne (1960), Wagner (1959), and Bowman (1959), respectively. In the following, ILP formulations concerning job sequencing and tool switching problems will be reviewed.

The precedence-based formulation is probably the most popular ILP representation of scheduling problems. The precedence-based variables indicate whether a job precedes another job in the sequence. The first formulation for the classic single-machine sequencing problem was provided by Potts (1980) and extended by Guinet (1991) for scheduling sequence-dependent jobs on uniform parallel machines. Since then, research efforts have dealt with formulations for many variations of the scheduling problem on parallel machines. Yet, the majority of the published articles focuses on identical parallel machines without considering either tooling constraints or sequence-dependent setup times. Fanjul-Peyro et al. (2019), for instance, propose a new precedence-based MILP formulation for the unrelated parallel machine scheduling problem with setup times. Only recently, Fanjul-Peyro (2020) extended this work for specific resources. Bektur and Saraç (2019) study the case of a common resource for setups which implies sequence-dependent setup times but not machine-dependent setup times. A comprehensive study on scheduling problems with setup times is provided by Allahverdi (2015) and Kravchenko and Werner (2011). Few papers cover precedence-based MILP formulations for the SSP. Laporte et al. (2004) formulate a precedence-based model for the single-machine uniform SSP. Tighter bounds for their formulation have later been presented by Catanzaro et al. (2015). Özpeynirci et al. (2016) present two precedence-based MILP formulations for the SSP for unrelated parallel machines without considering the magazine capacity but including a limited number of tool copies with the objective to minimize the makespan. A formulation for the SSP on identical parallel machines is presented by Beezão et al. (2017) under the objective of minimizing the makespan.

The first position-based formulations for the uniform SSP were a non-linear program proposed by Bard (1988) and an ILP by Tang and Denardo (1988). The position-based variables indicate in which position of a sequence a job is processed. Matzliach and Tzur (2000), Tzur and Altmann (2004), Van Hop (2005) and Hirvikorpi et al. (2006b) consider a single machine but non-uniform tool sizes. Matzliach and Tzur (2000) and Hirvikorpi et al. (2006b) present ILPs for a variation of the SSP in the context of printed circuit board assembly. They assume that tools can have different sizes and each job only requires one tool. During their research, Matzliach and Tzur (2000) extend the formulation to multiple tools required per job. Tzur and Altmann (2004) present an ILP for the SSP with non-uniform tool sizes and a tool-size independent transfer cost. For the single-machine SSP with non-uniform tool sizes and relaxed magazine capacity constraints, Van Hop (2005) present a position-based ILP formulation that considers the maximisation of concurrent tool changes and the minimisation of total tool changes in a single objective approach. Hirvikorpi et al. (2006a) and Dadashi et al. (2016) present MILP formulations for the uniform SSP including tool wear. Only one position-based formulation for the SSP with identical parallel machines exists for minimizing makespan (Beezão et al. 2017).

Time-index-based formulations have received far less attention than position-based or precedence-based formulations. Formulations exist for the general single or parallel machine scheduling problem (see, e.g., Sousa and Wolsey 1992; van den Akker et al. 2000; Williams 1997),

extensions with sequence-dependent setup times (Nogueira et al. 2019) and unrelated parallel machines (Berghman et al. 2018). However, no attempts have been made to develop an ILP formulation for the SSP using time-indexed based variables. In the time-index-based formulation, the time-index-based variables indicate the starting period of a job. Thereby, a time period or time-bucket  $k$  refers to the time interval  $[k, k + 1]$  during a planning period ( $k = 0, \dots, K$ ).  $K$  denotes the length of the planning period. Since the number of binary variables depends on  $K$ , the problem is difficult to solve for a large planning period. Therefore, in many cases, the time-index-based models are solved by relaxation techniques or column generation approaches (see, e.g., Sousa and Wolsey 1992; van den Akker et al. 2000; Williams 1997).

In this article, three types of mathematical formulations for the SSP-NPM are presented. Extensive computational experiments are conducted on newly generated instances in order to compare the performance of these models. In the remainder, Section 2 characterizes the SSP-NPM and three different MILP formulations for the SSP-NPM. Subsequently, Section 3 presents the computational study and its results comparing the three different formulations. Finally, Section 4 provides a conclusion and future research directions.

## 2. Problem Description and Formulations

### 2.1. Problem Characteristics

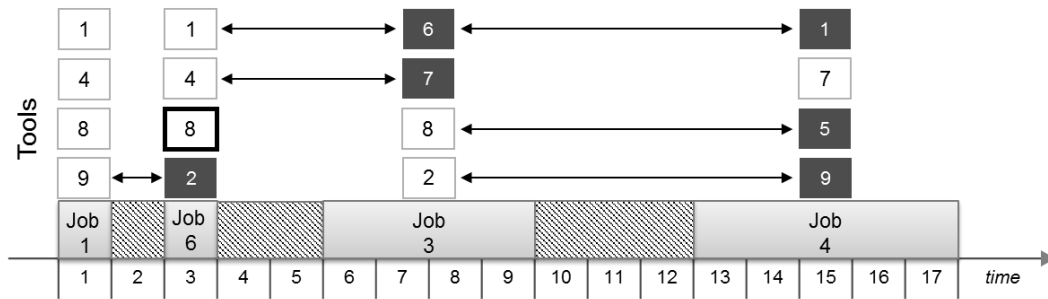
The SSP-NPM considers a set of jobs  $J = \{1, \dots, J\}$  which has to be processed in a manufacturing environment with a set of non-identical parallel machines  $M = \{1, \dots, M\}$ . Each job  $j$  is available for processing at time zero and it is assumed that each machine can be used. Jobs are processed sequentially on each machine and job-splitting is not allowed. The processing time  $p_{jm}$  of a job  $j$  on machine  $m$  is machine-dependent and the machines may have different magazine capacities  $C_m$ . The time to switch one tool on a machine  $sw_m$  may be different for the various machines, i.e., depends on the machine and not on the tool.  $T = \{1, \dots, T\}$  denotes the set of tools required for processing all jobs. It is assumed that each tool occupies only one slot in the tool magazine of a machine and there is at least one machine which can hold all the tools necessary for processing a job. Each job  $j$  requires a subset of tools  $T_j$ . The processing of a job can only start if the required tools are present in the magazine of the machine on which the job  $j$  is to be processed.  $J_t$  denotes the subset of jobs that require a certain tool  $t \in T$ . The nature of the SSP requires that the tool magazine capacity  $C_m$  of each machine  $m$  does not provide enough tool slots for processing all jobs, so that tool switches may become necessary for two successive jobs. The initial loading does not count as a tool switch and tool switching cannot happen while the processing of a job is ongoing. The two conflicting objectives presented are: (a) minimize the makespan ( $Fmax$ ), and (b) minimize total flowtime ( $TFT$ ). An example of the SSP-NPM is given in Table 1. The example consists of 6 jobs and 2 machines with different capacities and different switching times.

Table 1. Example with  $J = 6$ ,  $T = 9$  and  $M = 2$  with  $C_1 = 4$ ,  $C_2 = 3$ ,  $sw_1 = 1$  and  $sw_2 = 2$ .

Jobs	1	2	3	4	5	6
	1	1	2	1	3	1
Tools	4	3	6	5	5	2
	8	5	7	7	8	4
	9		8	9		
$p_{j1}$	1	3	4	5	6	1
$p_{j2}$		4			3	1

An optimal solution to the initial example for minimizing the total flowtime is presented in the following Figure 1.

Machine 1



Machine 2

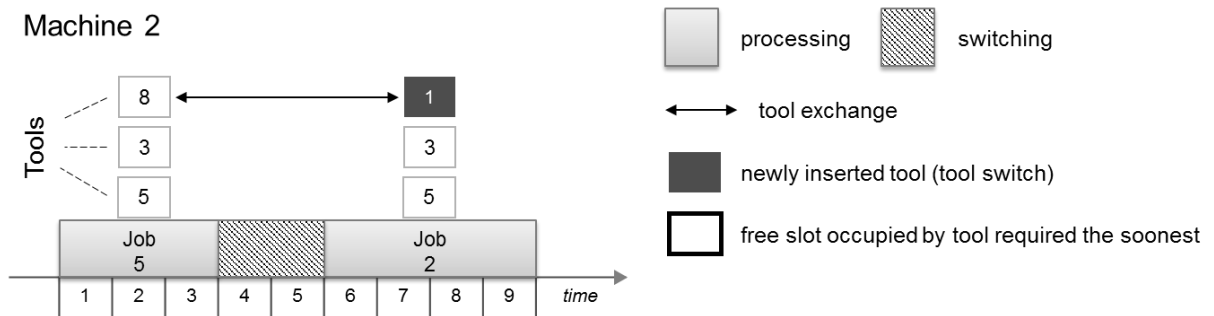


Figure 1. Layout of the example problem environment of the SSP-NPM.

## 2.2. Precedence-based MILP formulation

The formulations of Laporte et al. (2004) and Beezão et al. (2017) provide the basis for the following mathematical formulation with the additional consideration of non-identical parallel machines and sequence and machine-dependent setup times. The precedence-based binary variables  $x_{ijm}$  are equal to one if and only if job  $i$  is immediately followed by job  $j$  ( $i, j \in J$ ) in the sequence on machine  $m$ . Binary variables  $a_{jm}$  ( $\omega_{jm}$ ) are equal to one if and only if job  $j$  is the first (last) job processed on machine  $m$ . Binary variables  $u_{jm}$  are equal to one if and only if job  $j$  is assigned to machine  $m$ . Binary variables  $v_{jt}$  are equal to one if and only if tool  $t$  is present in the magazine while job  $j$  is processed. Binary variables  $w_{jt}$  are equal to one if and only if tool  $t$  needs to be inserted before starting to process job  $j$ . The continuous variables  $f_j$  denote the completion time of job  $j$ .  $G = \sum_{j=1}^J \max_m (p_{jm}) + (J-1) \cdot \max_m (sw_m \cdot C_m)$  is a large constant.

$$\sum_{m \in M} \sum_{j \in J, j \neq i} x_{ijm} \leq 1 \quad \forall i \in J \quad (1)$$

$$\sum_{m \in M} \sum_{i \in J, i \neq j} x_{ijm} \leq 1 \quad \forall j \in J \quad (2)$$

$$\sum_{k \in J} x_{jkm} - \sum_{i \in J} x_{ijm} \leq \alpha_{jm} \quad \forall j \in J, \forall m \in M \quad (3)$$

$$\sum_{i \in J} x_{ijm} - \sum_{k \in J} x_{jkm} \leq \omega_{jm} \quad \forall j \in J, \forall m \in M \quad (4)$$

$$\sum_{t \in T} v_{jt} \leq \sum_{m \in M} C_m \cdot u_{jm} \quad \forall j \in J \quad (5)$$

$$x_{ijm} + v_{jt} - v_{it} \leq w_{jt} + 1 \quad \forall i \in J, \forall j \in J \setminus \{i\}, \forall m \in M, \forall t \in T \quad (6)$$

$$\sum_{j \in J} \alpha_{jm} \leq 1 \quad \forall m \in M \quad (7)$$

$$\sum_{j \in J} \omega_{jm} \leq 1 \quad \forall m \in M \quad (8)$$

$$\sum_{m \in M} \alpha_{jm} \leq 1 \quad \forall j \in J \quad (9)$$

$$\sum_{m \in M} \omega_{jm} \leq 1 \quad \forall j \in J \quad (10)$$

$$\sum_{m \in M} u_{jm} = 1 \quad \forall j \in J \quad (11)$$

$$\alpha_{jm} \leq u_{jm} \quad \forall j \in J, \forall m \in M \quad (12)$$

$$\omega_{jm} \leq u_{jm} \quad \forall j \in J, \forall m \in M \quad (13)$$

$$2x_{ijm} \leq u_{im} + u_{jm} \quad \forall i \in J, \forall j \in J \setminus \{i\}, \forall m \in M \quad (14)$$

$$\sum_{i \in J, i \neq j} x_{ijm} + \alpha_{jm} = u_{jm} \quad \forall j \in J, \forall m \in M \quad (15)$$

$$\sum_{i \in J, i \neq j} x_{jim} + \omega_{jm} = u_{jm} \quad \forall j \in J, \forall m \in M \quad (16)$$

$$f_j \geq f_i + p_{jm} u_{jm} + s w_m \sum_{t \in T_j} w_{jt} - G(1 - x_{ijm}) \quad \forall i \in J, \forall j \in J \setminus \{i\}, \forall m \in M \quad (17)$$

$$f_j \geq p_{jm} u_{jm} + s w_m \sum_{t \in T_j} w_{jt} \quad \forall j \in J, \forall m \in M \quad (18)$$

$$v_{jt} = 1 \quad \forall j \in J, \forall t \in T_j \quad (19)$$

$$w_{jt} = 0 \quad \forall j \in J, \forall t \in T \setminus T_j \quad (20)$$

$$\alpha_{jm}, \omega_{jm}, u_{jm} \in \{0, 1\} \quad \forall j \in J, \forall m \in M \quad (21)$$

$$v_{jt}, w_{jt} \in \{0, 1\} \quad \forall j \in J, \forall t \in T \quad (22)$$

$$x_{ijm} \in \{0, 1\} \quad \forall i, j \in J, \forall m \in M \quad (23)$$

Constraints (1) and (2) ensure that each job can have at most one successor and at most one predecessor in the sequence. Constraints (3) and (4) ensure that each machine employed in the process can have at most one first job and at most one last job. Constraints (5) ensure that the tool loading does not exceed the tool capacity limit while constraints (6) in combination with the objective function impose restrictions on the tool switches so the tool switches are determined correctly. The constraints (7) and (8) ensure that each machine has at most one start job and one end job while the constraints (9) and (10) denote that each job can only be the start / end job of at most one machine. Constraints (11) denote that each job is assigned to exactly one machine. Constraints (12) and (13) ensure that a job can only be a machine's first or last job, respectively, if the job is assigned to that machine. Constraints (14) guarantee that successive jobs must be processed on the same machine. Constraints (15) and (16) impose that each job assigned to a machine cannot have a preceding job, respectively a subsequent job, if the job is the first job, respectively the last job, processed on that machine. Constraints (17) and (18) restrict the completion time of a job. Constraints (19) guarantee that the tools required for job  $j$ 's processing are available in the tool magazine. Constraints (20) ensure that a tool switch will not be counted if a tool  $t$  is not needed for processing a job  $j$ . Finally, constraints (21) – (23) denote the integrality conditions.

The objective function may now minimize the total flowtime (*TFT*) (24), or minimize the makespan (*Fmax*) (25) in combination with the additional constraints (26).

$$\min TFT = \sum_{j \in J} f_j \quad (24)$$

$$\min Fmax \quad (25)$$

$$Fmax \geq f_j \quad \forall j \in J \quad (26)$$

### 2.3. Position-based MILP formulation

The position-based model is based on the formulation of Beezão et al. (2017). The position-based variables  $x_{jrm}$  are equal to one if and only if job  $j$  is processed in the  $r^{\text{th}}$  position on machine  $m$ . Binary variables  $v_{trm}$  are equal to one if and only if tool  $t$  is present in machine  $m$  during the processing of the job in the  $r^{\text{th}}$  position. Binary variables  $w_{trm}$  are equal to one if and only if tool  $t$

is inserted in the tool magazine of machine  $m$  exactly before the  $r^{\text{th}}$  job is treated. The continuous variables  $f_{jrm}$  denote the completion time of job  $j$  in the  $r^{\text{th}}$  position on machine  $m$ .

$G = \sum_{j=1}^J \max_m(p_{jm}) + (J-1) \cdot \max_m(sw_m \cdot C_m)$  is a large constant.

$$\sum_{r \in J} \sum_{m \in M} x_{jrm} = 1 \quad \forall j \in J \quad (27)$$

$$\sum_{j \in J} x_{jrm} \leq 1 \quad \forall r \in J, \forall m \in M \quad (28)$$

$$\sum_{j \in J} x_{jrm} \leq \sum_{j \in J} x_{j(r-1)m} \quad \forall r \in J \setminus \{1\}, \forall m \in M \quad (29)$$

$$\sum_{j \in J} x_{jrm} \leq v_{trm} \quad \forall t \in T, \forall r \in J, \forall m \in M \quad (30)$$

$$\sum_{t \in T} v_{trm} \leq C_m \quad \forall r \in J, \forall m \in M \quad (31)$$

$$v_{trm} - v_{t(r-1)m} \leq w_{trm} \quad \forall t \in T, \forall r \in J \setminus \{1\}, \forall m \in M \quad (32)$$

$$f_{j1m} = p_{jm} \cdot x_{j1m} \quad \forall j \in J, \forall m \in M \quad (33)$$

$$f_{jrm} \geq \sum_{i \in J, i \neq j} f_{i(r-1)m} + sw_m \sum_{t \in T} w_{trm} + p_{jm} x_{jrm} - G(1 - x_{jrm}) \quad \forall j \in J, \forall r \in J \setminus \{1\}, \forall m \in M \quad (34)$$

$$v_{trm}, w_{trm} \in \{0, 1\} \quad \forall t \in T, \forall r \in J, \forall m \in M \quad (35)$$

$$x_{jrm} \in \{0, 1\} \quad \forall j \in J, \forall r \in J, \forall m \in M. \quad (36)$$

Constraints (27) denote that each job is assigned to exactly one machine and position. Constraints (28) impose that each position on machine is used by at most one job. Constraints (29) ensure that if there is a job in the  $r^{\text{th}}$  position on machine  $m$  then there must be a job in position  $r-1$ . Constraints (30) guarantee that the tools required for job  $j$  are available in the tool magazine in the moment of job  $j$ 's processing. Constraints (31) ensure that the tool loading does not exceed the tool magazine capacity. Constraints (32) determine whether tool  $t$  is inserted in the magazine of machine  $m$  before the processing of a job in position  $r$ . The completion times of the initial jobs are calculated by the constraints (33) while the completion times of any other job are restricted by the constraints (34) as the sum of the completion time of the job processed in position  $r-1$ , the setup time and the processing time. Constraints (35) and (36) denote the integrality conditions.

The objective function may now minimize the total flowtime (*TFT*) (37), or minimize the makespan (*Fmax*) (38) in combination with the additional constraints (39).

$$\min TFT = \sum_{j \in J} \sum_{r \in J} \sum_{m \in M} f_{jrm} \quad (37)$$



$$\min Fmax \tag{38}$$

$$Fmax \geq f_{jrm} \quad \forall j \in J, \forall r \in J, \forall m \in M \tag{39}$$

**2.4. Time-index-based MILP formulation**

In the following, a time-index-based MILP formulation for the SSP, specifically for the SSP-NPM, is presented for the first time. Unlike previous time-index-based formulations for scheduling problems, a period or time bucket  $k$  is defined here as the time interval  $[k^{start}, k^{end}]$ , i.e., it starts at the beginning of period  $k$  at time  $k^{start}$  and ends at the end of period  $k$  at time  $k^{end}$ . The time-index-based variables  $x_{jmk}$  are equal to one if and only if job  $j$ 's setup (tool switching) or processing on machine  $m$  starts in period  $k \in K, K = \{1, \dots, K\}$ . Note that  $K$  has to be sufficiently large (at least  $\sum_{j=1}^J \max_m(p_{jm})$ ) to allow for feasible solutions and as small as possible to ensure short computation times. A suitable large upper bound to  $K$  is  $\sum_{j=1}^J \max_m(p_{jm}) + (J-1) \cdot \max_m(sw_m \cdot C_m)$ . Since the setup time may depend on the tool loading of previous jobs and is not known in advance, binary variables  $y_{jmk}$  are equal to one if and only if job  $j$ 's processing or setup is initiated or ongoing on machine  $m$  in the time period  $k$ . In order to ensure that no unwanted switching is performed during setup or during processing, binary variables  $z_{jmk}$  are equal to one if and only if job  $j$  is being processed in period  $k$  on machine  $m$  or if job  $j$ 's tool setup is already ongoing in period  $k$  on machine  $m$  because setup has been initiated in a preceding period. Figure 2 illustrates the definition of the binary variables for setup initiation and ongoing setup.

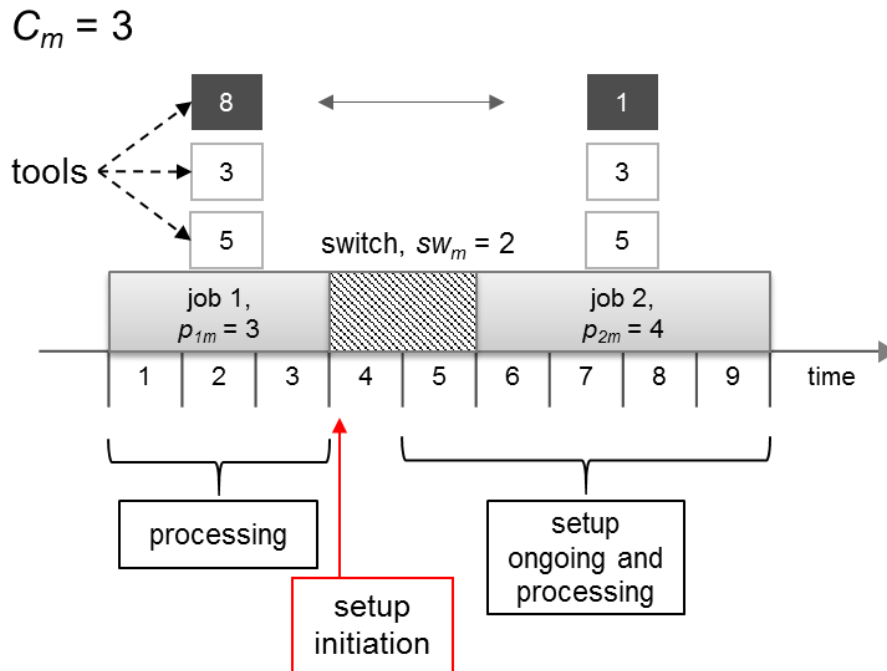


Figure 2. Representation of setup and processing in the time-index-based formulation.

The auxiliary binary variables  $\delta_{mk}$  are equal to one if and only if a tool setup is initiated at the beginning of period  $k$  on machine  $m$ , and job-related binary variables  $\Delta_j$  are equal to one if and only if a tool setup is required immediately before job  $j$ 's processing. Binary variables  $v_{tmk}$  are equal to one if and only if tool  $t$  is present in the magazine of machine  $m$  at the beginning of period  $k$ . Binary variables  $w_{tmk}$  are equal to one if and only if tool  $t$  is inserted in the tool magazine of machine  $m$  at the beginning of period  $k$ . The continuous variables  $s_j$ ,  $f_j$  and  $st_j$  denote the starting time of job  $j$ , the completion time of job  $j$  and the setup time of job  $j$ , respectively.

$$\sum_{m \in M} \sum_{k \in K} x_{jmk} = 1 \quad \forall j \in J \quad (40)$$

$$\sum_{j \in J} x_{jmk} \leq 1 \quad \forall m \in M, \forall k \in K \quad (41)$$

$$\sum_{m \in M} x_{jmk} \leq \sum_{m \in M} y_{jmk} \quad \forall j \in J, \forall k \in K \quad (42)$$

$$\sum_{j \in J} y_{jmk} \leq 1 \quad \forall m \in M, \forall k \in K \quad (43)$$

$$\sum_{m \in M} y_{jmk} \leq 1 \quad \forall j \in J, \forall k \in K \quad (44)$$

$$\sum_{j \in J} y_{jmk} \leq \sum_{j \in J} y_{jm(k-1)} \quad \forall m \in M, \forall k \in K \setminus \{1\} \quad (45)$$

$$\sum_{j \in J} y_{jmk} \leq v_{tmk} \quad \forall t \in T, \forall m \in M, \forall k \in K \quad (46)$$

$$\sum_{t \in T} v_{tmk} \leq C_m \quad \forall m \in M, \forall k \in K \quad (47)$$

$$v_{tmk} - v_{tm(k-1)} \leq w_{tmk} \quad \forall t \in T, \forall m \in M, \forall k \in K \setminus \{1\} \quad (48)$$

$$\sum_{j \in J} z_{jmk} \leq 1 \quad \forall m \in M, \forall k \in K \quad (49)$$

$$\sum_{m \in M} z_{jmk} \leq \sum_{m \in M} y_{jmk} \quad \forall j \in J, \forall k \in K \quad (50)$$

$$\sum_{k \in K} y_{jmk} \leq K \cdot \sum_{k \in K} x_{jmk} \quad \forall j \in J, \forall m \in M \quad (51)$$

$$\sum_{k \in K} z_{jmk} \leq K \cdot \sum_{k \in K} x_{jmk} \quad \forall j \in J, \forall m \in M \quad (52)$$

$$st_j \geq sw_m \sum_{t \in T} w_{tmk} - (\max_m (sw_m \cdot C_m) + 1) \cdot (1 - x_{jmk}) \quad \forall j \in J, \forall m \in M, \forall k \in K \quad (53)$$

$$st_j \leq sw_m \sum_{t \in T} w_{tmk} + (\max_m (sw_m \cdot C_m) + 1) \cdot (1 - x_{jmk}) \quad \forall j \in J, \forall m \in M, \forall k \in K \quad (54)$$

$$\sum_{m \in M} \sum_{k \in K} y_{jmk} = st_j + \sum_{m \in M} \sum_{k \in K} p_{jm} \cdot x_{jmk} \quad \forall j \in J \quad (55)$$

$$\sum_{m \in M} \sum_{k \in K} z_{jmk} = st_j + \sum_{m \in M} \sum_{k \in K} p_{jm} \cdot x_{jmk} - \Delta_j \quad \forall j \in J \quad (56)$$

$$f_j - s_j + 1 = st_j + \sum_{m \in M} \sum_{k \in K} p_{jm} x_{jmk} \quad \forall j \in J \quad (57)$$

$$f_j \geq k \cdot \sum_{m \in M} y_{jmk} \quad \forall j \in J, \forall k \in K \quad (58)$$

$$s_j \leq \sum_{m \in M} \sum_{k \in K} k \cdot x_{jmk} + \Delta_j \quad \forall j \in J \quad (59)$$

$$s_j \leq k \cdot \sum_{m \in M} z_{jmk} + K \cdot (1 - \sum_{m \in M} z_{jmk}) \quad \forall j \in J, \forall k \in K \quad (60)$$

$$\Delta_j \leq st_j \quad \forall j \in J \quad (61)$$

$$\delta_{mk} + \sum_{j \in J} z_{jmk} \leq 1 \quad \forall m \in M, \forall k \in K \quad (62)$$

$$\delta_{mk} \leq \sum_{t \in T} w_{tmk} \quad \forall m \in M, \forall k \in K \quad (63)$$

$$\sum_{t \in T} w_{tmk} \leq C_m \cdot \delta_{mk} \quad \forall m \in M, \forall k \in K \quad (64)$$

$$\sum_{t \in T} w_{tm1} = 0 \quad \forall m \in M \quad (65)$$

$$\delta_{m1} = 0 \quad \forall m \in M \quad (66)$$

$$x_{jmk}, y_{jmk}, z_{jmk} \in \{0, 1\} \quad \forall j \in J, \forall m \in M, \forall k \in K \quad (67)$$

$$v_{tmk}, w_{tmk} \in \{0, 1\} \quad \forall t \in T, \forall m \in M, \forall k \in K \quad (68)$$

$$\Delta_j \in \{0, 1\} \quad \forall j \in J \quad (69)$$

$$\delta_{mk} \in \{0, 1\} \quad \forall m \in M, \forall k \in K \quad (70)$$

Constraints (40) denote that each job begins tool switching or processing on exactly one machine in exactly one time period. Constraints (41) ensure that each time slot on a machine is occupied by at most one job. Constraints (42) match job  $j$ 's initiation with its machine utilization. Constraints (43) assign at most one job to each machine at a time period, and at most one machine is occupied with job  $j$ 's processing or tool-setup in period  $k$  (44). Constraints (45) prohibit idle times between two consecutive jobs on the machines. Constraints (46) guarantee that at least the tools required for job  $j$ 's processing are available in the magazine of machine  $m$  at the beginning of period  $k$ , while constraints (47) guarantee that at most  $C_m$  tools are present in the magazine of a machine at any period. Constraints (48) determine the number of tool switches in combination with the objective function. At most one job can utilize a machine for ongoing tool-setup or processing at a time (49). The time span needed for job  $j$ 's total setup and processing must be greater than or equal to the time span for the ongoing setup and processing (50). Constraints (51) and (52) set a bound to the utilization period and ensure that a job  $j$ 's tool setup or processing can only happen if that job is assigned to that machine. The tool setup time  $st_j$  of job  $j$  is equal to the correct tool setup time if job  $j$ 's machine utilization is starting in period  $k$  on machine  $m$ , otherwise it is not limited, (53) and (54). Constraints (55) ensure that job  $j$ 's machine utilization period and constraints (56) state that job  $j$ 's utilization period without the

setup initialization period are calculated correctly. Constraints (57) ensure that the difference of job  $j$ 's completion and starting time make up its utilization time. Constraints (58) set a lower bound to the completion time of job  $j$ . Constraints (59) and (60) set a lower bound to the jobs' starting time. Tool setup time must be positive if a tool setup is preceding job  $j$ 's processing (61) and either tool setup is initiated in period  $k$  on machine  $m$  or setup or processing is already ongoing (62). Constraints (63) and (64) together ensure that tool switches will only be counted on machine  $m$  in period  $k$  if tool setup is initiated on machine  $m$  in that period. Constraints (64) set an upper bound to the number of tool switches. The initial loading does not constitute a tool switch, (65) and (66). Finally, constraints (67) – (70) denote the integrality conditions of the variables.

The objective function may now minimize the total flowtime (*TFT*) (71), or minimize the makespan (*Fmax*) (72) in combination with the additional constraints (73).

$$\min TFT = \sum_{j \in J} f_j \tag{71}$$

$$\min Fmax \tag{72}$$

$$Fmax \geq f_j \quad \forall j \in J \tag{73}$$

### 3. Computational Experiments

This section evaluates the computational performance of the mathematical formulations. Experiments were conducted on a 3.20 GHz Intel Core i8-8700 processor with 32 GB of memory running under Windows 10. IBM CPLEX 12.8 on GAMS 25.1.3 was used to implement and solve the mathematical model while allowing CPLEX to use all cores in parallel. The GAMS models are available on <https://git.io/JvLrn>. The results are compared to an iterated local search method (*ILS*) applying an iteration limit of 100 perturbation moves. The heuristic was implemented and run with R 3.5.1 (using RStudio 1.1.463). The pseudocodes are provided in the Appendix since the focus of this paper is on the mathematical formulations. The code of the heuristics and a short description is available on <https://git.io/JvLrC>. Section 3.1 provides the characteristics of the problem instances. The performance of the models is analysed and summarized in section 3.2.

#### 3.1. Description of the Instances

The formulations are tested on a newly generated data set, since the problem has not been addressed in research so far. Table 2 summarizes the specifications of the test instances considered in the experimental evaluation. Ten instances were generated per instance type similar to the instance generation of Beezão et al. (2017). Processing times  $p_{jm}$ , tool switching times  $sw_m$  and tool capacities  $C_m$  are random integers generated from a uniform distribution over the intervals [1, 10], [2, 4] and [5, 7], respectively. In order to investigate the assumption of

Burger et al. (2015) that the difference between the magazine size and the number of tools required per job influences the performance of mathematical models and heuristics, the job-tool combinations, depending on the number of required tools, are either sparse or dense. Sparse matrices were randomly generated based on the number of required tools per job  $|T_j|$  using a uniform distribution over the interval  $[\min\left\lceil\frac{C_m}{4}\right\rceil, \min\left\lceil\frac{C_m}{2}\right\rceil]$  while for dense matrices  $|T_j|$  is generated over the interval  $[\max\left\lceil\frac{C_m}{2}\right\rceil, \max(C_m)]$ . The required tools are randomly chosen from the tool set. Note that it was ensured that the dominance criterion (Laporte et al. 2004) is met which means that any job's tool set is never a subset of any other job's tool set. A time limit of 1800 seconds was imposed for the solution of each instance. 180 instances in total were run for the two objectives. The instances are available on <http://doi.org/dj5t>.

**Table 2. Characteristics of the test instances.**

M	J	T	Job-Tool-Matrix Density
2	5, 10	10	sparse, dense
2	5, 10, 15	15	sparse, dense
3	15, 25	15	sparse, dense
4	25	15	sparse, dense
4	25	20	sparse, dense

A tight bound is required in the case of the time-index-based formulation for the number of periods  $K$  in order to allow efficient run times. The best solution obtained by either the precedence-based and position-based MILP models or the ILS method is used as a tight upper bound for  $K$  for the objective of minimizing makespan. For the objective of minimizing total flowtime, the required number of required periods may be higher. It was assumed that  $\sum_{j=1}^J \max_m(p_{jm})$  is large enough to allow optimal solutions for sparse problems and that  $\sum_{j=1}^J \max_m(p_{jm}) + \max_m(sw_m \cdot C_m)$  is large enough to allow optimal solutions for dense problems when tool switches become more likely.

### 3.2. Experimental Results

Table 3 to 6 summarize the computational results for the two objectives with a differentiation between sparse and dense problem instances. The formulations are analysed with respect to the average relative percentage deviation (RPD(%)) from the best known solution found by either the solver or the heuristic, as well as the average total runtime in seconds (t(s)) and the number of instances solved to optimality (#opt) over 10 variations of a problem type. Bold face values highlight the best results. Statistical significance was tested with the Wilcoxon signed-rank test (\*  $p < 0.05$ ).

For  $M = 2$  machines and  $J = 5$  jobs the position-based model and the precedence-based model are capable of finding the optimum solution values for both objectives as well as for dense and sparse matrices within a few seconds. The time-index-based model requires a

significant higher computation time to solve the problems to optimality. Moreover, it is not able to solve all dense instances with  $M = 2$  machines,  $J = 5$  jobs and a maximum of  $T = 15$  different tools to optimality. The time-index-based model is not able to find integer solution values for larger problems with either more jobs or tools within 1800 seconds since the number of variables depends highly on  $K$ .

In the large, the position-based model requires less time to reach optimality than the precedence-based model. For instances with up to  $J = 15$  jobs both the position-based model and the precedence-based model find good or even the best solution very quickly, however, the time limit of 1800 seconds is not enough for the models to prove optimality. When the problem size is increased to  $J = 25$  jobs, the RPD of the mathematical models becomes noticeable high. Figure 3 and Figure 4 show the box plots for the average relative deviation of sparse and dense matrices for minimizing makespan and total flowtime respectively. For minimizing makespan, it is shown that the average RPD as well as the average deviation of the RPD across dense instances is lower for the precedence-based formulation than for the position-based formulation. For minimizing total flowtime, both models yield lower RPD values for sparse instances in average across all instances. Figure 5 to Figure 8 present the comparison of the solution quality (bars) and the computation time (lines) of the position-based and the precedence based model and the benchmark ILS algorithm. The performance is measured by the RPD and the average computation time given in seconds. For minimizing makespan and all sparse problems, the position-based formulation shows the most robust results in terms of solution quality. Yet, the ILS is able to find better solutions for large problems with  $M = 4$  machines,  $J = 25$  jobs and  $T = 20$  tools within a short time. For dense matrices, however, the precedence-based model outperforms the position-based model in terms of solution quality but not in terms of computation time. Still, the ILS is able to yield a significant lower average RPD and runtime for problems with  $M = 4$  machines.

For minimizing total flowtime, the position-based model yields a high solution quality and thus a low RPD value for up to  $J = 15$  jobs for sparse and dense problems. However, for instances with more than  $J = 15$  jobs and up to  $T = 15$  tools, the precedence-based model yields better results within the given time limit. For the group of the largest problem instances, the time limit is not sufficient for the precedence-based model to find good solutions. Still, the performance of the mathematical models cannot compete with the ILS heuristic for larger problems. It is interesting to note that the position-based formulation and the precedence-based formulation require a higher computation time in average for sparse matrices. Although sparse matrices require fewer tool switches, the number of empty slots increases the number of tools that can be kept in the magazine because they may be used in the future.

Overall, the precedence-based formulation and the position-based formulation work better, in terms of solution quality and computation time, on instances where the minimum number of tools for a job is close to the magazine capacity, i.e. instances with a high job-tool-matrix density. The assumption of Burger et al. (2015) and Laporte et al. (2004) regarding the performance

differences for sparse and dense matrices for the SSP can thus be confirmed for the SSP-NPM. However, their claim that the precedence-based formulation outperforms the position-based formulation for dense problems can only be confirmed if the time limit is sufficient so that the precedence-based model can converge to good solutions.

**Table 3. Comparison of the performance of sparse matrices for minimizing makespan.**

M	J	T	position-based			precedence-based			time-index-based			ILS	
			RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)
2	5	10	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	14	<b>10</b>	8	12
2	5	15	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	26	<b>10</b>	12	12
2	10	10	<b>0</b>	220	<b>10</b>	<b>0</b>	568	9	0*	1630	1	10	<b>15</b>
2	10	15	<b>0</b>	1179	<b>8</b>	<b>0</b>	1800	0	n/a	1800	0	8	<b>16</b>
2	15	15	<b>0</b>	1800	0	1	1800	0	n/a	1800	0	7	<b>30</b>
3	15	15	<b>0</b>	1800	0	3	1800	0	n/a	1800	0	13	<b>21</b>
3	25	15	<b>3</b>	1800	0	12	1800	0	n/a	1800	0	5	<b>63</b>
4	25	15	<b>4</b>	1800	0	24	1800	0	n/a	1800	0	8	<b>55</b>
4	25	20	4	1800	0	19	1800	0	n/a	1800	0	<b>1</b>	<b>53</b>

\* for instances with integer solution found  
n/a: no integer solutions found within 1800 seconds

**Table 4. Comparison of the performance of dense matrices for minimizing makespan.**

M	J	T	position-based			precedence-based			time-index-based			ILS	
			RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)
2	5	10	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	172	<b>10</b>	5	12
2	5	15	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	0*	1393	3	2	12
2	10	10	1	<b>74</b>	<b>10</b>	<b>0</b>	313	<b>10</b>	n/a	1800	0	5	<b>19</b>
2	10	15	<b>0</b>	<b>106</b>	<b>10</b>	<b>0</b>	623	<b>10</b>	n/a	1800	0	5	<b>20</b>
2	15	15	4	1800	0	2	1800	0	n/a	1800	0	7	<b>40</b>
3	15	15	<b>1</b>	1800	0	<b>1</b>	1800	0	n/a	1800	0	10	<b>28</b>
3	25	15	12	1800	0	8	1800	0	n/a	1800	0	<b>1</b>	<b>97</b>
4	25	15	27	1800	0	10	1800	0	n/a	1800	0	<b>1</b>	<b>69</b>
4	25	20	26	1800	0	9	1800	0	n/a	1800	0	<b>0</b>	<b>68</b>

\* for instances with integer solution found  
n/a: no integer solutions found within 1800 seconds

**Table 5. Comparison of the performance of sparse matrices for minimizing total flowtime.**

M	J	T	position-based			precedence-based			time-index-based			ILS	
			RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)
2	5	10	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	36	<b>10</b>	2	12
2	5	15	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	214	<b>10</b>	3	12
2	10	10	<b>0</b>	321	<b>10</b>	<b>0</b>	575	<b>10</b>	n/a	1800	0	6	<b>17</b>
2	10	15	<b>0</b>	818	<b>10</b>	<b>0</b>	1800	0	n/a	1800	0	3	<b>20</b>
2	15	15	<b>0</b>	1800	0	1	1800	0	n/a	1800	0	6	<b>49</b>
3	15	15	<b>1</b>	1800	0	3	1800	0	n/a	1800	0	6	<b>28</b>
3	25	15	7	1800	0	5	1800	0	n/a	1800	0	<b>3</b>	<b>115</b>
4	25	15	13	1800	0	8	1800	0	n/a	1800	0	<b>1</b>	<b>90</b>
4	25	20	13	1800	0	17	1800	0	n/a	1800	0	<b>1</b>	<b>91</b>

n/a: no integer solutions found within 1800 seconds

**Table 6. Comparison of the performance of dense matrices for minimizing total flowtime.**

M	J	T	position-based			precedence-based			time-index-based			ILS	
			RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)	#opt	RPD (%)	t(s)
2	5	10	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	16*	661	9	4	12
2	5	15	<b>0</b>	<b>0</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>10</b>	9*	1672	2	<b>0</b>	12
2	10	10	<b>0</b>	298	<b>10</b>	<b>0</b>	772	<b>10</b>	n/a	1800	0	4	<b>21</b>
2	10	15	<b>0</b>	356	<b>10</b>	<b>0</b>	1673	2	n/a	1800	0	4	<b>22</b>
2	15	15	<b>0</b>	1800	0	4	1800	0	n/a	1800	0	5	<b>56</b>
3	15	15	<b>2</b>	1800	0	<b>2</b>	1800	0	n/a	1800	0	6	<b>36</b>
3	25	15	11	1800	0	6	1800	0	n/a	1800	0	<b>0</b>	<b>145</b>
4	25	15	11	1800	0	8	1800	0	n/a	1800	0	<b>1</b>	<b>95</b>
4	25	20	14	1800	0	31	1800	0	n/a	1800	0	<b>1</b>	<b>99</b>

\* for instances with integer solution found  
n/a: no integer solutions found within 1800 seconds



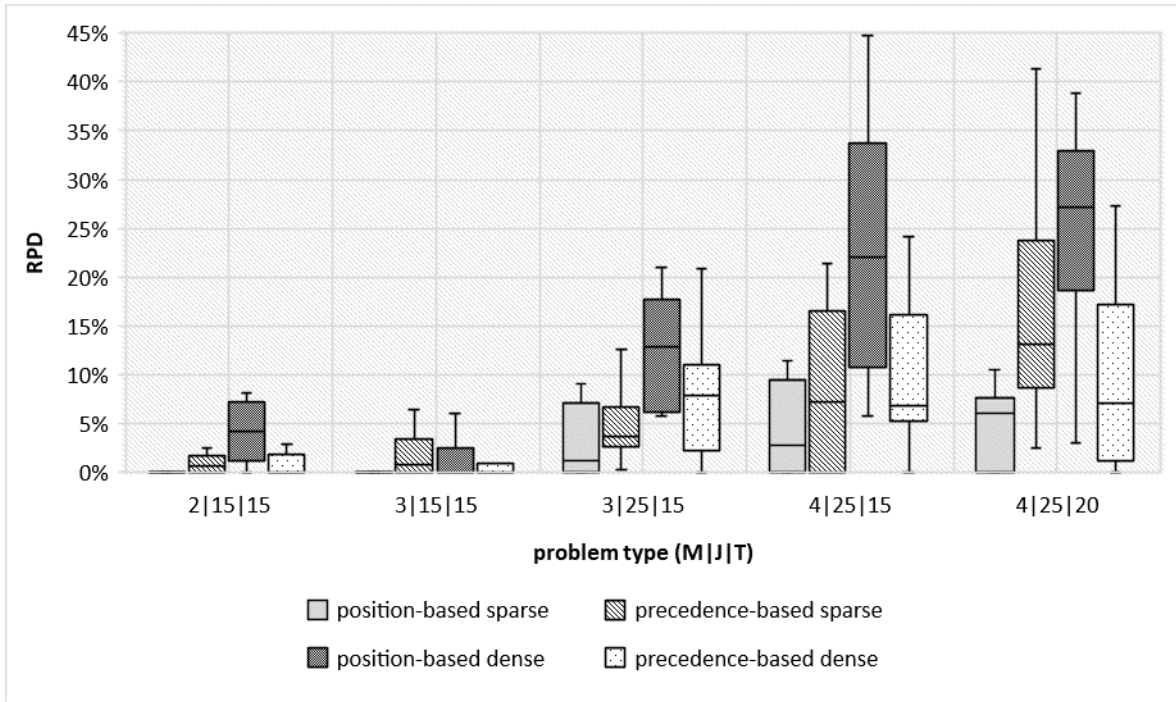


Figure 3. Percentile deviation of the position-based and precedence-based models when compared to the best known solutions for minimizing makespan.

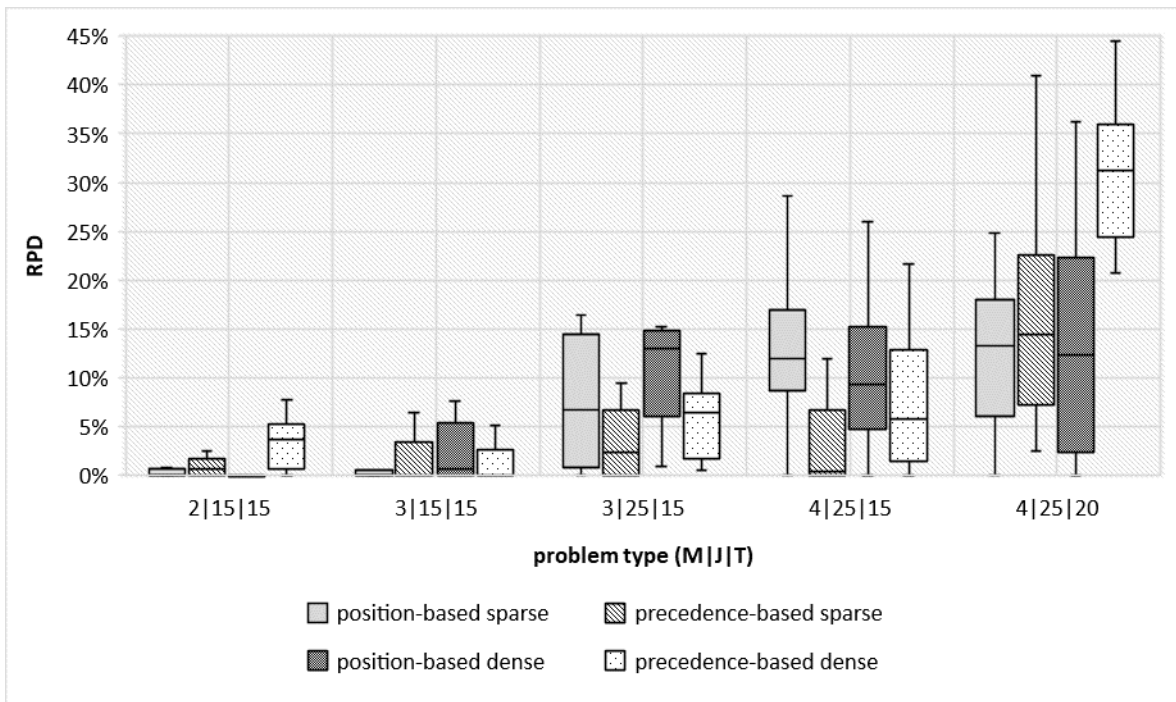


Figure 4. Percentile deviation of the position-based and precedence-based models when compared to the best known solutions for minimizing total flowtime.

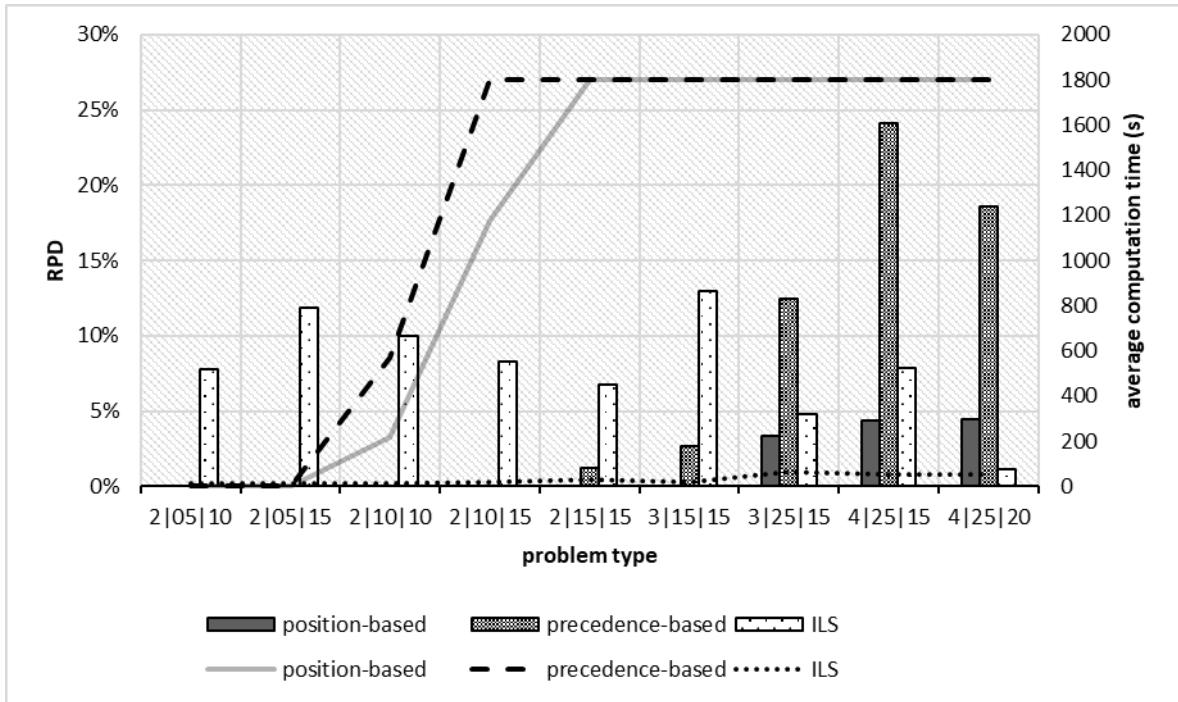


Figure 5. Comparison of the computation time and the average percentage deviation of sparse matrices for minimizing makespan (lines: average computation time, bars: RPD).

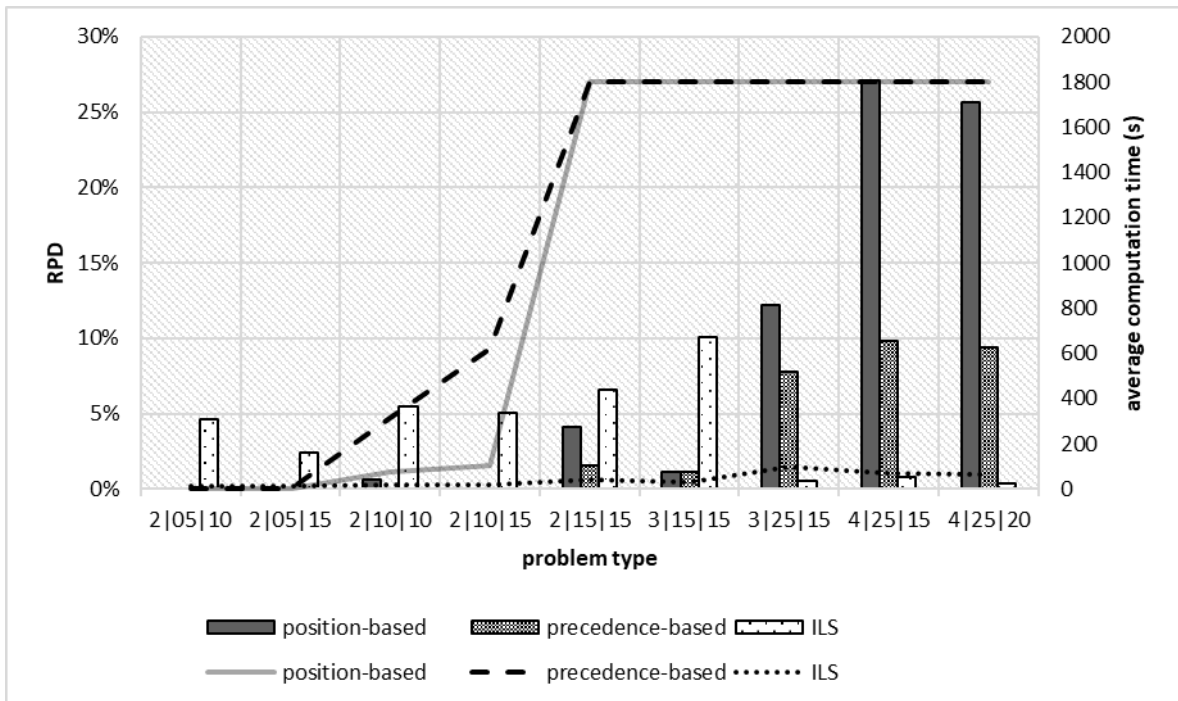


Figure 6. Comparison of the computation time and the average percentage deviation of dense matrices for minimizing makespan (lines: average computation time, bars: RPD).

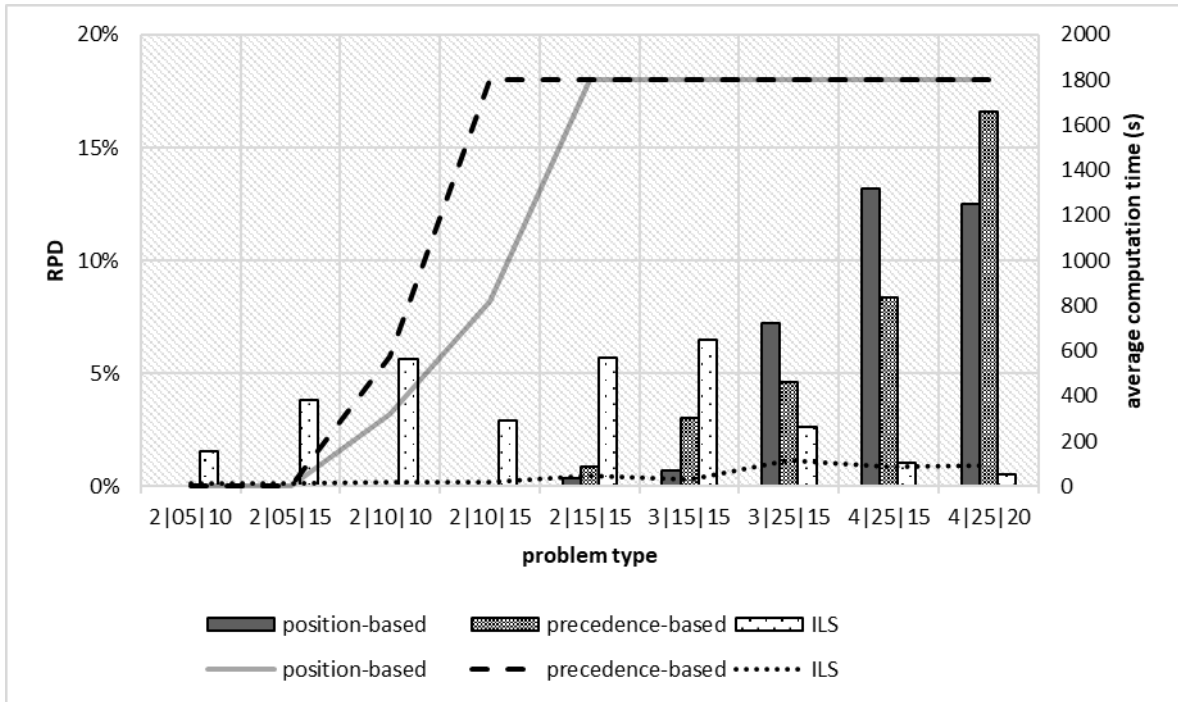


Figure 7. Comparison of the computation time and the average percentage deviation of sparse matrices for minimizing total flowtime (lines: average computation time, bars: RPD).

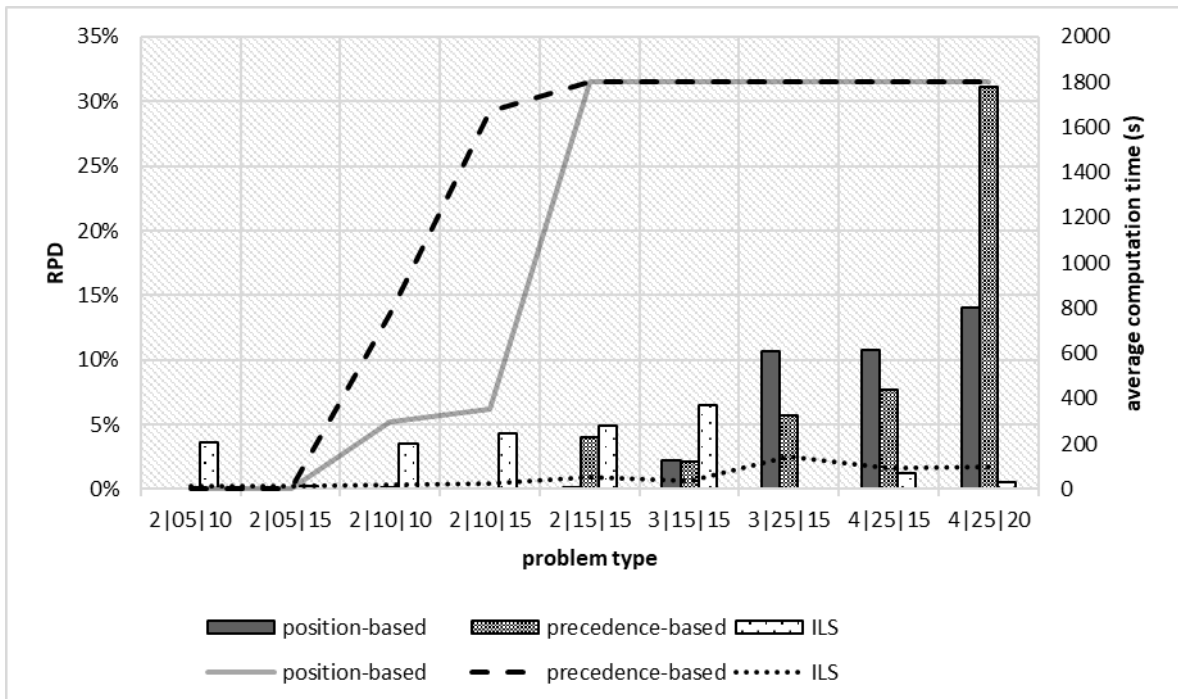


Figure 8. Comparison of the computation time and the average percentage deviation of dense matrices for minimizing total flowtime (lines: average computation time, bars: RPD).

## 4. Conclusion

This paper presents three different MILP formulations for the job sequencing and tool switching problem with non-identical parallel machines. The performance of the models is analysed using newly generated test problems. The results show that the SSP-NPM is a difficult optimization problem and only small problems can be solved to optimality within reasonable runtime. As expected, the time-index-based formulation shows the worst performance in terms of computation time and solution quality. The position-based model outperforms the other two models regarding runtime performance for small instances. The solution quality of the precedence-based model is the highest for dense matrices given the computation time limit. Moreover, the models yielded different results for different objective functions. However, with an increasing problem size the ILS metaheuristic requires significant less time to find good solutions.

Future research may focus on the generation of effective lower bounds in order to increase the performance of the proposed models and efficient search strategies other than the standard branch-and-bound technique of the CPLEX-solver may be proposed. Efficient heuristics are required for larger problem instances or real-world problems which generally contain more than fifty jobs (Shirazi and Frizelle 2001). The SSP-NPM offers plenty of possibilities for heuristic and meta-heuristic approaches. A notable computational benefit may be achieved by combining heuristic solution approaches with mathematical formulations by using initial heuristic solutions generated as starting solutions for the solver. Finally, the models could be extended to different tool sizes, since in reality large tools often occupy more than one slot in the tool magazine. The models may then have to consider tool switching times that depend on the size of the tool as well as decision variables that take into account the position of a tool in the magazine.

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## Appendix

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### Algorithm A.1: Iterated Local Search (ILS)

---

```

1  Let  $S_0$  be an initial solution obtained by the construction heuristic (see A.2);
2   $S^* \leftarrow \text{LocalSearch}(S_0)$ ;
3  for  $m = 1, 2, \dots, M$  do
4    // Swap each pair of jobs  $(j_1, j_2) \mid j_1 = 1, 2, \dots, J_m - 1$  and  $j_2 = j_1 + 1, j_1 + 2, \dots, J_m$  assigned to machine
    //  $m$ ; if the generated solution is better than the current best solution restart the swapping on the
    // current machine  $m$  //
6  end for
7  while iteration limit not reached do
8     $S' \leftarrow \text{Perturbation}(S^*, \text{search history})$ ; // Perturb the current solution ( $S^*$ ) //
9    // remove the job  $j'$  with the highest tool switching and processing time from the machine  $m'$  with
    // the highest completion time of the last job //
10   // insert the job  $j'$  in the position which yields the lowest approximated sum of processing and
    // tool switching time on another machine  $m''$  with sufficient tool magazine capacity //
11    $S^{*'} \leftarrow \text{LocalSearch}(S')$ ;
12    $S^* \leftarrow \text{AcceptanceCriterion}(S^*, S^{*'}, \text{search memory})$ ;
13   // Replace the current solution; best known solutions always replace the current solution; if the
    // solution has not improved the best solution obtained by the local search ( $S^{*'}$ ) is used for the next
    // perturbation move //
14  end while;
```

---



---

### Algorithm A.2: Construction Heuristic

---

```

1  initialise
    $S_0 \leftarrow \{ \}$  // initial solution // ;  $L \leftarrow \{1, \dots, J\}$  // set of unassigned jobs // ;
2  for  $m = 1, 2, \dots, M$  do
3     $S_0 \leftarrow \text{AssignFirstJob}(j^* \in L)$ ;
    // assign as a first job to machine  $m$  the job with the lowest processing time on that machine //
4     $L \leftarrow L \setminus \{j^*\}$ ;
5  end for
6  while  $L \neq \{ \}$  do
7     $m^* \leftarrow \text{argmin}\{f_m : m \in M\}$ ;
    // select the machine with the current minimum completion time of the last job  $l$  //
8     $j^* \leftarrow \text{argmin}\{p_{jm^*} + sw_{m^*} \cdot |T_j \setminus T_l| : j \in L\}$ ;
9     $S_0 \leftarrow \text{AssignNextJob}(j^* \in L)$ ;
    // append the job  $j^*$  with the lowest approximated sum of processing and tool switching time //
10    $L \leftarrow L \setminus \{j^*\}$ ;
11  end while
12  return  $S_0$ ;
```

---



# IV

## Heuristics for Solving the Job Sequencing and Tool Switching Problem with Non-Identical Parallel Machines

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### **Abstract**

*The job sequencing and tool switching problem (SSP) is an NP-hard combinatorial optimization problem in the context of flexible manufacturing machines. Tool switches denote the interchange of tools between the global tool storage and the local tool magazine of a machine since the tool magazine capacity of the machine is limited and cannot hold all tools necessary for processing all jobs. The presented work considers the SSP with non-identical parallel machines (SSP-NPM) for the different objectives minimizing the number of tool switches, minimizing makespan and minimizing total flowtime. A simple and fast heuristic approach for the SSP-NPM is presented that, step-by-step, assigns jobs to machines and, in the process, determines the loading of the tools. The performance of the heuristics is analyzed with respect to computation time and solution quality for different objectives.*

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## 1. Introduction

Modern manufacturing systems have to provide different module functions such as milling, drilling and turning, or tool and work-piece handling operations to efficiently deal with product variety and changing customer requirements. Each machine is equipped with a tool magazine of limited capacity that should hold at least the number of tools needed for processing a single job. Sequencing of product variations is a challenging task, since different operations require different sets of tools. In general, the number of tools required to process all jobs exceeds the tool magazine capacity, such that tools must be brought to and from the tool storage to the local machine magazine, and tool switches may be required within the machine magazine between two consecutive jobs. The setup time of a machine for a job is the time span needed for tool switching. If the tools cannot be interchanged during job processing then switching time becomes especially crucial when the switching time is significant in regard to the processing time of a job. The challenge of the job sequencing and tool switching problem (SSP) is to find the best job sequence such that, e.g., the number of tool switches is minimized. The uniform SSP for a single machine has first been addressed by Tang and Denardo (1988) who showed that the problem is solvable in polynomial-time by the ‘Keep Tool Needed Soonest’ (KTNS) policy and was proven to be NP-hard by Crama et al. (1994).

This paper is directed to the SSP for multiple non-identical parallel machines (SSP-NPM). The SSP-NPM is defined by three interdependent problems: (i.) assign a set of jobs to each of the machines, and (ii.) sequence the jobs on the machines, while in the process, (iii.) defining the tool loading so that a given objective is optimized. Non-identical implies that all of the machines can execute the same operations but may have different magazine capacities and different tools, and the processing time of a job need not be equal for all machines.

The SSP for multiple machines was first mentioned by Bard (1988) for tandem machines. Heuristics for the SSP for identical parallel machines have been addressed by Fathi and Barnette (2002) who conclude that the problem is NP-hard. Sarmadi and Gholami (2011) present a mixed-integer nonlinear program for machines with identical working conditions but different magazine capacities. Beezão et al. (2017) extend the IP formulation of Tang and Denardo (1988) and Laporte et al. (2004) for identical parallel machines and given processing times with the objective of minimizing makespan. Özpeynirci et al. (2016) and Gökgür et al. (2018) investigate the SSP for unrelated parallel machines without considering the magazine capacity but including a limited amount of tool copies to minimize the makespan. So far, the SSP-NPM with time aspects has not been addressed in literature. However, related problems for sequencing PCBs exist. Ghrayeb et al. (2003) and Van Hop and Nagarur (2004) consider the scheduling of printed circuit packs on multiple parallel sequencers that are equipped with a number of dispensing heads that have to be loaded with the required input tapes.

The remainder of this article is as follows. The problem definition is given in Section 2, followed by the description of the heuristics for the SSP-NPM in Section 3. Computational results are presented in Section 4. Section 5 concludes the study.

## 2. Problem Statement

For the SSP-NPM, a given set of jobs  $J$  has to be processed on a set of non-identical parallel machines  $M$ . Each machine  $m$  is theoretically able to process all jobs and sufficient tools are available to process all jobs on all machines. Only one job  $j$  can be processed on each machine at a time  $k$  and each job has to be assigned to exactly one machine. The processing of the jobs on each machine happens sequentially. The term non-identical means here that the processing times  $p_{jm}$  of any job  $j$  can depend on the machine  $m$ , and that the machines may have different magazine capacities  $C_m$ .  $K$  is a set of time periods  $k$ , needed to include timetabling in the extended model. A time instant  $k$  is measured at the end of period  $k$ .  $T$  denotes the set of tools that is required for processing all jobs. It is assumed that each tool occupies only one slot in the tool magazine of a machine. Each job requires a subset of tools  $T_j$  that has to be present in the tool magazine before this job is processed and  $J_t$  denotes the subset of jobs that require a certain tool  $t$ . However, the tool magazine capacity  $C_m$  of any machine  $m$  cannot hold the tools necessary for processing all jobs, so that tool switches may become necessary for two successive jobs. A tool switch is defined as the removal of a tool from its slot and inserting another tool in the same place (Tang and Denardo 1988). It is assumed that tools cannot be changed during the processing. The time to switch any tool on a machine  $m$  is defined as  $sw_m$ .

The SSP-NPM consists of simultaneously finding the assignment of jobs to machines as well as the right tool loading. The objective in general is to find for each machine the set of jobs to be processed and their sequence, such that the total number of tool switches ( $TS$ ) is minimized. In reality, not only the number of tool switches but different time-related objectives have to be considered like minimizing total flowtime ( $TFT$ ) or minimizing makespan ( $Fmax$ ). These objectives additionally require the completion time  $f_j$  of job  $j$  for all jobs. Table 1 presents the parameters of an illustrative example with 6 jobs, 9 tools and 2 machines with  $C_1 = 4$  and  $C_2 = 3$ , and  $sw_1 = 1$  and  $sw_2 = 2$ . The solution for minimizing  $TS$  is illustrated in Figure 1.

**Table 1. Example: tools used for each job and processing times  $p_{j1}$  and  $p_{j2}$  (in time periods), magazine capacities  $C_1 = 4$  and  $C_2 = 3$ .**

Jobs	1	2	3	4	5	6
	1	1	2	1	3	1
Tools	4	3	6	5	5	2
	8	5	7	7	8	4
	9		8	9		
$p_{j1}$	1	3	4	5	6	1
$p_{j2}$	2	4	3	5	3	1

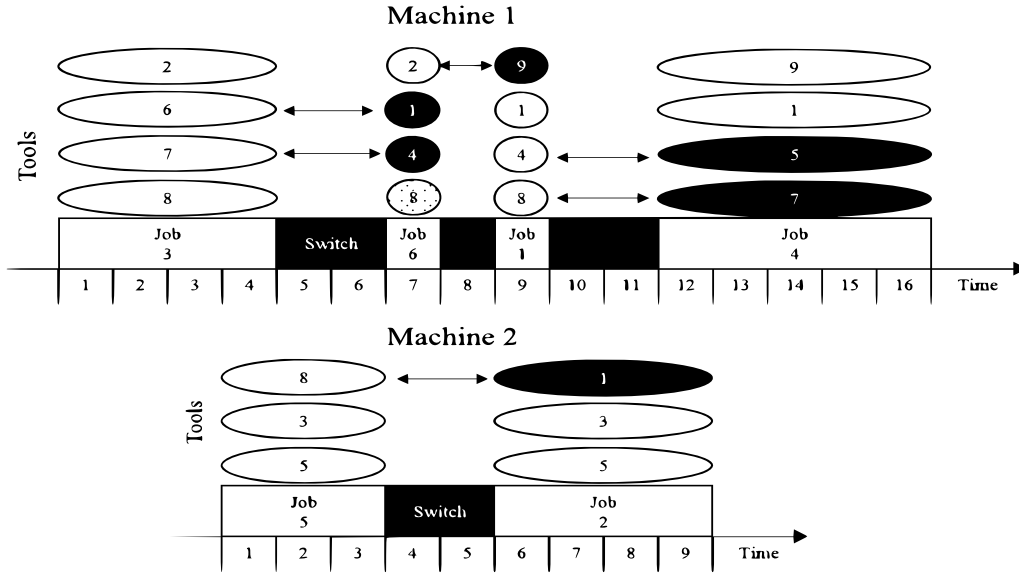


Figure 1. Solution to the initial example with arrows indicating tool switches;  $\min TS = 6$ .

### 3. Heuristics for the SSP-NPM

#### 3.1. Structure of the Heuristics

Each heuristic generates a job sequence for each machine. Therefore, let  $([j], m)$  denote the job found in position  $[j]$  in the sequence  $\Pi_m$  of jobs processed on machine  $m$ . Ties are always broken so that the element with the lowest index is selected.

---

#### Algorithm 1: Basic heuristic scheme

---

- 1 initialize  $\Pi_m = \emptyset, i_m = 0$
  - 2 **for** each machine **do**
  - 3      $generate\_sequence(i_m, r) \Pi_m$  according to  $assignment\_rule r \in \rho$
  - 4      $generate\_tool\_load(j_i, T_j, \Pi_m)$  with KTNS-policy
  - 5 **end for**
- 

#### 3.2. Rules for assignment

In this section, three simple assignment rules  $\rho$  are presented, simple to the extent that tool switching is not considered during the process. Each  $assignment\_rule r \in \rho$  is used to generate different job sequences for each machine. The basic scheme for generating the job sequence for any rule is presented below (Algorithm 2). The selection of the jobs itself is depending on the assignment rule.

---

**Algorithm 2: Basic scheme for *generate.sequence*( $i_m, r$ )**


---

```

1  initialize  $J\_left = J$ ,
2  while  $J\_left \neq \emptyset$  do
3     $m\_selected(i)$  // select 'free' machine,  $m\_selected \leftarrow \operatorname{argmin}_m(i)$ 
4     $j\_selection(r, m\_selected)$  // select the job,  $j\_selected \in J\_left$  according to rule  $r$ ,
5     $\Pi_m \leftarrow \Pi_m \cup \{j\_selected\}$  // append  $j\_selected$  to the sequence on the free machine
6     $i_m \leftarrow i_m + p_{j\_selected, m\_selected}$  // update  $i$ 
7     $J\_left \leftarrow J\_left \setminus \{j\_selected\}$  // remove selected job
8  end while

```

---

**SPT-based heuristic ( $r = 1$ ).** The shortest processing time (SPT)-based heuristic requires jobs being sorted in non-descending order of their processing times for all machines while satisfying the capacity restrictions. On the machine which is available earliest, the job with the smallest processing time is selected for assignment:  $j\_selected \leftarrow \operatorname{argmin}_j (p_{j, m\_selected})$

**LPT-based Heuristic ( $r = 2$ ).** The longest processing time (LPT)-based heuristic requires jobs being sorted in non-ascending order of their processing times for all machines while satisfying the capacity restrictions. On the machine which is available earliest the job with the highest processing time is selected for assignment:  $j\_selected \leftarrow \operatorname{argmax}_j (p_{j, m\_selected})$

**GI-Heuristic ( $r = 3$ ).** The greatest intersection (GI) requires the number of intersections between two possible consecutive jobs in a job sequence on a machine. At the beginning of the sequences, the jobs with the highest number of tools is selected. Subsequently, on the selected machine the job with the greatest intersection of tools compared to the previously processed job is selected for assignment on that machine.

---

**Algorithm 3: Basic scheme for *j.selection* ( $r = 3, m\_selected$ )**


---

```

1  if  $i_m = 0$  then
2     $j\_selected \leftarrow \operatorname{argmax}_j |T_j|$ 
3  end if
4  else if  $i_m > 0$  then
5     $intersect_j = (|T_j \cap T_{[j-1]}|)$ 
6     $j\_selected \leftarrow \operatorname{argmax}_j (intersect_j)$ 
7  end if

```

---

## 4. Computational Results

Experiments were conducted on a 2.50 GHz Intel Core i7-4710 processor with 16 GB of memory running under Windows 8. RStudio 1.1.453 with R 3.5.1 was used to implement and solve the heuristics. The instances of Beezão et al. (2017) were used but had been modified for multiple non-identical parallel machines by adding machine specific processing and tool switching times. Each problem group consists of 120 instances for the small ( $|J| \leq 25$ )

instances and 60 instances for the large ( $|J| \geq 50$ ) instances. A total of 1440 small instances and 1440 large instances had been tested.

Table 2 summarizes the results and shows the percentage of finding the best known solution per heuristic. Overall, the mean CPU time was 0.05 seconds for the SPT and LPT heuristics and 0.47 seconds for the GI-heuristic. Even large instances could be solved below 1 second.

**Table 2. Average percentage (%) of finding the best known solution for TS, TFT and Fmax.**

Problem Type	SPT-based heuristic			LPT-based heuristic			GI-heuristic		
	TS	TFT	Fmax	TS	TFT	Fmax	TS	TFT	Fmax
Small	10.8	<b>84.7</b>	<b>58.8</b>	9.6	0.6	3.3	<b>88.5</b>	14.8	38.1
Large	3.5	48.8	44.4	0.2	0.1	0.0	<b>96.3</b>	<b>51.1</b>	<b>55.6</b>

*Note.* Boldface numbers indicate the maximum percentage among the heuristics.

The results confirm that the SPT-based heuristic performs well for minimizing *TFT* or *Fmax*. The LPT-based heuristic performs worst for all objectives and the GI-heuristic performs best for minimizing *TS* and well for minimizing time-related objectives especially for large instances. Yet, the SPT-based heuristic outperforms the GI-based heuristic in terms of solution quality for small problem instances.

## 5. Conclusion

This paper presents simple and fast heuristics for the SSP-NPM with timetabling. Small and large instances were solved for different objective functions. The steadiest performance is achieved by the GI-heuristic for minimizing the number of tool switches while the SPT heuristic works rather well for minimizing total flow time or makespan. Further investigations and statistics tests are required in order to investigate the influence of the problem instance specifications on the solution quality. The quality of the solutions seems to differ significantly for variations in the relation between processing time and tool switching time but also variation of the job-tool matrix density. Future research may integrate the tool setup time as reducing the tool switches becomes especially important when the switching time is significant in regard to the processing time of a job. Overall, the heuristics seem to provide promising initial solutions for further local search procedures or metaheuristics.

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V

# An Iterated Local Search Procedure for the Job Sequencing and Tool Switching Problem with Non-Identical Parallel Machines

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**Under Review in** European Journal of Operations Research.

## **Abstract**

*In this paper, a new generalisation of the uniform job sequencing and tool switching problem is presented by considering non-identical parallel machines, which differ in tool magazine capacity and setup times. Applications of the problem can be found in the metal working or semiconductor manufacturing industries when the jobs require different tool sets for processing. The paper provides a Mixed Integer Programming formulation for the job sequencing and tool switching problem with machine-dependent processing and tool switching times under the consideration of three conflicting objectives (minimizing the total flowtime, minimizing the makespan and minimizing the total number of tool switches). Different efficient construction heuristics and Iterated Local Search methods are proposed and evaluated, using 640 new and publicly available instances. The results of the construction heuristics, the Iterated Local Search schemes and a Mixed Integer Programming Solver are discussed. The extensive computational experiments show the merit of the perturbation strategy in order to overcome local optima. It is shown that certain methods are more or less suitable depending on the objective function.*

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## 1. Introduction

Modern manufacturing systems have to allow for an adjustable machine structure in order to respond to product changes and complex product requirements with the upcoming of ‘smart factory’ and ‘industry 4.0’. A manufacturing machine may be equipped with a tool magazine of limited capacity and may provide different functions such as milling, turning, or tool handling operations. In general, the number of tools that is required to process a variety of jobs on a machine is so large that it exceeds the tool magazine capacity, and hence tool switches - defined by removing a tool from its slot and inserting another tool in the free slot Tang and Denardo (1988) - become necessary. If the tools cannot be interchanged during job processing, then the switching time is particularly significant if it is relatively high compared to the processing time of a job. In most real manufacturing systems, component or tool switching is the most time-consuming process (Van Hop and Nagarur 2004), and must be avoided. The objective of the standard uniform job sequencing and tool switching problem (SSP) is, therefore, to find the best sequence of jobs for a given set of jobs that minimizes the number of tool switches on a single machine. This problem has been addressed in production and operations research literature for more than 30 years, with a sharp increase in the last 5 years (Calmels 2019).

In the following, the job sequencing and tool switching problem with non-identical parallel machines (SSP-NPM) is addressed which is better adapted to challenges in the modern production environment. More precisely, the SSP-NPM is defined by three interdependent problems (see Figure 1): (1) assigning a set of jobs to machines, (2) sequencing the allocated jobs on the machines, and (3) arranging the tool loading. In contrast to the single machine problem, time-related objectives such as minimizing the makespan or total flowtime become more important when considering multi-machine problems. As the machines have a limited tool capacity, the number of tools to switch and hence the tool setup time of a job are influenced by the job sequence. Non-identical machines imply that all the machines can execute the same operations but may have different magazine capacities and different tools, and the processing time of a job and the tool switching time need not be equal for all machines.

The main contributions of this work include the formulation of a mixed integer linear (MIP) model that allows for time-related objectives, and the development of several heuristic solution methods. The mathematical formulation presents a more realistic and general approach to existing SSP research. Moreover, the paper provides two new data sets for the SSP-NPM and examines the solution quality of different problem groups. The remainder of this article is as follows. Section 2 presents an overview of related work. A problem description and the mathematical formulation are given in Section 3, followed by presenting the heuristic approaches in section 4. The computational experiments and the analysis are presented in section 5. The final section 6 concludes the study.

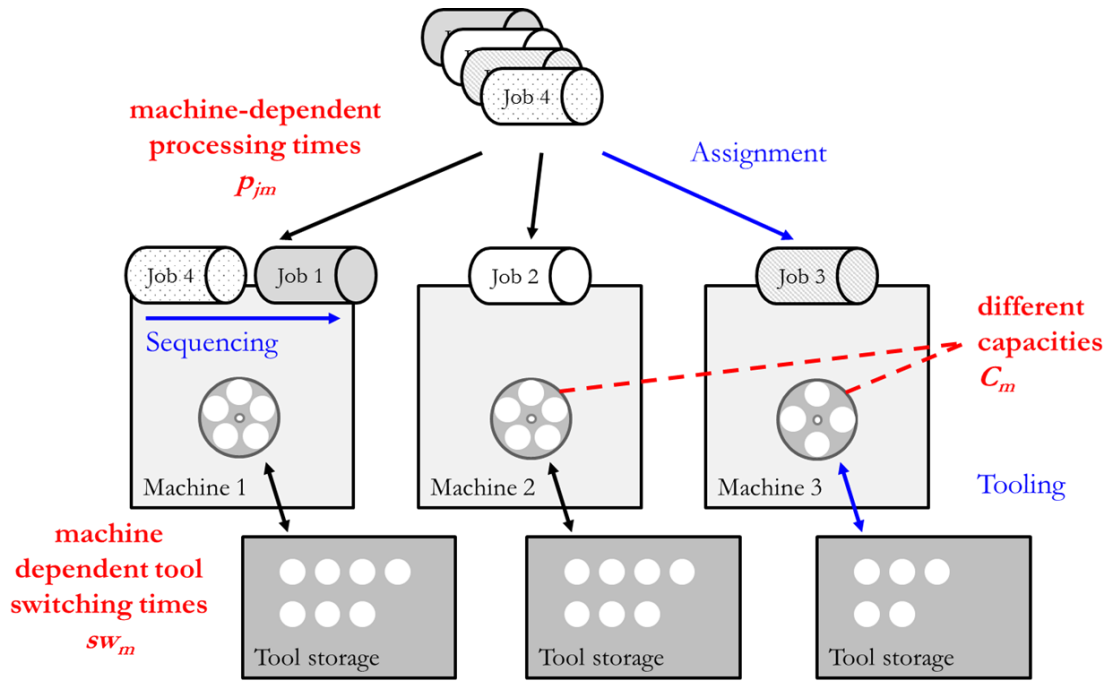


Figure 1. Schematic layout of the problem environment.

## 2. Related Work

Scheduling parallel machines has been widely discussed in literature and most of the problems have been shown to be NP-complete for different objectives (Lenstra et al. 1977). The interested reader is referred to Allahverdi (2015) and Kravchenko and Werner (2011). Although the SSP is directly related to machine scheduling, it developed its own research directions. The uniform SSP for a single machine with uniform tool size and equal and sequence-independent setup times was first introduced by Tang and Denardo (1988) who showed that the tool loading sub-problem can be solved to optimality by the ‘*keep tool needed soonest policy*’ (KTNS) in polynomial time. The uniform SSP was proven to be NP-hard by Crama et al. (1994). Therefore, researchers have mostly concentrated on heuristics or meta-heuristics. Only few articles consider exact algorithms or integer programming (IP) methods. A detailed review of the research on the SSP is provided by Calmels (2019).

Job sequencing with tool switching occurs in various industries (Shirazi and Frizelle 2001, Crama et al. 2007), and related problems have been established in diverse areas. Analogies to the tool switching problem in manufacturing industries can be found in the electronics industry for sequencing printed circuit boards (PCBs) (Ghrayeb et al. 2003, Tzur and Altmann 2004, Raduly-Baka and Nevalainen 2015, Hirvikorpi et al. 2006b) or in computer systems for caching and paging or k-server problems (Djellab et al. 2000, Privault and Finke 2000, Ghiani et al. 2007).

The SSP for multiple machines was first mentioned by Bard (1988) for tandem machines. Fathi and Barnette (2002) present heuristics for the SSP with identical parallel machines and conclude that the problem is NP-hard. A mixed-integer nonlinear program for machines with

identical working conditions but different magazine capacities is addressed by Sarmadi and Gholami (2011). Beezão et al. (2017) extend the IP formulations of Tang and Denardo (1988) and Laporte et al. (2004) to identical parallel machines with given processing times and the objective of minimizing makespan. Özpeynirci et al. (2016) and Gökgür et al. (2018) investigate the SSP for unrelated parallel machines without considering the magazine capacity but including a limited amount of tool copies to minimize the makespan. So far, only one article addresses the SSP-NPM with time aspects and few related studies exist for sequencing PCBs. Ghrayeb et al. (2003) and Van Hop and Nagarur (2004) consider the scheduling of printed circuit packs on multiple parallel sequencers that are equipped with a number of dispensing heads that have to be loaded with the required input tapes. Recently, Calmels et al. (2019) presented several sequencing policies for the SSP-NPM. It is shown that the SSP-NPM for different objective functions requires different strategies in order to ensure a good performance. Thus, the heuristics presented in Section 4 were adjusted to different objective functions.

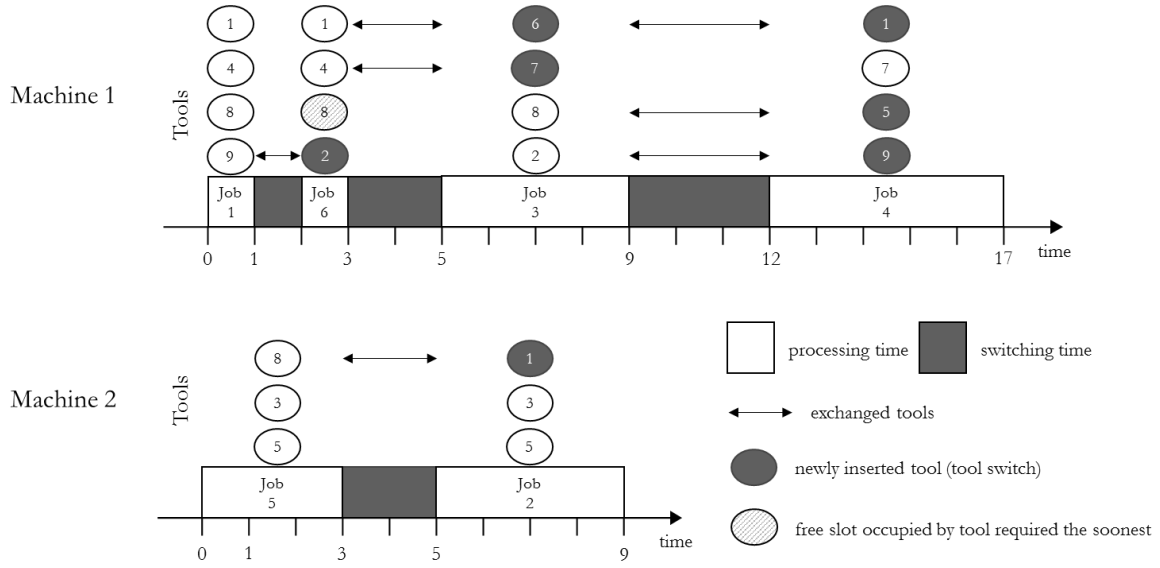
### 3. Problem Formulation

A set of jobs  $J = \{1, \dots, J\}$  has to be processed in a manufacturing environment with a set of non-identical parallel machines  $M = \{1, \dots, M\}$ . Each job  $j$  is available for processing at time zero and it is assumed that each machine can be used. Each machine is able to process any job and jobs are processed sequentially on each machine. The processing time  $p_{jm}$  of a job  $j$  on machine  $m$  is machine-dependent and the machines may have different magazine capacities  $C_m$ . The time to switch one tool on a machine  $sm_m$  may be different for the various machines, i.e., depends on the machine and not on the tool.  $T = \{1, \dots, T\}$  denotes the set of tools required for processing all jobs. It is assumed that each tool occupies only one slot in the tool magazine of a machine and at least one machine can hold all tools necessary for processing a job. Each job  $j$  requires a subset of tools  $T_j$ . The processing of a job can only start if the required tools are present in the magazine of the machine on which the job  $j$  is processed.  $J_t$  denotes the subset of jobs that require a certain tool  $t \in T$ . The nature of the SSP requires that the tool magazine capacity  $C_m$  of each machine  $m$  does not provide enough tool slots for processing all jobs, so that tool switches may become necessary for two successive jobs. The initial loading does not count as a tool switch and tool switching cannot happen while the processing of a job is ongoing. The three presented conflicting objectives are: (a) minimize the makespan ( $FMAX$ ), and (b) minimize total flowtime ( $TFT$ ), and (c) minimizing the total number of tool switches ( $TS$ ).

An example of the SSP-NPM is given in Table 1. The example consists of 6 jobs and 2 machines with different capacities and switching times. An optimal solution for minimizing the total flowtime is presented in Figure 2. The tool loading shows that although *job 6* requires only three tools, *tool 8* is kept in the free slot since it is required again for *job 3*. Note that minimizing  $TS$ ,  $TFT$  or  $FMAX$  are conflicting objectives. Consequently, the optimal solutions of this example for minimizing  $TS$  or  $FMAX$  are different from the displayed solution.

**Table 1. Example with  $J = 6$ ,  $T = 9$  and  $M = 2$  with  $C_1 = 4$ ,  $C_2 = 3$ ,  $sw_1 = 1$  and  $sw_2 = 2$ .**

Jobs	1	2	3	4	5	6
	1	1	2	1	3	1
Tools	4	3	6	5	5	2
	8	5	7	7	8	4
	9		8	9		
$p_{j1}$	1	3	4	5	6	1
$p_{j2}$		4			3	1



**Figure 2. Layout of the problem environment for optimizing TFT.**

The formulation Beetzão et al. (2017) provides the basis for the following mathematical formulation with the additional consideration of non-identical parallel machines and sequence and machine-dependent setup times. The variables  $x_{jrm}$  are equal to one if and only if job  $j$  is processed in the  $r^{\text{th}}$  position on machine  $m$ . Binary variables  $v_{trm}$  are equal to one if and only if tool  $t$  is present in machine  $m$  during the processing of the job in the  $r^{\text{th}}$  position. Binary variables  $w_{trm}$  are equal to one if and only if tool  $t$  is inserted in the tool magazine of machine  $m$  exactly before the  $r^{\text{th}}$  job is treated. The continuous variables  $f_{jrm}$  denote the completion time of job  $j$  in the  $r^{\text{th}}$  position on machine  $m$ .  $G = \sum_{j=1}^J \max_m(p_{jm}) + (J-1) \cdot \max_m(sw_m \cdot C_m)$  is a large constant.

$$\sum_{r \in J} \sum_{m \in M} x_{jrm} = 1 \quad \forall j \in J \quad (1)$$

$$\sum_{j \in J} x_{jrm} \leq 1 \quad \forall r \in J, \forall m \in M \quad (2)$$

$$\sum_{j \in J} x_{jrm} \leq \sum_{j \in J} x_{j(r-1)m} \quad \forall r \in J \setminus \{1\}, \forall m \in M \quad (3)$$

$$\sum_{j \in J_r} x_{jrm} \leq v_{trm} \quad \forall t \in T, \forall r \in J, \forall m \in M \quad (4)$$

$$\sum_{t \in T} v_{trm} \leq C_m \quad \forall r \in J, \forall m \in M \quad (5)$$

$$v_{trm} - v_{t(r-1)m} \leq w_{trm} \quad \forall t \in T, \forall r \in J \setminus \{1\}, \forall m \in M \quad (6)$$

$$f_{jlm} = p_{jm} \cdot x_{jlm} \quad \forall j \in J, \forall m \in M \quad (7)$$

$$f_{jrm} \geq \sum_{i \in J, i \neq j} f_{i(r-1)m} + s w_m \sum_{t \in T} w_{trm} + p_{jm} x_{jrm} - G(1 - x_{jrm}) \quad \forall j \in J, \forall r \in J \setminus \{1\}, \forall m \in M \quad (8)$$

$$v_{trm}, w_{trm} \in \{0, 1\} \quad \forall t \in T, \forall r \in J, \forall m \in M \quad (9)$$

$$x_{jrm} \in \{0, 1\} \quad \forall j \in J, \forall r \in J, \forall m \in M. \quad (10)$$

Constraints (1) denote that each job is assigned to exactly one machine and position. Constraints (2) impose that each position on machine is used by at most one job. Constraints (3) ensure that if there is a job in the  $r^{\text{th}}$  position on machine  $m$  then there must be a job in position  $r-1$ . Constraints (4) guarantee that the tools required for job  $j$  are available in the tool magazine in the moment of job  $j$ 's processing. Constraints (5) ensure that the tool loading does not exceed the tool magazine capacity. Constraints (6) determine whether tool  $t$  is inserted in the magazine of machine  $m$  before the processing of a job in position  $r$ . The completion times of the initial jobs are calculated by the constraints (7) while the completion times of any other job are restricted by the constraints (8) as the sum of the completion time of the job processed in position  $r-1$ , the setup time and the processing time. Constraints (9) and (10) denote the integrality conditions.

The objective functions consider the minimization of the total flowtime (*TFT*) (11), minimization of the makespan (*Fmax*) (12) in combination with the additional constraints (13), and the minimization of the total number of tool switches (14).

$$\min TFT = \sum_{j \in J} \sum_{r \in J} \sum_{m \in M} f_{jrm} \quad (11)$$

$$\min Fmax \quad (12)$$

$$Fmax \geq f_{jrm} \quad \forall j \in J, \forall r \in J, \forall m \in M \quad (13)$$

$$\min TS = \sum_{t \in T} \sum_{r \in J} \sum_{m \in M} w_{trm} \quad (14)$$

#### 4. Solution approaches for the SSP-NPM

This section presents several solution procedures for the SSP-NPM. Three construction heuristics are introduced (Section 4.1), which build the initial solutions for the proposed iterated local search (ILS) (Section 4.2). The solution methods are evaluated by the extensive computational experiments reported in Section 5.

#### **4.1. Construction Heuristics**

The performance of many exact and heuristic approaches depends on the quality of their initial solution. This section presents two rule-based heuristics and a Multi-Start-Random heuristic. Building a good initial solution is extremely important for the SSP-NPM because the optimal tool switches and the allocation of tools to free slots can only be determined for a given sequence. The purpose of the construction heuristics is to assign the jobs to machines and to sequence the jobs on the machines. The optimal tool loading can be determined using the KTNS-policy (Tang and Denardo 1988): (1) no tool is inserted unless it is required by the next job, (2) if the number of tools needed for a next job is less than the magazine capacity, then tools needed the soonest by subsequent jobs are kept in the remaining free slots of the tool magazine and are not removed.

**IEACT (Iterated Earliest Artificial Completion Time):** This heuristic is an altered version of the IECT (Iterated Earliest Completion Time) heuristic proposed by Pessoa and Andrade (2018) for the flowshop scheduling problem with delivery dates. It extends the SPT-based heuristic for the SSP-NPM of Calmels et al. (2019) by adding the approximated tool setup time to the processing time. The calculation of the artificial completion time is an adaptation of the concept proposed by Liu and Reeves (2001) for the permutation flowshop scheduling problem with minimizing total flow time objective. A solution is built from scratch by iteratively appending a job at the end of a machine's partial solution. The machine with the minimum completion time of the last job is always selected for job assignment. The first job added is the job with the lowest processing time. After that, each unscheduled job is evaluated according to its earliest artificial completion time. The job with the lowest artificial completion time is added to the partial sequence. All ties are broken randomly. The KTNS-algorithm (Tang and Denardo 1988) is used to subsequently determine the tool loading that minimize the number of tool switches for the given sequence. The pseudocode (Algorithm 1) is provided in the appendix.

**IGI (Iterated Greatest Intersection):** Similar to the IEACT heuristic, this heuristic builds a solution by iteratively appending a job at the end of a machine's partial solution. The basic structure of this algorithm was proposed by Tang and Denardo (1988) and several variations exist for the single machine problem (Crama et al. 1994, Follonier 1994). Following their ideas, a new iterative construction heuristic is proposed for the SSP-NPM. The machine with the minimum current artificial completion time of the last job is always selected for job assignment. The first job added is the job that requires the maximum number of tools (with less than or equal to the magazine capacity of the selected machine) in order to prevent later tool switching. After that, each unscheduled job is evaluated according to the number of tools in common with the last job in sequence on the selected machine. The job with the currently greatest intersection of tools compared to the job last in sequence is added to the partial sequence. The artificial completion time of the job being added is updated afterwards. All ties are broken randomly. Note that the optimum tool loading can only be evaluated for a given sequence and the actual intersection between two jobs may actually differ from the number of tool switches in the

optimal solution. The tool loading is subsequently optimized for the final constructed solution using KTNS (Tang and Denardo 1988). The pseudocode (Algorithm 2) is provided in the appendix.

**MSR (Multi-Start-Random):** The multi-start random heuristic generates a random permutation of all jobs. Afterwards, the jobs in the sequence of the generated permutation are allocated cyclically to the machines starting with the first machine. The idea behind is that for most real-world problems the machine load has to be balanced in order to reduce the completion time for all machines. If a job cannot be assigned to the machine under consideration, because the capacity restrictions would be violated, the job is randomly assigned to a machine with sufficient magazine slots. The tool loading is subsequently optimized by the KTNS-policy (Tang and Denardo 1988) and the process restarts until the iteration limit is reached. The best solution for each objective is returned. The pseudocode (Algorithm 3) is provided in the appendix.

#### ***4.2. An Iterated Local Search Method (ILS)***

Although construction heuristics can usually provide a good solution very quickly, an improvement of the solution quality may be obtained by applying local search algorithms. In this section, an iterated local search method is presented. ILS has been applied to a wide range of scheduling problems (Lourenço et al. 2019) since it avoids the extensive tuning of parameters. For the general ILS algorithm and the review of some applications see, for example, Talbi (2009), and Lourenço et al. (2019). ILS applications to the SSP are provided by Bard (1988) and Paiva and Carvalho (2017) for the uniform single machine SSP, and by Hirvikorpi et al. (2006a) under the consideration of tool wear. Algorithm 4 describes the general ILS scheme. Starting with an initial solution, ILS iteratively applies intensification and diversification through local search and perturbation methods until a stopping criterion is reached. In the small-step phase, a swapping-based local search is performed on each machine. A large-step optimization is performed afterwards by transferring jobs between machines using the newly proposed perturbation methods.

##### **4.2.1. Local Search with Restart**

An initial solution is constructed by one of the construction heuristics presented in section 4.1. The local search method (see Algorithm 5) further explores the neighbourhood of the initial solution in order to find a local minimum. Here, the neighbourhood of the initial solution is explored by an iterated swapping scheme. After swapping two jobs processed on a machine, the tool loading is optimized by the KTNS procedure (Tang and Denardo 1988) to obtain a new solution  $\mathcal{S}'$ . The new solution is only accepted if its objective value  $F(\mathcal{S}')$  is better than the best-known objective value  $F(\mathcal{S}^{best})$ , hence if  $F(\mathcal{S}') < F(\mathcal{S}^{best})$ . In this case, the local search restarts on the machine where an improvement has been generated, otherwise the next pair of jobs is swapped on the machine being considered. All possible swaps on one machine are analysed before the swaps are performed on the next machine. This is repeated until all machines have

been considered. The local search is limited to the neighbourhood of a solution without modifying the job assignment to the machines. Subsequently to the local search, a large step perturbation is performed by altering the job assignment by inserting jobs on different machines.

#### **4.2.2. Perturbation**

Three different perturbation strategies are explored due to the conflicting nature of the different objectives. In order to address the difficulty that the problem-specific perturbations (P.1) may result in the algorithm being stuck in local optima a randomized procedure (P.2) as well as a combination of the problem-specific and randomized perturbation (P.3) are presented. Ties are always broken randomly.

**Objective-specific perturbations (P.1):** The paper considers three different objectives of which two objectives are time-related (total flowtime and makespan) and one objective is related to tool switches. Therefore, two different perturbation procedures are applied.

- **Time-based perturbation (P.1a):**

The makespan and the total flowtime are influenced by many factors, among them the processing and setup time of each job. These objective values can only be decreased by decreasing the completion time of at least one job. The new perturbation concept is an insertion-based method. Given a current solution, select the bottleneck machine  $m_1$  with the highest completion time of the last job ( $f_{m_1}$ ), and for which there exists a job that can be relocated to another machine  $m_2$ . The job  $j_1 = [q^*]_{m_1}$ , in position  $q^*$  on machine  $m_1$ , with the highest processing plus setup time cost is selected. Note that the job is only selected if it can be relocated to any of the other machines, thus the relocation does not violate the capacity restrictions. Job  $j_1$  is reinserted on a different machine  $m_2$  that must provide a sufficiently large tool capacity. Job  $j_1$  is inserted on a different machine  $m_2$  between two jobs such that the sum of processing time and approximated tool switching times is minimized over the different machines and insertion positions. Note that in the case of removing as well as inserting a job from the first or the last position, the calculations reduce because, as per definition, tool switches do not occur before processing the first job and after processing the last job on a machine. The pseudocode (Algorithm 6) is provided in the appendix.

- **Tool-Switch-based perturbation (P.1b):**

The perturbation for minimizing the number of tool switches is similar to the previous perturbation concept, but ignores time-related aspects. The bottleneck machine  $m_1$  with the highest total number of tool switches is selected, and for which there exists a job that can be relocated to another machine.  $t_j$  denotes the number of tool switches required immediately before processing job  $j$ . The job  $j_1$  processed on  $m_1$  with the largest number of tool switches required immediately before its processing is selected for reinsertion on another machine. Job  $j_1$  is inserted on a different machine  $m_2$  such that the number of tool switches before and after processing job  $j_1$  on machine  $m_2$  is minimized over the different machines and insertion positions.



Figure 3 illustrates the selection and insertion. Note that in this example, both machines have a total number of tool switches of 5. Job 6 on machine 2 is selected. Together with job 3, job 6 currently requires the most tool switches but can be allocated to another machine (machine 1). It is randomly assigned to either position 1 or position 4 on machine 1 in the position with the least approximated tool switches. The pseudocode (Algorithm 7) is provided in the appendix.

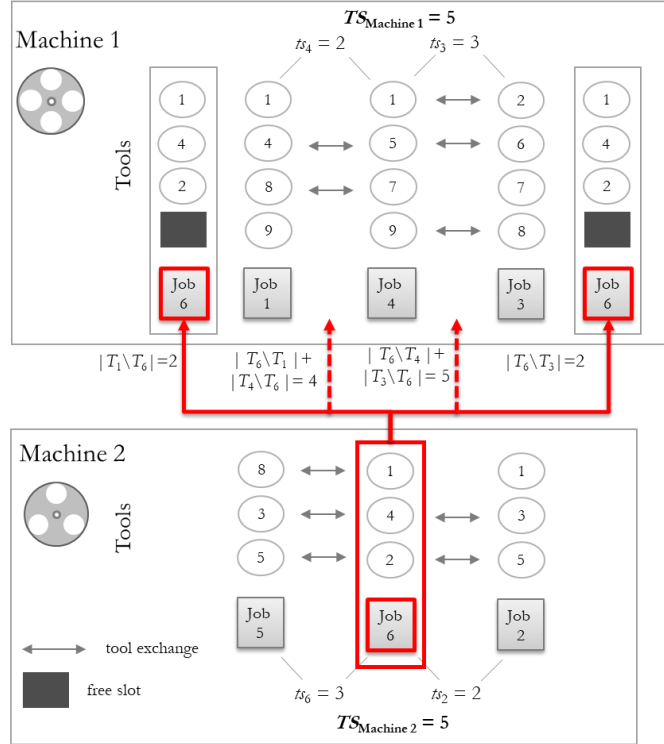


Figure 3. Illustration of the removal and insertion phase for tool switching.

**Random Perturbation (P.2):** For the random permutation,  $n$  jobs of job set  $J$  are selected at random. The jobs are successively relocated to random positions in the sequence of a randomly selected machines with sufficient tool capacity. Based on the observations of Paiva and Carvalho (2017)  $n$  is obtained by  $n = \lfloor \beta \cdot |J| \rfloor$ , with parameter  $\beta$ ,  $0 < \beta < 1$ .

**Combined Perturbation (P.3):** This perturbation algorithms combines the objective-specific perturbation (P.1) and the random perturbation (P.2) in order to overcome local optima created by the systematic objective-specific perturbation. A random perturbation is performed with a fixed probability  $\gamma$ , with  $0 < \gamma < 1$ , after an iteration without improvement. For this, a random number ( $rand$ ) is generated from a uniform distribution in the interval  $0 < \gamma < 1$ . If  $rand < \gamma$ , a random perturbation is performed, for example  $\gamma = 0.25$  would mean that a random perturbation is applied in average every fourth deterioration.

The perturbations are followed by the aforementioned local search. Note that the local search that follows the perturbation must only be performed for the machines on which the perturbation has altered the sequence.

### **4.2.3. Acceptance and Termination Criteria**

Accepting only improved solutions would result in the algorithm converging to a local optimum. Therefore, the acceptance criterion ensures that even an inferior solution may replace the current solution. An improved solution always replaces the current solution. The best solution obtained after the perturbation and local search step is always accepted thus allowing a large diversification until a maximum number of perturbation iterations  $i$  or a time limit is reached.

## **5. Computational Experiments**

This section analyses the computational performance of the heuristics and the mathematical formulation. First, the characteristics of the test instances are provided (section 5.1). Then, the tuning of the parameters is described (section 5.2). The performance of the solution methods is summarized and discussed in section 5.3.

Experiments were conducted on a 3.20 GHz Intel Core i8-8700 processor with 32 GB of memory running under Windows 10. IBM CPLEX 12.8 on GAMS 25.1.3 was used to implement and solve the mathematical model while allowing CPLEX to use all cores in parallel. A time limit of 600 seconds was imposed for the solution of each instance. The heuristics were implemented and run with R 3.5.1 (using RStudio 1.1.463). The codes of the mathematical model and the heuristics, as well as a brief description of the algorithms are available on <https://git.io/JvLrC>.

### **5.1. Description of the Instances**

The solution methods have been tested on two new data sets, SSP-NPM-I and SSP-NPM-II, since the problem has not been addressed in literature so far. SSP-NPM-I has been introduced in order to explore the limits of the mathematical model and provides ‘small’ instances. Since the focus of this paper is the evaluation of the heuristics the time limit for the mathematical model is 600 seconds. SSP-NPM-II is proposed in order to explore the limits of the heuristic solution methods and provides ‘large’ instances. Table 2 and Table 3 summarize the specifications of the problem sets considered in the experimental evaluation. 20 instances were randomly generated for each problem type. Processing times  $p_{jm}$  are random integers generated from a uniform distribution over the intervals [1, 10]. The instances are publicly available on <https://git.io/Jvsqp>.

Data set SSP-NPM-I provides a total of 160 instances. The number of tools per job is randomly drawn from the interval [3, 5] for two-machine instances and from the interval [5, 7] for three-machine instances. The required tools are randomly chosen from the tool set. Note that for both data sets the dominance criterion (Laporte et al. 2004) is met which means that any job’s tool set is never a subset of any other job’s tool set.

**Table 2. Characteristics of SSP-NPM-I.**

$ M $	$ J $	$ T $	$C_m$	$sw_m$
2	{10, 15}	{10, 15}	(5, 7)	(2, 4)
3	{15, 20}	{15, 20}	(7, 10, 13)	(2, 3, 4)

Data set SSP-NPM-II provides 480 instances. Additional instances were defined for several sub-categories in order to evaluate the impact of different switching times and different quantities of required tools per job. The tool switching times  $sw_m$  were assumed to be either relatively low or high compared to the processing times. The tool switching time  $sw_m$  on machine  $m$  is either low,  $\lfloor 0.75 \times \text{mean}(p_m) \rfloor$ , or high,  $\lceil 1.15 \times \text{mean}(p_m) \rceil$ , similar to the instance generation of Beezão et al. (2017). In order to investigate the assumption of Burger et al. (2015) that the difference between the magazine size and the quantity of tools required per job influences the performance of the heuristics, the job-tool combinations, depending on the number of required tools, are either sparse or dense. Sparse matrices were randomly generated based on the number of required tools per job  $|T_j|$  using a uniform distribution over the interval  $[\min \left\{ \frac{C_m}{4}, \min \left\{ \frac{C_m}{2} \right\} \right\}]$  while for dense matrices  $|T_j|$  is generated over the interval  $[\max \left\{ \frac{C_m}{2}, \max (C_m) \right\}]$ .

**Table 3. Characteristics of SSP-NPM-II.**

$ M $	$ J $	$ T $	$C_m$	$sw_m$	Job-Tool-Matrix Density
4	{40, 60}	60	$(25+(m-1) \cdot 5)$	{low, high}	{sparse, dense}
4	{40, 60}	120	$(25+(m-1) \cdot 5)$	{low, high}	{sparse, dense}
6	{80, 120}	120	$(45+(m-1) \cdot 5)$	{low, high}	{sparse, dense}

## 5.2. Parameter Settings

Among the heuristics, only the MSR and the ILS require parameter calibrations. The iteration limit of the MSR was set to 1,000. The components of the ILS include (1) the heuristic used to build the initial solution, (2) the type of perturbation move applied, (3) the acceptance threshold, and (4) the stopping criterion. The instances of data set SSP-NPM-I were used to obtain suitable parameter values. The parameter  $\beta$  for the random permutation (P.2) was analysed for  $\beta \in \{0.2, 0.4, 0.6, 0.8\}$ . The Wilcoxon Signed-Rank test showed that the computation time and the objective values are not significantly different ( $*p > .05$ ) for different levels of  $\beta$ . Therefore,  $\beta$  was set to 0.2 for minimizing total flowtime and makespan and 0.8 for minimizing the number of tool switches since these levels resulted in the best average relative deviations.

For the combined perturbation (P.3), the parameter  $\gamma$  was analysed for  $\gamma \in \{0.05, 0.1, 0.25, 0.5\}$  since the main structure of a good solution should be retained. The parameter  $\beta$  was set to  $\beta \in \{0.2, 0.4, 0.6, 0.8\}$ . All possible combinations of  $\beta$  and  $\gamma$  were tested. Results showed that small values of  $\beta$  obtained the best results for all  $\gamma$ . Since no combination was significantly better than all other combinations, the levels with the best average relative deviation values were

chosen. For minimizing the number of tool switches and for minimizing the makespan the parameters were chosen as  $\beta = 0.2$  and  $\gamma = 0.1$ , and for minimizing total flowtime  $\beta = 0.2$  and  $\gamma = 0.05$ . Initially, an adequate time-limit for the ILS variations had been evaluated by using 1000 iterations for different problems. It was shown that the algorithm improves the initial solution very quickly and starts to converge after a few iterations. The maximum computation limit was therefore set to 600 seconds for the final evaluation of the different ILS approaches.

### **5.3. Experimental Results**

For each instance, the relative percentage deviation (RPD(%)) between the solution value found with the considered method and the best known solution value (BKS) were computed as well as the average percentage deviation (AvPD(%)) across all the instances / all the problem sets. To confirm the results, the conclusions of the comparisons were tested applying the Wilcoxon Signed-Rank test, assuming a significance level of  $*p > .05$ .

#### **5.3.1. Evaluation of the Construction Heuristics**

Figure 4 depicts the box plots of the RPDs of the construction heuristics from the BKS obtained among construction heuristics. The results show that the best starting solutions for minimizing the number of tool switches and minimizing the makespan were obtained by the multi-start random heuristic for small problems (Figure 4 a). For minimizing the makespan the IGI method yields the worst RPD values and varies widely. However, the average number of total tool switches is very low for small problems, so that even a very small deviation from the best known value results in a high RPD. Since the MSR was run for 1,000 iterations, its performance decreased for large problems (Figure 4 b). The MSR yielded the worst results for all objectives for large problems, while the best results were obtained by the IGI method for minimizing the total number of tool switches and by the IEAC method for minimizing total flowtime. The computation time of the MSR was significantly higher than the computation time of the IEACT and the IGI for both sets of instances (see Figure 5). The computation times of IEACT and IGI are insignificant even for very large problems. Since a good solution should be obtained very fast, MSR cannot compete with the greedy construction methods. Therefore, IEACT was used for minimizing makespan and total flowtime and IGI was used for minimizing the total number of tool switches for the following local search and iterated local search methods.

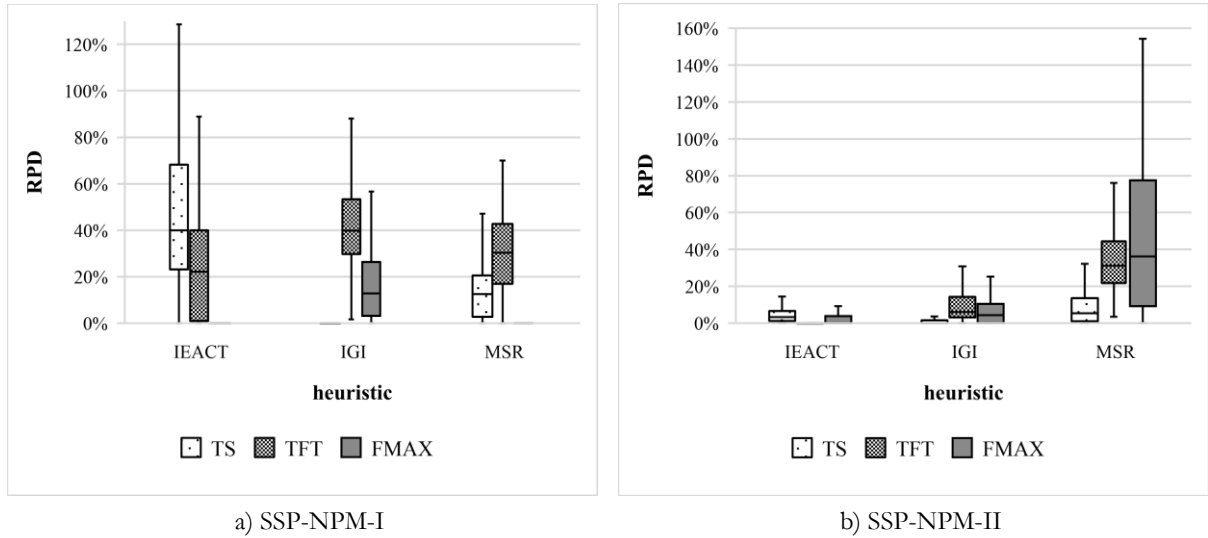


Figure 4. Percentage deviation relative to the best solution found considering the construction heuristics IEACT, IGI and MSR for each objective.

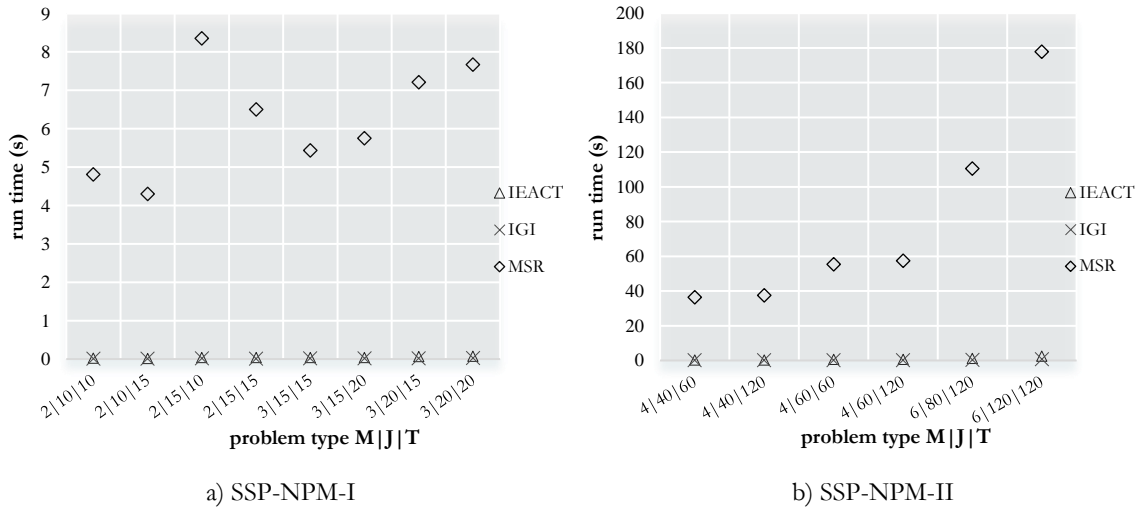


Figure 5. Comparison of the average computation times per problem type of the construction heuristics IEACT, IGI and MSR.

### 5.3.2. Evaluation of the Local Search

The local search (Algorithm 5) has the advantage that it is rather simple and easy to implement, and it requires no parameter tuning. The results show that applying an initial LS to the construction heuristics significantly improves the solution quality. The average percentage improvement for different problem types in SSP-NPM-I lies between 3 % and 13 % improvement of the construction heuristics for minimizing TS, between 3 % and 8 % for minimizing TFT and between 4 % and 7 % for minimizing FMAX (Figure 6). For SSP-NPM-II, the average percentage improvement lies between 1 % and 6 % improvement of the construction heuristics for minimizing TS, between 6 % and 13 % for minimizing TFT and between 1 % and 6 % for minimizing FMAX (Figure 7). The results show no significant difference in the improvement for instances with different tool switching times but a significant difference for sparse and dense matrices (Figure 8). The improvement for sparse matrices is significantly higher than for dense matrices but requires higher computation times (Figure 9).

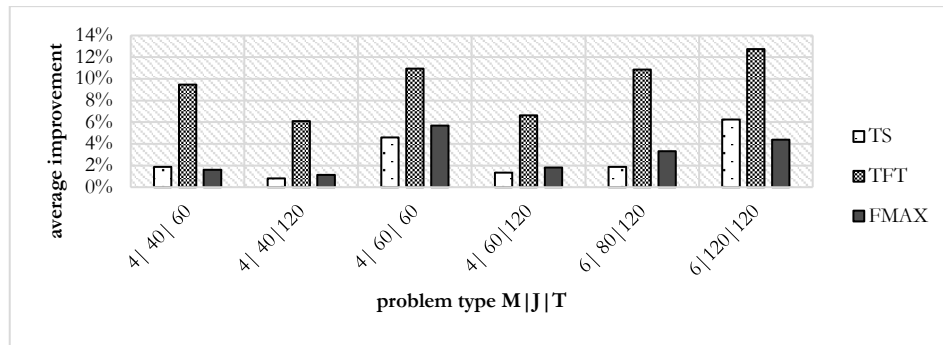


Figure 6. Average percentage improvement per problem type using local search for SSP-NPM-I.

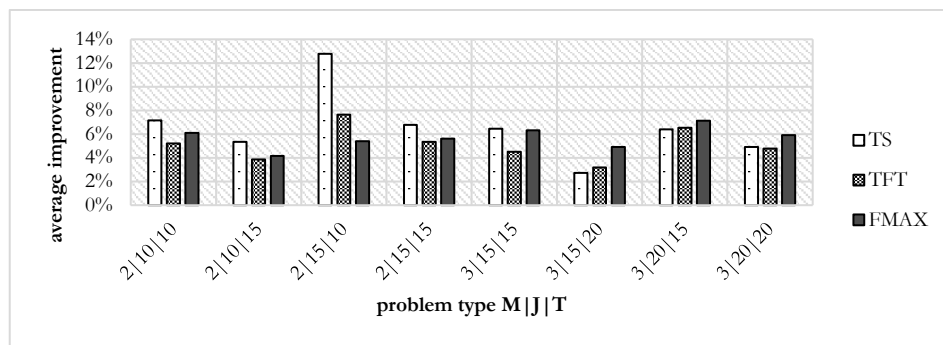


Figure 7. Average percentage improvement per problem type using local search for SSP-NPM-II.

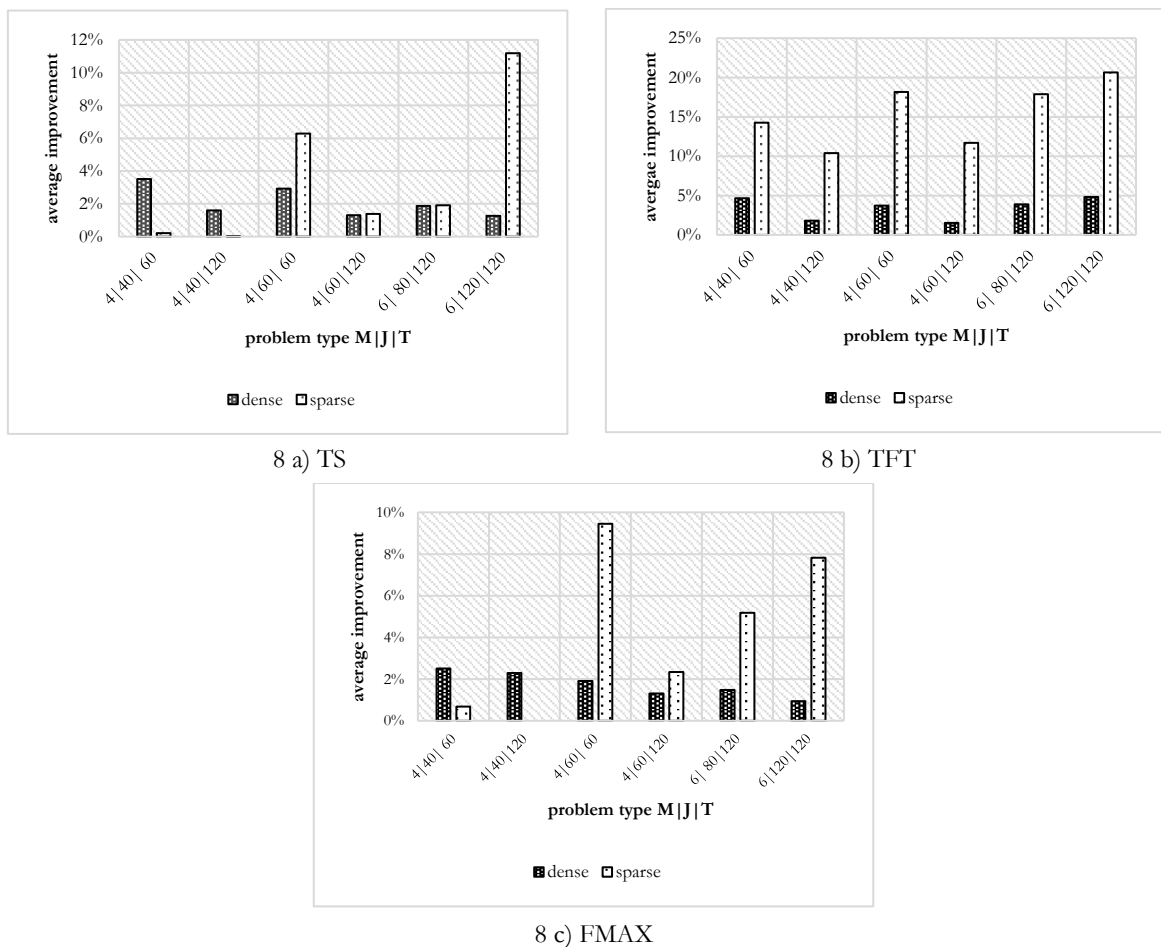


Figure 8. Average percentage improvement per problem type using local search for sparse and dense matrices of SSP-NPM-II.

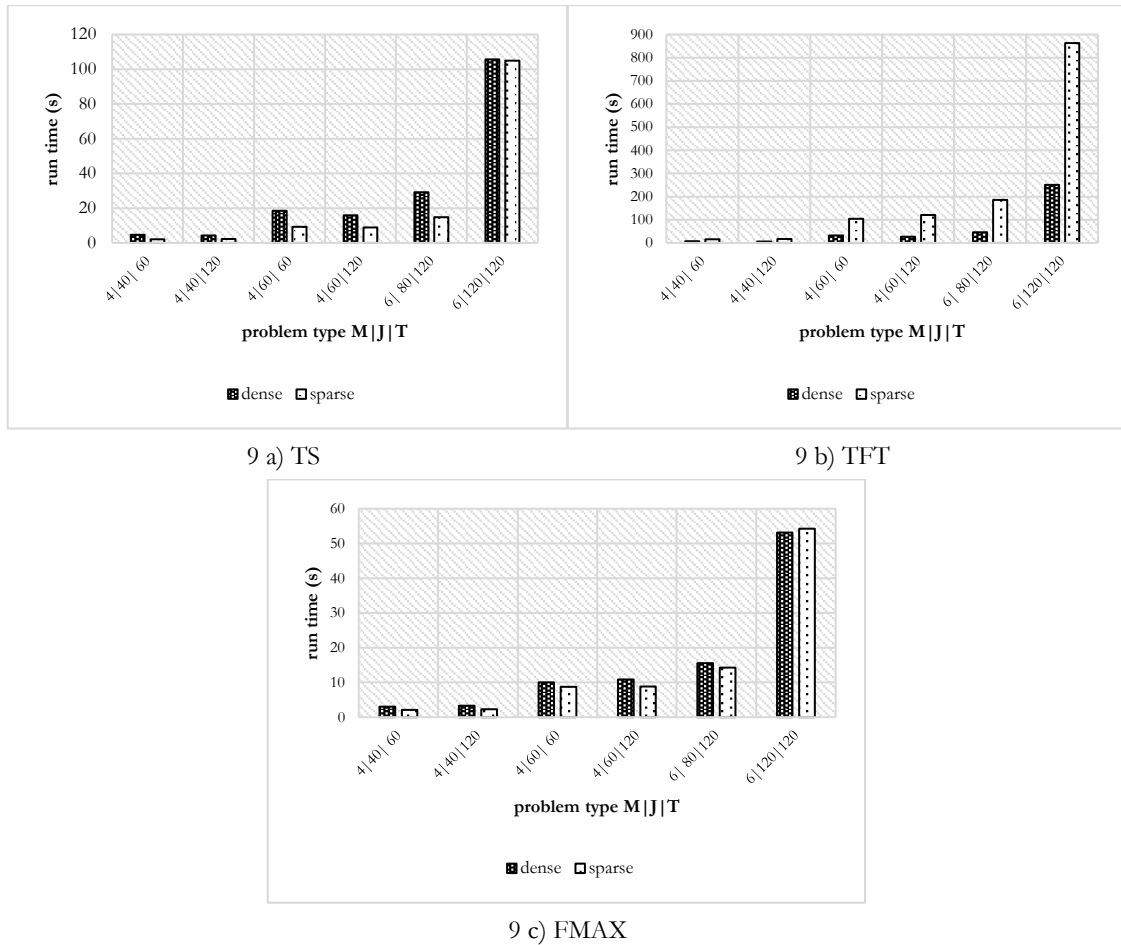


Figure 9. Comparison of the average computation times per problem type of the local search for sparse and dense matrices of SSP-NPM-II.

### 5.3.3. Evaluation of the ILS Methods

The results of the ILS methods had been compared to the mathematical formulation using the data-set SSP-NPM-I. Table 4 summarizes the performance of the mathematical formulation. The fourth, seventh and tenth column provide the average total tool switches (avTS), the average total flowtime (avTFT) and the average makespan (avFMAX) per problem type as additional information. Moreover, the average computation time in seconds (time(s)) and then number of instances solved to optimality (#Opt) per 20 problem type instances are provided. It is shown that only few instances can be solved to optimality given the time-limit of 600 seconds and heuristics have to be used for larger-sized problems. The model especially struggles with the time-related objectives where only instances with 10 jobs can be solved to optimality.

Table 5 shows the performance comparison of the mathematical formulation and the ILS methods. Underlined values indicate the best results. The AvPD is calculated based on the best solution found considering the different ILS methods and the mathematical formulation. For the objective of minimizing the number of tool switches (TS) the mathematical formulation significantly outperforms the ILS heuristics. It has to be noted that the high deviation derives from the low tool switching values, so that even a solution which is very close to the solution

of the solver yields a high relative deviation. For small problems (SSP-NPM-I), the combination of problem-specific and randomized perturbation steps (P.3) yields the best results out of the ILS methods for each objective and can compete even with the performance of the mathematical model. The ILS heuristic even outperforms the mathematical formulation for time-related objectives. Table 6 shows a direct comparison of the ILS versions for small instances and highlights the statement that the P.3 outperforms the other ILS methods for small instances.

For larger problems (SSP-NPM-II) the random component is responsible for a deterioration of the performance of the random perturbation (P.2) and the combined perturbation (P.3). The results are summarized in Table 7. The problem-specific perturbation (P.1) outperforms the other perturbation schemes except for minimizing the number of tool switches of dense problems where a random component is required in order to overcome local optima. Although P.1 yields the best results for SSP-NPM-II in many of the problem instances it has to be mentioned that the combined perturbation (P.3) overall provides good and robust results for any problem type, even for sparse and dense matrices.

Figure 10, Figure 11, and Figure 12 show the detailed average percentage deviations for different problem types considering the objectives TS, TFT, and FMAX, respectively. Different switching times did not provide a significant difference in the performance of the heuristics. For sparse and dense problems, however, it can be observed that the different methods yield different results for each objective. For minimizing the number of tool switches the problem-specific perturbation method (P.1b) outperforms the other methods for sparse problems since for sparse problems there exist many more possibilities to fill empty tool slots. For dense matrices, however, with less empty slots, the problem-specific method seems to get stuck in local optima which leads to worse results. Here, the random perturbation (P.2) yields extremely good results. The minimization of the total flowtime shows different results. The problem-specific perturbation (P.1a) and the combined perturbation (P.3) outperform the random perturbation (P.2) for sparse and dense problems. On a closer look, it can be observed that P.1a always yields a lower AvPD than P.3 for sparse problems. The results of minimizing the makespan are similar to the results of minimizing the total flowtime. The random perturbation (P.2) always yields the worst results. For each method, the AvPD-values for dense problems are lower than the values for sparse problems showing that sparse problems are more difficult to solve because of the many tool optimization possibilities.



**Table 4. Performance of the mathematical formulation for SSP-NPM-I.**

M	J	T	TS			TFT			FMAX		
			avTS	time(s)	#Opt	avTFT	time(s)	#Opt	avFMAX	time(s)	#Opt
2	10	10	3	8	20	129	494	11	29	322	19
2	10	15	6	61	20	164	600	0	37	570	3
2	15	10	4	377	12	280	600	0	45	600	0
2	15	15	10	600	0	346	600	0	55	600	0
3	15	15	1	272	13	163	600	0	26	600	0
3	15	20	5	600	0	197	600	0	34	600	0
3	20	15	2	517	6	294	600	0	37	600	0
3	20	20	8	600	0	399	600	0	51	600	0
<b>Average</b>			<b>5</b>	<b>379</b>	<b>9</b>	<b>247</b>	<b>587</b>	<b>1</b>	<b>39</b>	<b>562</b>	<b>3</b>

**Table 5. Average Percentage Deviation relative to the best solution found considering the MIP and the different ILS methods for SSP-NPM-I.**

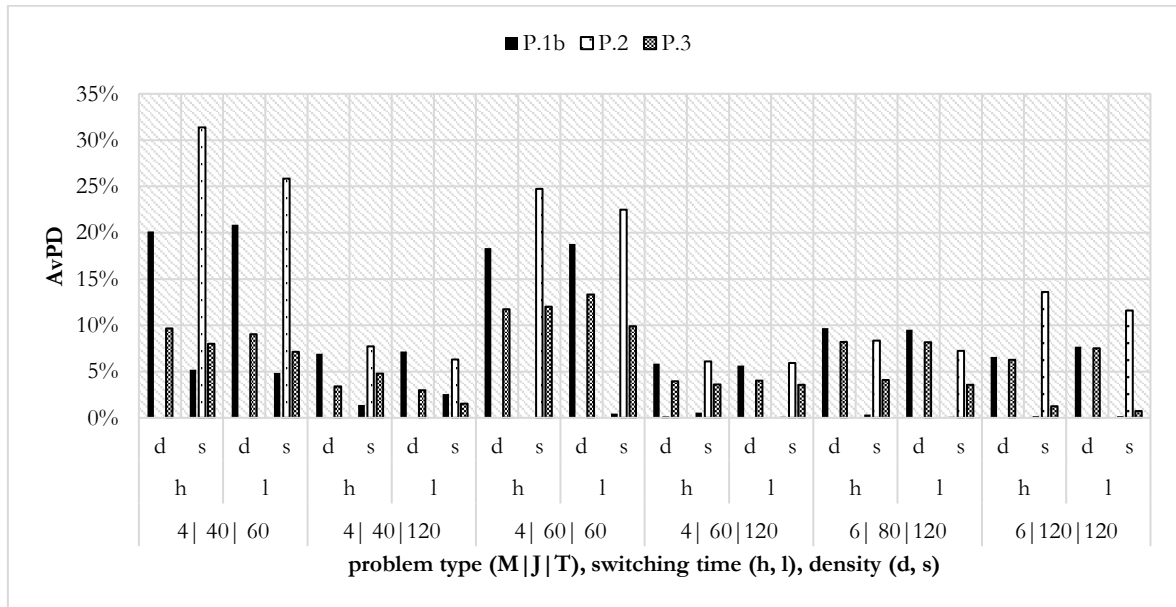
M	J	T	AvPD TS				AvPD TFT				AvPD FMAX			
			MIP	P.1b	P.2	P.3	MIP	P.1a	P.2	P.3	MIP	P.1a	P.2	P.3
2	10	10	<u>0.00</u>	42.08	6.67	3.33	<u>0.00</u>	4.01	0.84	0.30	<u>0.00</u>	6.03	0.48	<u>0.00</u>
2	10	15	<u>0.00</u>	33.86	6.56	6.23	<u>0.20</u>	4.34	0.71	0.31	<u>0.00</u>	5.85	0.85	<u>0.00</u>
2	15	10	<u>0.00</u>	57.08	41.67	33.08	1.80	5.46	5.24	<u>0.95</u>	1.86	6.42	10.53	<u>0.70</u>
2	15	15	<u>0.00</u>	25.33	24.85	18.82	1.35	6.47	5.30	<u>1.24</u>	3.72	6.54	10.21	<u>0.18</u>
3	15	15	<u>0.00</u>	168.42	236.84	5.26	<u>1.04</u>	11.04	18.47	1.72	2.23	17.54	22.05	<u>1.03</u>
3	15	20	<u>0.00</u>	92.81	74.37	30.27	<u>1.20</u>	12.50	16.48	1.88	4.66	18.38	22.19	<u>0.82</u>
3	20	15	<u>0.00</u>	185.00	382.50	57.50	3.79	10.18	22.41	<u>1.73</u>	8.20	18.77	29.68	<u>0.37</u>
3	20	20	<u>0.00</u>	66.26	103.89	47.97	6.77	5.20	13.18	<u>0.78</u>	13.98	9.91	24.10	<u>0.12</u>
<b>Average</b>			<b><u>0.00</u></b>	<b>83.86</b>	<b>109.67</b>	<b>25.31</b>	<b>2.02</b>	<b>7.40</b>	<b>10.33</b>	<b>1.11</b>	<b>4.33</b>	<b>11.18</b>	<b>15.01</b>	<b>0.40</b>

**Table 6. Average Percentage Deviation relative to the best solution found considering only the different ILS methods for SSP-NPM-I.**

M	J	T	AvPD TS			AvPD TFT			AvPD FMAX		
			P.1b	P.2	P.3	P.1a	P.2	P.3	P.1a	P.2	P.3
2	10	10	37.92	3.33	<u>0.00</u>	3.80	0.64	<u>0.09</u>	6.03	0.48	<u>0.00</u>
2	10	15	30.59	3.83	<u>3.50</u>	4.22	0.59	<u>0.19</u>	5.85	0.85	<u>0.00</u>
2	15	10	25.01	11.50	<u>4.92</u>	4.55	4.34	<u>0.09</u>	5.71	9.78	<u>0.00</u>
2	15	15	8.44	7.84	<u>2.57</u>	5.38	4.24	<u>0.20</u>	6.54	10.11	<u>0.09</u>
3	15	15	163.16	228.95	<u>0.00</u>	9.23	16.64	<u>0.03</u>	16.40	20.83	<u>0.00</u>
3	15	20	46.63	37.14	<u>0.00</u>	10.43	14.45	<u>0.05</u>	17.47	21.19	<u>0.00</u>
3	20	15	77.50	212.50	<u>0.00</u>	8.48	20.59	<u>0.15</u>	18.33	29.24	<u>0.00</u>
3	20	20	13.34	40.10	<u>1.00</u>	4.79	12.76	<u>0.40</u>	9.91	24.10	<u>0.12</u>
<b>Average</b>			<b>50.32</b>	<b>68.15</b>	<b>1.50</b>	<b>6.36</b>	<b>9.28</b>	<b>0.15</b>	<b>10.78</b>	<b>14.57</b>	<b>0.03</b>

**Table 7. Average Percentage Deviation relative to the best solution found considering the different ILS methods for SSP-NPM-II.**

Density	M	J	T	AvPD TS			AvPD TFT			AvPD FMAX		
				P.1b	P.2	P.3	P.1a	P.2	P.3	P.1a	P.2	P.3
sparse	4	40	60	<u>5.02</u>	28.60	7.56	<u>1.19</u>	21.44	1.91	<u>2.01</u>	26.05	2.80
sparse	4	40	120	<u>1.97</u>	7.01	3.17	<u>0.31</u>	14.26	1.11	2.07	15.06	<u>1.25</u>
sparse	4	60	60	<u>0.22</u>	23.61	10.96	<u>0.16</u>	18.34	1.35	<u>0.63</u>	23.49	5.32
sparse	4	60	120	<u>0.33</u>	6.01	3.60	<u>0.12</u>	10.79	0.28	<u>0.32</u>	11.90	2.54
sparse	6	80	120	<u>0.24</u>	7.80	3.83	<u>0.03</u>	16.29	0.24	<u>0.67</u>	17.47	2.92
sparse	6	120	120	<u>0.18</u>	12.60	1.01	<u>0.06</u>	11.08	0.22	<u>0.25</u>	24.57	3.61
<b>Average</b>				<b>1.33</b>	<b>14.27</b>	<b>5.02</b>	<b>0.31</b>	<b>15.37</b>	<b>0.85</b>	<b>0.99</b>	<b>19.76</b>	<b>3.07</b>
dense	4	40	60	20.51	<u>0.00</u>	9.36	<u>0.39</u>	3.75	0.52	<u>0.44</u>	6.16	1.32
dense	4	40	120	7.05	<u>0.00</u>	3.19	<u>0.09</u>	1.79	0.20	<u>0.51</u>	6.15	0.53
dense	4	60	60	18.56	<u>0.00</u>	12.53	<u>0.27</u>	3.21	0.44	<u>0.00</u>	3.53	0.94
dense	4	60	120	5.75	<u>0.01</u>	3.99	<u>0.01</u>	1.54	0.22	<u>0.16</u>	4.45	0.46
dense	6	80	120	9.61	<u>0.00</u>	8.19	<u>0.15</u>	2.21	0.18	<u>0.04</u>	2.54	0.18
dense	6	120	120	7.14	<u>0.00</u>	6.88	0.18	2.16	<u>0.17</u>	<u>0.00</u>	2.09	0.23
<b>Average</b>				<b>11.43</b>	<b>0.00</b>	<b>7.36</b>	<b>0.18</b>	<b>2.44</b>	<b>0.29</b>	<b>0.19</b>	<b>4.15</b>	<b>0.61</b>
<b>Total Average</b>				<b>6.38</b>	<b>7.14</b>	<b>6.19</b>	<b>0.25</b>	<b>8.90</b>	<b>0.57</b>	<b>0.59</b>	<b>11.96</b>	<b>1.84</b>



**Figure 10. Comparison of the average percentage deviations of the ILS methods per problem type for high and low switching times and sparse and dense matrices of SSP-NPM-II for TS.**

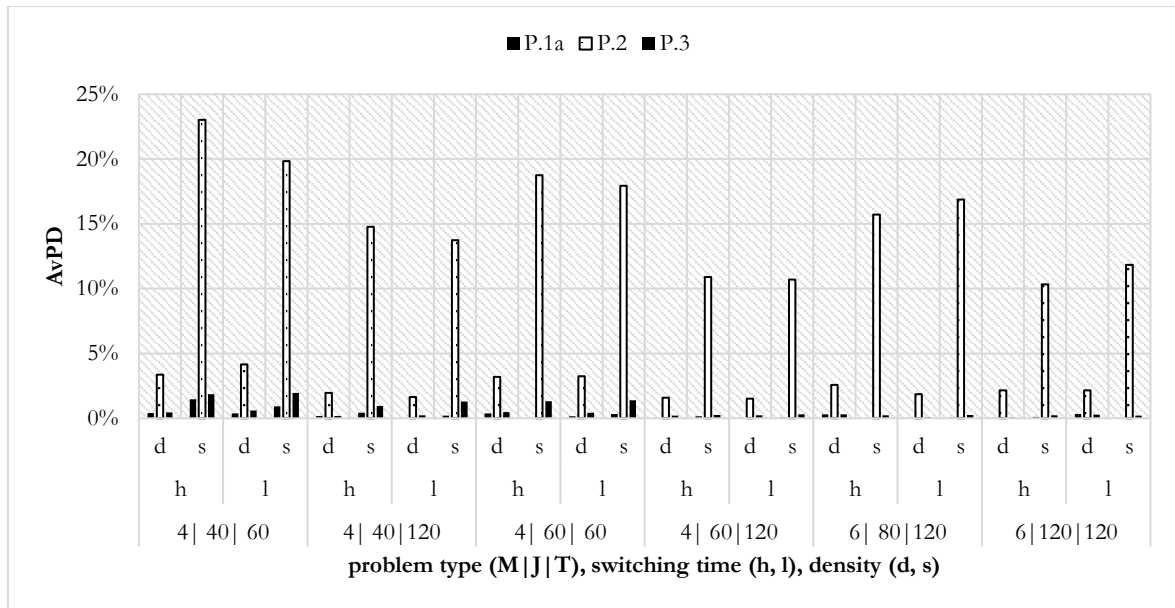


Figure 11. Comparison of the average percentage deviations of the ILS methods per problem type for high and low switching times and sparse and dense matrices of SSP-NPM-II for TFT.

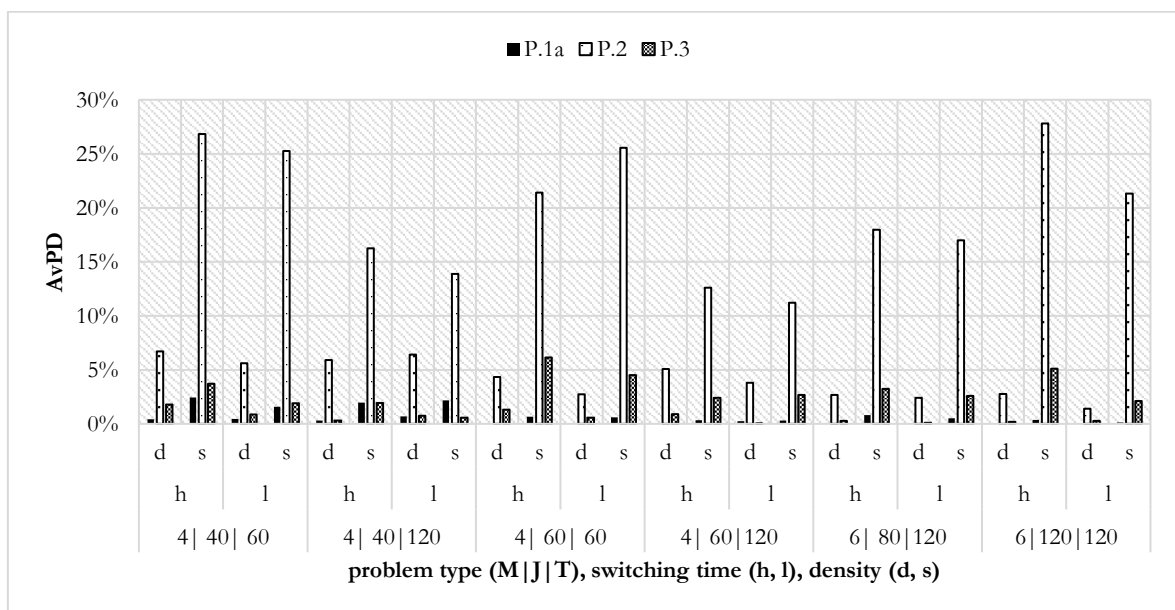


Figure 12. Comparison of the average percentage deviations of the ILS methods per problem type for high and low switching times and sparse and dense matrices of SSP-NPM-II for FMAX.

## 6. Conclusion

In this paper, the challenging job sequencing and tool switching problem in the context of non-identical parallel machines is investigated. A new MIP formulation is presented that can be applied to different objective functions. The computational experiments show that only small problems can be solved to optimality. New ILS methods are proposed since large problems cannot be solved to optimality within reasonable run time. Several construction heuristics and

perturbation schemes are evaluated. It is shown that the local search is indispensable and that the proposed ILS methods are able to provide good solutions even for large problem instances. In general, the ILS method with problem-specific and randomized perturbation moves outperforms the problem-specific ILS method as well as the randomized ILS method for small problems. Although the problem-specific heuristics tend to converge to local optima they are able to find good solutions faster than the ILS heuristics with a random component. The randomized heuristic requires more time to find promising areas of the solution space but may overcome local optima which proves useful for minimizing the number of tool switches of dense problems.

The focus of this work are different perturbation strategies for three different objectives, and thus only one local search method had been included in the experimental evaluation. Further research may investigate the impact of different local search techniques on the performance of the ILS or meta-heuristics. Moreover, examining different acceptance and stopping criteria may prove useful. In the presented problem-specific ILS, any iteration could return to a previously examined solution. Implementing a tabu-list may improve the performance of the ILS by prohibiting the problem-specific perturbation to get stuck in a local optimum.

Extensions of the SSP-NPM may consider tool wear or different tool sizes and tool-dependent setup times. The SSP with different tool sizes has already been studied for a single-machine (see, for example, Raduly-Baka et al. 2005, Van Hop 2005, Hirvikorpi et al. 2006b). Different tool sizes appear for example in the metal-working industry where different metal-working operations require tools of different sizes. Some tools may also require special care or handling so that the tool switching time may not be equal for each tool. Another interesting extension of the SSP-NPM may consider that the number of available tools may be limited and that some tools could be handled by only specific machines.

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## Appendix

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### Algorithm 1: Iterated Earliest Artificial Completion Time Heuristic (IEACT)

---

```

1  Let  $[r]_m$  denote the job processed in position  $r$  on machine  $m$  and let  $\mathcal{S}_m = ([1]_m, [2]_m, \dots, [l]_m)$ 
   be the job sequence on machine  $m$ , and  $\mathcal{T}_m$  the corresponding optimal tool loading on machine  $m$ ,  $m$ 
   = 1, 2, ..., M. Let  $\mathcal{AC}_j$  be the Artificial Completion time of job  $j$ ,  $j = 1, 2, \dots, J$ .
2  Initialize
3   $\mathcal{L} \leftarrow \{1, \dots, J\}$ ; // set of jobs to be scheduled //
4   $\mathcal{S}_m \leftarrow \emptyset, \forall m \in M$ ; // job sequence on machine  $m$  //
5   $\mathcal{T}_m \leftarrow \emptyset, \forall m \in M$ ; // optimal tool loading on machine  $m$  //
6   $f_m \leftarrow 0, \forall m \in M$ ; // artificial completion time of the last job on machine  $m$  //
7  while  $\mathcal{L} \neq \emptyset$  do
8  |    $m' \leftarrow \operatorname{argmin} \{f_m \mid \exists j \in \mathcal{L} : (|T_j| \leq C_m), m \in M\}$ ;
   |   // select the machine  $m'$  with the minimum completion time of the last job ( $f_{m'}$ ) and for which there exists at least
   |   one remaining job that can be processed on that machine without violating capacity restrictions //
9  |   if  $f_{m'} = 0$ 
10 | |    $j' \leftarrow \operatorname{argmin} \{p_{jm'} \mid j \in \mathcal{L} : (|T_j| \leq C_{m'})\}$ ;
   | |   // select the job ( $j'$ ) with the minimum processing time ( $p_{jm'}$ ) on the selected machine which requires less
   | |   tools than the capacity of that machine ( $C_{m'}$ ) //
11 | |    $f_{m'} \leftarrow p_{jm'}$ ;
   | |   // update the artificial completion time of the last job on machine  $m'$  //
12 | |   else
13 | | |   for each  $j \in \mathcal{L} : (|T_j| \leq C_{m'})$ 
14 | | | |    $\mathcal{AC}_j = p_{jm'} + \operatorname{sw}_{m'} \cdot |\{t \in T_j \mid t \notin T_{[t]_{m'}}\}|$ ;
   | | | |   // calculate the artificial completion time increase ( $\mathcal{AC}_j$ ) for each remaining job //
15 | | |   end for each
16 | | |    $j' \leftarrow \operatorname{argmin} \{\mathcal{AC}_j \mid j \in \mathcal{L} : (|T_j| \leq C_{m'})\}$ ;
   | | |   // select the job  $j'$  with the minimum earliest artificial completion time ( $\mathcal{AC}_j$ ) which requires less tools
   | | |   than the tool magazine capacity of the selected machine ( $C_{m'}$ ) //
17 | | |    $f_{m'} \leftarrow f_{m'} + \mathcal{AC}_{j'}$ ;
   | | |   // update the artificial completion time of the last job on machine  $m'$  //
18 | |   end if
19 |    $\mathcal{S}_{m'} \leftarrow \mathcal{S}_{m'}, \{j'\}$ ;
   |   // append the job  $j'$  to the job sequence  $\mathcal{S}_{m'}$  of machine  $m'$  //
20 |    $\mathcal{L} \leftarrow \mathcal{L} \setminus \{j'\}$ ; // remove  $j'$  from  $\mathcal{L}$  //
21 end while
22 for each  $m \in M$ 
23 |    $\mathcal{T}_m \leftarrow \text{KTNS}(\mathcal{S}_m)$ ;
   |   // apply the "Keep Tool Needed Soonest"-policy using the obtained sequence  $\mathcal{S}_m$  in order to optimize the tool
   |   loading on machine  $m$  //
24 end for each
25 return  $\mathcal{S}^0 = (\mathcal{S}_1, \mathcal{S}_2, \dots, \mathcal{S}_M)$ ;  $\mathcal{T}^0 = (\mathcal{T}_1, \mathcal{T}_2, \dots, \mathcal{T}_M)$ ;
   // return the job sequences  $\mathcal{S}^0$  and the corresponding optimal tool loadings  $\mathcal{T}^0$  //

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**Algorithm 2:** Iterated Greatest Intersection Heuristic (IGI)

---

```

1  Let  $[r]_m$  denote the job processed in position  $r$  on machine  $m$  and let  $\mathcal{S}_m = ([1]_m, [2]_m, \dots, [l]_m)$  be
   the job sequence on machine  $m$ , and  $\mathcal{J}_m$  the corresponding optimal tool loading on machine  $m$ ,  $m =$ 
    $1, 2, \dots, M$ .
2  Initialize
3   $\mathcal{L} \leftarrow \{1, \dots, J\}$ ; // set of jobs to be scheduled //
4   $\mathcal{S}_m \leftarrow \emptyset, \forall m \in M$ ; // job sequence on machine  $m$  //
5   $\mathcal{J}_m \leftarrow \emptyset, \forall m \in M$ ; // optimal tool loading on machine  $m$  //
6   $f_m \leftarrow 0, \forall m \in M$ ; // artificial completion time of the last job on machine  $m$  //
7  while  $\mathcal{L} \neq \emptyset$  do
8       $m' \leftarrow \operatorname{argmin} \{f_m \mid \exists j \in \mathcal{L} : (|T_j| \leq C_m), m \in M\}$ ;
      // select the machine  $m'$  with the minimum completion time of the last job ( $f_{m'}$ ) and for which there exists at
      // least one remaining job that can be processed on that machine without violating capacity restrictions //
9      if  $f_{m'} = 0$ 
10          $j' \leftarrow \operatorname{argmax} \{|T_j| \mid j \in \mathcal{L} : (|T_j| \leq C_{m'})\}$ ;
            // select the job ( $j'$ ) with the maximum number of required tools ( $|T_{j'}|$ ) on the selected machine, and
            // which requires less tools than the capacity of that machine ( $C_{m'}$ ) //
11          $f_{m'} \leftarrow p_{j'}$ ;
            // update the artificial completion time of the last job on machine  $m'$  //
12         else
13              $j' \leftarrow \operatorname{argmax} \{|T_j \cap T_{[l]_{m'}}| \mid j \in \mathcal{L} : (|T_j| \leq C_{m'})\}$ ;
                // select the job  $j'$  with the maximum number of tool intersections with the currently last job in the
                // sequence on machine  $m'$ , and which requires less tools than the tool magazine capacity of the selected
                // machine ( $C_{m'}$ ) //
14              $f_{m'} \leftarrow f_{m'} + p_{j'} + \operatorname{sw}_{m'} \cdot |\{t \in T_{j'} \mid t \notin T_{[l]_{m'}}\}|$ ;
                // update the artificial completion time of the last job on machine  $m'$  //
15         end if
16          $\mathcal{S}_{m'} \leftarrow \mathcal{S}_{m'}, \{j'\}$ ;
            // append the job  $j'$  to the job sequence  $\mathcal{S}_{m'}$  of machine  $m'$  //
17          $\mathcal{L} \leftarrow \mathcal{L} \setminus \{j'\}$ ; // remove  $j'$  from  $\mathcal{L}$  //
18     end while
19     for each  $m \in M$ 
20          $\mathcal{J}_m \leftarrow \text{KTNS}(\mathcal{S}_m)$ ;
            // apply the "Keep Tool Needed Soonest"-policy using the obtained sequence  $\mathcal{S}_m$  in order to optimize the tool
            // loading on machine  $m$  //
21     end for each
22     return  $\mathcal{S}^0 = (\mathcal{S}_1, \mathcal{S}_2, \dots, \mathcal{S}_M)$ ;  $\mathcal{J}^0 = (\mathcal{J}_1, \mathcal{J}_2, \dots, \mathcal{J}_M)$ ;
        // return the job sequences  $\mathcal{S}^0$  and the corresponding optimal tool loadings  $\mathcal{J}^0$  //

```

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**Algorithm 3:** Multi-Start-Random Heuristic (MSR)

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```

1  Let  $[r]_m$  denote the job processed in position  $r$  on machine  $m$  and let  $\mathcal{S}_m = ([1]_m, [2]_m, \dots, [l]_m)$ 
   be the job sequence on machine  $m$ , and  $\mathcal{T}_m$  the corresponding optimal tool loading on machine  $m$ ,  $m$ 
   = 1, 2, ..., M.
2  Initialize
3   $\mathcal{S}_m \leftarrow \emptyset, \forall m \in M$ ; // job sequence on machine  $m$  //
4   $\mathcal{T}_m \leftarrow \emptyset, \forall m \in M$ ; // optimal tool loading on machine  $m$  //
5  I; // iteration limit //
6  for  $i = 1, 2, \dots, I$  do
7  |    $\mathcal{S}_{rand} \leftarrow \text{random.permutation}\{1, \dots, J\}$ ;
   |   // generate a random job permutation, i.e. a "giant-sequence" //
8  |    $m' \leftarrow 1$ ; // selected machine //
9  |    $r' \leftarrow 1$ ; // job  $[r']$  in position  $r'$  in  $\mathcal{S}_{rand}$  //
10 |   while  $r' \leq J$  do
11 |   |   if  $|T_{[r']}| \leq C_{m'}$ 
12 |   |   |    $\mathcal{S}_{m'} \leftarrow \mathcal{S}_{m'}, \mathcal{S}_{rand}[r']$ ;
   |   |   |   // append the job in position  $r'$  in  $\mathcal{S}_{rand}$  to the job sequence  $\mathcal{S}_{m'}$  of machine  $m'$  //
13 |   |   |    $m' \leftarrow m' + 1$ ; // select next machine //
14 |   |   |   if  $m' > M$ 
15 |   |   |   |    $m' \leftarrow 1$ ; // if there is no next machine, restart with machine 1 //
16 |   |   |   end if
17 |   |   else
18 |   |   |    $m' \leftarrow \text{random.machine}\{m \in M \mid (|T_{[r']}| \leq C_m)\}$ ;
   |   |   |   // randomly chose a machine with sufficient tool magazine capacity //
19 |   |   |    $\mathcal{S}_{m'} \leftarrow \{\mathcal{S}_{m'}, \mathcal{S}_{rand}[r']\}$ ;
   |   |   |   // append the job in position  $r'$  in  $\mathcal{S}_{rand}$  to the job sequence  $\mathcal{S}_{m'}$  of machine  $m'$  //
20 |   |   end if
21 |   |    $r' \leftarrow r' + 1$ ; // select the next job //
22 |   end while
23 end for
24 for each  $m \in M$ 
25 |    $\mathcal{T}_m \leftarrow \text{KTNS}(\mathcal{S}_m)$ ;
   |   // apply the "Keep Tool Needed Soonest"-policy using the obtained sequence  $\mathcal{S}_m$  in order to optimize the tool
   |   loading on machine  $m$  //
26 end for each
27 return  $\mathcal{S}^0 = (\mathcal{S}_1, \mathcal{S}_2, \dots, \mathcal{S}_M)$ ;  $\mathcal{T}^0 = (\mathcal{T}_1, \mathcal{T}_2, \dots, \mathcal{T}_M)$ ;
   // return the job sequences  $\mathcal{S}^0$  and the corresponding optimal tool loadings  $\mathcal{T}^0$  //

```

---

---

**Algorithm 4:** General Iterated Local Search Scheme

---

```

1  Let  $S_0$  be an initial solution obtained by a construction heuristic;
2   $S^* \leftarrow \text{LocalSearch}(S_0)$ ;
3  while termination criterion not satisfied do
4       $S' \leftarrow \text{Perturbation}(S^*, \text{search history})$ ;
5       $S^{*'} \leftarrow \text{LocalSearch}(S')$ ;
6       $S^* \leftarrow \text{AcceptanceCriterion}(S^*, S^{*'}, \text{search memory})$ ;
7  end while
8  return  $S^*$ ;

```

---

**Algorithm 5:** Local Search (LS)

---

```

1  Let  $[r]_m$  denote the job processed in position  $r$  on machine  $m$  and let  $\mathcal{S}_m = ([1]_m, [2]_m, \dots, [l]_m)$  be the job sequence on machine  $m$ , and  $\mathcal{T}_m$  the corresponding optimal tool loading on machine  $m$ ,  $m = 1, 2, \dots, M$ . Let  $\mathcal{S}^0 = (\mathcal{S}^0_1, \mathcal{S}^0_2, \dots, \mathcal{S}^0_M)$  and  $\mathcal{T}^0 = (\mathcal{T}^0_1, \mathcal{T}^0_2, \dots, \mathcal{T}^0_M)$  be the initial solution and the corresponding optimal tool loading obtained by a construction heuristic. Let  $\mathcal{S}^{best}$  denote the best known sequence and  $F(\mathcal{S}^{best})$  its objective value.
2  Initialize
3   $\mathcal{S}^{best} \leftarrow \mathcal{S}^0$ 
4   $\mathcal{T}^{best} \leftarrow \mathcal{T}^0$ 
5  for  $m = 1, 2, \dots, M$  do
6      improved  $\leftarrow$  TRUE ;
7      while improved = TRUE do
8          improved  $\leftarrow$  FALSE ;
9           $\mathcal{S}' \leftarrow \mathcal{S}^0$ 
10         for  $r_1 = 1, 2, \dots, l-1$ 
11             for  $r_2 = r_1 + 1, \dots, l$ 
12                  $\mathcal{S}'_m [[r_1]_m] \leftarrow \mathcal{S}^0_m [[r_2]_m]$ ;
13                  $\mathcal{S}'_m [[r_2]_m] \leftarrow \mathcal{S}^0_m [[r_1]_m]$ ;
14                  $\mathcal{T}' \leftarrow \text{KTNS}(\mathcal{S}')$ ;
15                 // apply the "Keep Tool Needed Soonest"-policy using the obtained sequence  $\mathcal{S}'$  in order to
16                 // optimize the tool loading on machine  $m$  //
17                 if  $F(\mathcal{S}') < F(\mathcal{S}^{best})$ 
18                      $\mathcal{S}^{best} \leftarrow \mathcal{S}'$ ; // update best known sequence //
19                      $\mathcal{T}^{best} \leftarrow \mathcal{T}'$ ; // update the optimal tool loading for the best known sequence //
20                      $\mathcal{S}^0 \leftarrow \mathcal{S}^{best}$ ; // the best known sequence replaces the current sequence //
21                     improved  $\leftarrow$  TRUE ;
22                     go to line 7; // restart the swapping on the current machine //
23                 else
24                      $\mathcal{S}' \leftarrow \mathcal{S}^0$ ; // maintain the old current solution //
25                 end if
26             end for
27         end for
28     end while
29 end for
30 return  $\mathcal{S}^{best}, \mathcal{T}^{best}$ ;

```

---

**Algorithm 6:** Time-based Perturbation (P.1a)

```

1  Let  $[r]_m$  denote the job processed in position  $r$  on machine  $m$  and let  $\mathcal{S}_m = ([1]_m, [2]_m, \dots, [l]_m)$  be
   the job sequence on machine  $m$ , and  $\mathcal{J}_m$  the corresponding optimal tool loading on machine  $m$ ,  $m = 1, 2, \dots, M$ . Let  $\mathcal{S}^0 = (\mathcal{S}^0_1, \mathcal{S}^0_2, \dots, \mathcal{S}^0_M)$  and  $\mathcal{J}^0 = (\mathcal{J}^0_1, \mathcal{J}^0_2, \dots, \mathcal{J}^0_M)$  be the initial solution and the
   corresponding optimal tool loading obtained by the Local Search. Let  $\mathcal{S}^{best}$  denote the best known
   sequence and  $F(\mathcal{S}^{best})$  its objective value. Let  $ts_{[r]_m}$  denote the number of tool switches required
   immediately before processing the job in the  $r^{\text{th}}$  position on machine  $m$ . Let  $\mathcal{C}_{j_1[r]_{m_2}}$  be the relocation
   cost when job  $j_1$  is relocated to position  $r$  on machine  $m_2$ .

2  Initialize
3   $\mathcal{S}^{best} \leftarrow \mathcal{S}^0$  ;
4   $\mathcal{J}^{best} \leftarrow \mathcal{J}^0$  ;
5  while termination criterion not reached do
6  |    $\mathcal{S}' \leftarrow \mathcal{S}^0$  ;
7  |    $m_1 \leftarrow \operatorname{argmax} \{f_m \mid m \in M \wedge (\exists j \in \mathcal{S}'_m : (|T_j| \leq C_{m_2}), m_2 \in M, m_2 \neq m)\}$  ;
   |   // select the machine  $m_1$  with the highest completion time of the last job ( $f_{m_1}$ ), and for which there exists at least
   |   one job that can be processed on another machine  $m_2$  without violating capacity restrictions //
8  |    $j_1 \leftarrow \operatorname{argmax} \{p_{[q]_{m_1}} + sw_{m_1} \cdot ts_{[q]_{m_1}} \mid q = \{1, \dots, |\mathcal{S}'_{m_1}|\} \wedge (|T_{[q]_{m_1}}| \leq C_{m_2}), m_2 \in M, m_2 \neq m_1)\}$  ;
   |   // select the job in position  $q^*$  on machine  $m_1$  with the highest processing time plus setup time, and which can be
   |   relocated to another machine  $m_2$  without violating capacity restrictions //
10 |   for  $m \in M \mid \{m \neq m_1 \wedge (|T_{j_1}| \leq C_m)\}$ 
11 |   |   for  $r = (1, \dots, |\mathcal{S}'_m| + 1)$ 
12 |   |   |   if  $r = 1$  // assigned to the first position //
13 |   |   |   |    $\mathcal{C}_{j_1, [r]_m} = p_{j_1} + sw_m \cdot |\{t \in T_{[r]_m} : t \notin T_{j_1}\}|$  ;
14 |   |   |   |   else if  $r = (|\mathcal{S}'_m| + 1)$  // assigned to the last position //
15 |   |   |   |    $\mathcal{C}_{j_1, [r]_m} = p_{j_1} + sw_m \cdot |\{t \in T_{j_1} : t \notin T_{[r-1]_m}\}|$  ;
16 |   |   |   |   else // assigned to any other position //
17 |   |   |   |    $\mathcal{C}_{j_1, [r]_m} = p_{j_1} + sw_m \cdot |\{t \in T_{[r]_m} : t \notin T_{j_1}\}| + sw_m \cdot |\{t \in T_{j_1} : t \notin T_{[r-1]_m}\}|$  ;
18 |   |   |   |   end if
19 |   |   |   end for
20 |   |   end for
21 |    $(r^*, m_2) \leftarrow \operatorname{argmin} \{\mathcal{C}_{j_1, [r]_m} \mid m \in M : \{m \neq m_1 \wedge (|T_{j_1}| \leq C_m)\} \wedge r = (1, \dots, |\mathcal{S}'_m| + 1)\}$  ;
22 |    $\mathcal{S}'_{m_1} \leftarrow \mathcal{S}'_{m_1} \setminus \{j_1\}$  ; // update sequence on machine  $m_1$  //
23 |    $\mathcal{S}'_{m_2} \leftarrow \text{job.insert}(j_1, [r^*]_{m_2}, \mathcal{S}'_{m_2})$  ; // insert job  $j_1$  in position  $r^*$  on machine  $m_2$  //
24 |    $\mathcal{J}'_{m_1} \leftarrow \text{KTNS}(\mathcal{S}'_{m_1})$  ;  $\mathcal{J}'_{m_2} \leftarrow \text{KTNS}(\mathcal{S}'_{m_2})$  ;
   |   // apply the "Keep Tool Needed Soonest"-policy to optimize the tool loadings on the machines  $m_1$  and  $m_2$  //
25 |   if  $F(\mathcal{S}') < F(\mathcal{S}^{best})$ 
26 |   |    $\mathcal{S}^{best} \leftarrow \mathcal{S}'$  ; // update best known sequence //
27 |   |    $\mathcal{J}^{best} \leftarrow \mathcal{J}'$  ; // update the optimal tool loading for the best known sequence //
28 |   end if
29 |    $(\mathcal{S}^{*'}, \mathcal{J}^{*'}) \leftarrow \text{Local.Search}(\mathcal{S}', \mathcal{S}'_{m_1}, \mathcal{S}'_{m_2})$ 
   |   // apply the local search to the machines  $m_1$  and  $m_2$  of the perturbed solution //
30 |    $\mathcal{S}^0 \leftarrow \mathcal{S}^{*'}$  // best solution from local search becomes new current solution //
31 end while
32 return  $\mathcal{S}^{best}$  ;  $\mathcal{J}^{best}$  ;

```

**Algorithm 7:** Tool-Switch-based Perturbation (P.1b)

```

1  Let  $[r]_m$  denote the job processed in position  $r$  on machine  $m$  and let  $\mathcal{S}_m = ([1]_m, [2]_m, \dots, [l]_m)$  be
   the job sequence on machine  $m$ , and  $\mathcal{J}_m$  the corresponding optimal tool loading on machine  $m$ ,  $m = 1, 2, \dots, M$ . Let  $\mathcal{S}^0 = (\mathcal{S}^0_1, \mathcal{S}^0_2, \dots, \mathcal{S}^0_M)$  and  $\mathcal{J}^0 = (\mathcal{J}^0_1, \mathcal{J}^0_2, \dots, \mathcal{J}^0_M)$  be the initial solution and the
   corresponding optimal tool loading obtained by the Local Search. Let  $\mathcal{S}^{best}$  denote the best known
   sequence and  $F(\mathcal{S}^{best})$  its objective value. Let  $TS_m$  denote the total number of tool switches on machine
    $m$  and  $ts_{[r]_m}$  the number of tool switches required immediately before processing job in the  $r$ -th
   position on machine  $m$ . Let  $\mathcal{C}_{j_1[r]_m_2}$  be the relocation cost when job  $j_1$  is relocated to position  $r$  on machine  $m_2$ .

2  Initialize
3   $\mathcal{S}^{best} \leftarrow \mathcal{S}^0$  ;
4   $\mathcal{J}^{best} \leftarrow \mathcal{J}^0$  ;
5  while termination criterion not reached do
6  |    $\mathcal{S}' \leftarrow \mathcal{S}^0$  ;
7  |    $m_1 \leftarrow \operatorname{argmax} \{ TS_m \mid m \in M \wedge (\exists j \in \mathcal{S}'_m : (|T_j| \leq C_{m_2}), m_2 \in M, m_2 \neq m) \}$  ;
   |   // select the machine  $m_1$  with the highest number of tool switches ( $TS_{m_1}$ ), and for which there exists at least one
   |   // job that can be processed on another machine  $m_2$  without violating capacity restrictions //
8  |    $j_1 \leftarrow \operatorname{argmax} \{ ts_{[q]_{m_1}} \mid q = \{1, \dots, k\} \wedge (|T_{[q]_{m_1}}| \leq C_{m_2}), m_2 \in M, m_2 \neq m_1 \}$  ;
   |   // select the job in position  $q^*$  on machine  $m_1$  with the largest number of tool switches, and which can be relocated
   |   // to another machine  $m_2$  without violating capacity restrictions //
10 |   for  $m \in M \mid \{m \neq m_1 \wedge (|T_{j_1}| \leq C_m)\}$ 
11 |   |   for  $r = (1, \dots, |\mathcal{S}'_m| + 1)$ 
12 |   |   |   if  $r = 1$  // assigned to the first position //
13 |   |   |   |    $\mathcal{C}_{j_1, [r]_m} = |\{t \in T_{[r]_m} : t \notin T_{j_1}\}|$  ;
14 |   |   |   |   else if  $r = (|\mathcal{S}'_m| + 1)$  // assigned to the last position //
15 |   |   |   |   |    $\mathcal{C}_{j_1, [r]_m} = |\{t \in T_{j_1} : t \notin T_{[r-1]_m}\}|$  ;
16 |   |   |   |   else // assigned to any other position //
17 |   |   |   |   |    $\mathcal{C}_{j_1, [r]_m} = |\{t \in T_{[r]_m} : t \notin T_{j_1}\}| + |\{t \in T_{j_1} : t \notin T_{[r-1]_m}\}|$  ;
18 |   |   |   |   end if
19 |   |   |   end for
20 |   |   end for
21 |   |    $(r^*, m_2) \leftarrow \operatorname{argmin} \{ \mathcal{C}_{j_1, [r]_m} \mid m \in M : \{m \neq m_1 \wedge (|T_{j_1}| \leq C_m)\} \wedge r = (1, \dots, |\mathcal{S}'_m| + 1) \}$  ;
22 |   |    $\mathcal{S}'_{m_1} \leftarrow \mathcal{S}'_{m_1} \setminus \{j_1\}$  ; // update sequence on machine  $m_1$  //
23 |   |    $\mathcal{S}'_{m_2} \leftarrow \text{job.insert}(j_1, [r^*]_{m_2}, \mathcal{S}'_{m_2})$  ; // insert job  $j_1$  in position  $r^*$  on machine  $m_2$  //
24 |   |    $\mathcal{J}'_{m_1} \leftarrow \text{KTNS}(\mathcal{S}'_{m_1})$  ;  $\mathcal{J}'_{m_2} \leftarrow \text{KTNS}(\mathcal{S}'_{m_2})$  ;
   |   // apply the "Keep Tool Needed Soonest"-policy to optimize the tool loadings on the machines  $m_1$  and  $m_2$  //
25 |   |   if  $F(\mathcal{S}') < F(\mathcal{S}^{best})$ 
26 |   |   |    $\mathcal{S}^{best} \leftarrow \mathcal{S}'$  ; // update best known sequence //
27 |   |   |    $\mathcal{J}^{best} \leftarrow \mathcal{J}'$  ; // update the optimal tool loading for the best known sequence //
28 |   |   end if
29 |   |    $(\mathcal{S}^{*'}, \mathcal{J}^{*'}) \leftarrow \text{Local.Search}(\mathcal{S}', \mathcal{S}'_{m_1}, \mathcal{S}'_{m_2})$ 
   |   // apply the local search to the machines  $m_1$  and  $m_2$  of the perturbed solution //
30 |   |    $\mathcal{S}^0 \leftarrow \mathcal{S}^{*'}$  // best solution from local search becomes new current solution //
31 |   end while
32 return  $\mathcal{S}^{best}$  ;  $\mathcal{J}^{best}$  ;

```

# Appendix A: Results of Study 2

The following tables contain the results of study 2 (Section III) for the 180 problem instances. The following identifiers are used due to space restrictions (Table A.1). Table A.2 provides the objective values and computation times of the mathematical models. Table A.3 provides the objective values and computation times of the heuristics. Table A.4 to Table A.7 provide the results of the statistical evaluation.

**Table A.1. Column identifiers of Appendix A.**

<b>M</b>	number of machines		<b>tib</b>	time-index-based model
<b>J</b>	number of jobs		<b>tft</b>	total flowtime
<b>T</b>	number of tools		<b>fmax</b>	makespan
<b>D (s/d)</b>	density (sparse/dense)		<b>time(s)</b>	computation time (seconds)
<b>V</b>	instance number per problem type		<b>IEACT</b>	iterated-earliest-artificial-completion-time-heuristic
<b>prb</b>	precedence-based model		<b>ILS</b>	iterated-local-search heuristic
<b>pob</b>	position-based model		<b>NA</b>	not available

**Table A.2. Overall results of the mathematical models for each problem instance.**

M	J	T	D	V	prb tft	prb tft time(s)	prb fmax	prb fmax time(s)	pob tft	pob tft time(s)	pob fmax	pob fmax time(s)	tib tft	tib tft time(s)	tib fmax	tib fmax time(s)
2	5	10	s	1	32	0	12	0	32	0	12	0	32	22	12	0
2	5	10	s	2	44	0	17	0	44	0	17	0	44	166	17	35
2	5	10	s	3	36	0	16	0	36	0	16	0	36	84	16	82
2	5	10	s	4	39	0	14	0	39	0	14	0	39	21	14	4
2	5	10	s	5	36	0	13	0	36	0	13	0	36	9	13	1
2	5	10	s	6	22	0	8	0	22	0	8	0	22	13	8	0
2	5	10	s	7	41	0	14	0	41	0	14	0	41	4	14	1
2	5	10	s	8	45	0	17	0	45	0	17	0	45	39	17	16
2	5	10	s	9	19	0	7	0	19	0	7	0	19	3	7	0
2	5	10	s	10	30	0	12	0	30	0	12	0	30	1	12	1
2	5	10	d	1	49	0	22	0	49	0	22	0	59	72	22	34
2	5	10	d	2	65	0	28	0	65	0	28	0	65	238	28	48
2	5	10	d	3	38	0	15	0	38	0	15	0	38	1143	15	32
2	5	10	d	4	82	0	36	0	82	0	36	0	82	372	36	186
2	5	10	d	5	36	0	20	0	36	0	20	0	36	1016	20	728
2	5	10	d	6	58	0	24	0	58	0	24	0	139	1800	24	360
2	5	10	d	7	32	0	17	0	32	0	17	0	32	44	17	85
2	5	10	d	8	63	0	25	0	63	0	25	0	63	340	25	104
2	5	10	d	9	36	0	13	0	36	0	13	0	36	1497	13	9
2	5	10	d	10	58	0	28	0	58	0	28	0	58	84	28	132
2	5	15	s	1	32	0	12	0	32	0	12	0	32	540	12	16
2	5	15	s	2	28	0	12	0	28	0	12	0	28	133	12	24
2	5	15	s	3	28	0	12	0	28	0	12	0	28	13	12	2
2	5	15	s	4	29	0	13	0	29	0	13	0	29	5	13	2
2	5	15	s	5	28	0	11	0	28	0	11	0	28	33	11	2
2	5	15	s	6	33	0	15	0	33	0	15	0	33	396	15	127
2	5	15	s	7	35	0	14	0	35	0	14	0	35	184	14	7
2	5	15	s	8	39	0	15	0	39	0	15	0	39	626	15	68
2	5	15	s	9	37	0	12	0	37	0	12	0	37	138	12	11
2	5	15	s	10	28	0	11	0	28	0	11	0	28	73	11	1

Table A.2. (Continued)

M	J	T	D	V	prb tft	prb tft time(s)	prb fmax	prb fmax time(s)	pob tft	pob tft time(s)	pob fmax	pob fmax time(s)	tib tft	tib tft time(s)	tib fmax	tib fmax time(s)
2	5	15	d	1	47	0	19	0	47	0	19	0	NA	1800	19	582
2	5	15	d	2	68	0	26	0	68	0	26	0	NA	1800	NA	1800
2	5	15	d	3	59	0	26	0	59	0	26	0	NA	1800	NA	1800
2	5	15	d	4	56	0	25	0	56	0	25	0	NA	1800	NA	1800
2	5	15	d	5	37	0	14	0	37	0	14	0	37	1094	14	52
2	5	15	d	6	36	0	16	0	36	0	16	0	36	1227	16	689
2	5	15	d	7	55	0	22	0	55	0	22	0	74	1800	NA	1800
2	5	15	d	8	47	0	21	0	47	0	21	0	NA	1800	21	1800
2	5	15	d	9	47	0	20	0	47	0	20	0	48	1800	NA	1800
2	5	15	d	10	52	0	22	0	52	0	22	0	NA	1800	NA	1800
2	10	10	s	1	111	727	25	611	111	365	25	269	NA	1800	NA	1800
2	10	10	s	2	113	729	27	1800	113	339	27	252	NA	1800	NA	1800
2	10	10	s	3	77	97	21	289	77	178	21	210	NA	1800	21	1800
2	10	10	s	4	67	204	15	81	67	184	15	73	NA	1800	15	1800
2	10	10	s	5	129	1634	29	685	129	512	29	238	NA	1800	NA	1800
2	10	10	s	6	106	641	25	643	106	341	25	312	NA	1800	NA	1800
2	10	10	s	7	101	514	24	471	101	385	24	300	NA	1800	NA	1800
2	10	10	s	8	91	441	21	482	91	330	21	184	NA	1800	NA	1800
2	10	10	s	9	106	629	26	503	106	403	26	254	NA	1800	NA	1800
2	10	10	s	10	91	132	21	116	91	175	21	104	NA	1800	21	69
2	10	10	d	1	244	949	55	189	244	395	55	135	NA	1800	NA	1800
2	10	10	d	2	275	1149	62	263	275	213	62	84	NA	1800	NA	1800
2	10	10	d	3	236	777	58	326	236	250	58	86	NA	1800	NA	1800
2	10	10	d	4	222	1371	45	180	222	320	45	60	NA	1800	NA	1800
2	10	10	d	5	167	502	46	596	167	228	46	187	NA	1800	NA	1800
2	10	10	d	6	229	620	49	82	229	224	49	35	NA	1800	NA	1800
2	10	10	d	7	227	542	47	89	227	259	47	38	NA	1800	NA	1800
2	10	10	d	8	238	528	59	174	238	447	59	72	NA	1800	NA	1800
2	10	10	d	9	192	754	38	215	189	155	38	17	NA	1800	NA	1800
2	10	10	d	10	159	524	31	1015	159	493	33	26	NA	1800	NA	1800
2	10	15	s	1	109	1800	30	1800	109	746	30	1350	NA	1800	NA	1800
2	10	15	s	2	148	1800	35	1800	148	855	35	1205	NA	1800	NA	1800
2	10	15	s	3	136	1800	33	1800	136	803	33	907	NA	1800	NA	1800
2	10	15	s	4	122	1800	29	1800	122	891	29	810	NA	1800	NA	1800
2	10	15	s	5	124	1800	32	1800	124	722	32	1208	NA	1800	NA	1800
2	10	15	s	6	172	1800	40	1800	172	663	40	914	NA	1800	NA	1800
2	10	15	s	7	107	1800	28	1800	107	882	28	1800	NA	1800	NA	1800
2	10	15	s	8	143	1800	36	1800	143	1039	36	1215	NA	1800	NA	1800
2	10	15	s	9	138	1800	33	1800	138	911	33	583	NA	1800	NA	1800
2	10	15	s	10	130	1800	34	1800	130	663	34	1800	NA	1800	NA	1800
2	10	15	d	1	278	971	65	570	278	129	65	25	NA	1800	NA	1800
2	10	15	d	2	292	1253	66	416	292	269	66	45	NA	1800	NA	1800
2	10	15	d	3	189	1800	45	740	189	154	45	75	NA	1800	NA	1800
2	10	15	d	4	288	1800	59	224	288	345	59	38	NA	1800	NA	1800
2	10	15	d	5	329	1800	82	517	329	928	82	183	NA	1800	NA	1800
2	10	15	d	6	217	1800	49	165	217	505	49	89	NA	1800	NA	1800
2	10	15	d	7	234	1800	50	931	234	523	50	107	NA	1800	NA	1800
2	10	15	d	8	335	1800	76	943	335	152	76	169	NA	1800	NA	1800
2	10	15	d	9	315	1800	73	1005	315	366	73	222	NA	1800	NA	1800
2	10	15	d	10	353	1800	85	724	353	193	85	108	NA	1800	NA	1800

Table A.2. (Continued)

M	J	T	D	V	prb tft	prb tft time(s)	prb fmax	prb fmax time(s)	pob tft	pob tft time(s)	pob fmax	pob fmax time(s)	tib tft	tib tft time(s)	tib fmax	tib fmax time(s)
2	15	15	s	1	306	1800	51	1800	301	1800	49	1800	NA	1800	NA	1800
2	15	15	s	2	227	1800	38	1800	228	1800	38	1800	NA	1800	NA	1800
2	15	15	s	3	276	1800	47	1800	271	1800	45	1800	NA	1800	NA	1800
2	15	15	s	4	254	1800	46	1800	256	1800	46	1800	NA	1800	NA	1800
2	15	15	s	5	258	1800	47	1800	254	1800	46	1800	NA	1800	NA	1800
2	15	15	s	6	275	1800	46	1800	275	1800	46	1800	NA	1800	NA	1800
2	15	15	s	7	272	1800	45	1800	277	1800	45	1800	NA	1800	NA	1800
2	15	15	s	8	341	1800	54	1800	343	1800	54	1800	NA	1800	NA	1800
2	15	15	s	9	250	1800	41	1800	244	1800	41	1800	NA	1800	NA	1800
2	15	15	s	10	303	1800	51	1800	299	1800	50	1800	NA	1800	NA	1800
2	15	15	d	1	471	1800	71	1800	417	1800	64	1800	NA	1800	NA	1800
2	15	15	d	2	435	1800	65	1800	417	1800	64	1800	NA	1800	NA	1800
2	15	15	d	3	361	1800	61	1800	359	1800	62	1800	NA	1800	NA	1800
2	15	15	d	4	419	1800	61	1800	416	1800	66	1800	NA	1800	NA	1800
2	15	15	d	5	476	1800	68	1800	457	1800	70	1800	NA	1800	NA	1800
2	15	15	d	6	528	1800	72	1800	490	1800	75	1800	NA	1800	NA	1800
2	15	15	d	7	498	1800	72	1800	499	1800	76	1800	NA	1800	NA	1800
2	15	15	d	8	441	1800	66	1800	422	1800	71	1800	NA	1800	NA	1800
2	15	15	d	9	419	1800	60	1800	412	1800	64	1800	NA	1800	NA	1800
2	15	15	d	10	417	1800	61	1800	404	1800	62	1800	NA	1800	NA	1800
3	15	15	s	1	130	1800	22	1800	128	1800	22	1800	NA	1800	NA	1800
3	15	15	s	2	119	1800	20	1800	125	1800	20	1800	NA	1800	NA	1800
3	15	15	s	3	165	1800	28	1800	161	1800	26	1800	NA	1800	NA	1800
3	15	15	s	4	130	1800	25	1800	130	1800	25	1800	NA	1800	NA	1800
3	15	15	s	5	153	1800	27	1800	130	1800	26	1800	NA	1800	NA	1800
3	15	15	s	6	129	1800	26	1800	129	1800	25	1800	NA	1800	NA	1800
3	15	15	s	7	176	1800	30	1800	176	1800	30	1800	NA	1800	NA	1800
3	15	15	s	8	150	1800	28	1800	150	1800	27	1800	NA	1800	NA	1800
3	15	15	s	9	180	1800	29	1800	169	1800	27	1800	NA	1800	NA	1800
3	15	15	s	10	147	1800	24	1800	147	1800	24	1800	NA	1800	NA	1800
3	15	15	d	1	325	1800	52	1800	325	1800	52	1800	NA	1800	NA	1800
3	15	15	d	2	340	1800	59	1800	359	1800	59	1800	NA	1800	NA	1800
3	15	15	d	3	361	1800	57	1800	380	1800	55	1800	NA	1800	NA	1800
3	15	15	d	4	352	1800	55	1800	335	1800	51	1800	NA	1800	NA	1800
3	15	15	d	5	314	1800	50	1800	338	1800	50	1800	NA	1800	NA	1800
3	15	15	d	6	359	1800	50	1800	315	1800	53	1800	NA	1800	NA	1800
3	15	15	d	7	393	1800	59	1800	402	1800	61	1800	NA	1800	NA	1800
3	15	15	d	8	294	1800	46	1800	294	1800	47	1800	NA	1800	NA	1800
3	15	15	d	9	296	1800	45	1800	300	1800	45	1800	NA	1800	NA	1800
3	15	15	d	10	342	1800	47	1800	336	1800	47	1800	NA	1800	NA	1800
3	25	15	s	1	453	1800	44	1800	423	1800	45	1800	NA	1800	NA	1800
3	25	15	s	2	396	1800	47	1800	429	1800	42	1800	NA	1800	NA	1800
3	25	15	s	3	468	1800	49	1800	479	1800	51	1800	NA	1800	NA	1800
3	25	15	s	4	349	1800	48	1800	391	1800	42	1800	NA	1800	NA	1800
3	25	15	s	5	427	1800	50	1800	471	1800	48	1800	NA	1800	NA	1800
3	25	15	s	6	505	1800	58	1800	497	1800	50	1800	NA	1800	NA	1800
3	25	15	s	7	343	1800	49	1800	322	1800	34	1800	NA	1800	NA	1800
3	25	15	s	8	425	1800	48	1800	418	1800	48	1800	NA	1800	NA	1800
3	25	15	s	9	475	1800	47	1800	469	1800	48	1800	NA	1800	NA	1800
3	25	15	s	10	523	1800	57	1800	576	1800	52	1800	NA	1800	NA	1800



Table A.2. (Continued)

M	J	T	D	V	prb tft	prb tft time(s)	prb fmax	prb fmax time(s)	pob tft	pob tft time(s)	pob fmax	pob fmax time(s)	tib tft	tib tft time(s)	tib fmax	tib fmax time(s)
3	25	15	d	1	655	1800	67	1800	640	1800	75	1800	NA	1800	NA	1800
3	25	15	d	2	816	1800	73	1800	872	1800	82	1800	NA	1800	NA	1800
3	25	15	d	3	866	1800	83	1800	928	1800	88	1800	NA	1800	NA	1800
3	25	15	d	4	746	1800	69	1800	757	1800	68	1800	NA	1800	NA	1800
3	25	15	d	5	692	1800	71	1800	784	1800	71	1800	NA	1800	NA	1800
3	25	15	d	6	765	1800	74	1800	720	1800	75	1800	NA	1800	NA	1800
3	25	15	d	7	846	1800	69	1800	926	1800	73	1800	NA	1800	NA	1800
3	25	15	d	8	825	1800	81	1800	890	1800	88	1800	NA	1800	NA	1800
3	25	15	d	9	707	1800	67	1800	753	1800	70	1800	NA	1800	NA	1800
3	25	15	d	10	768	1800	81	1800	797	1800	76	1800	NA	1800	NA	1800
4	25	15	s	1	389	1800	53	1800	420	1800	37	1800	NA	1800	NA	1800
4	25	15	s	2	368	1800	35	1800	351	1800	39	1800	NA	1800	NA	1800
4	25	15	s	3	380	1800	43	1800	404	1800	34	1800	NA	1800	NA	1800
4	25	15	s	4	345	1800	46	1800	367	1800	32	1800	NA	1800	NA	1800
4	25	15	s	5	336	1800	44	1800	390	1800	35	1800	NA	1800	NA	1800
4	25	15	s	6	314	1800	43	1800	299	1800	32	1800	NA	1800	NA	1800
4	25	15	s	7	318	1800	37	1800	337	1800	31	1800	NA	1800	NA	1800
4	25	15	s	8	349	1800	39	1800	416	1800	37	1800	NA	1800	NA	1800
4	25	15	s	9	321	1800	38	1800	329	1800	39	1800	NA	1800	NA	1800
4	25	15	s	10	434	1800	42	1800	403	1800	38	1800	NA	1800	NA	1800
4	25	15	d	1	608	1800	59	1800	545	1800	63	1800	NA	1800	NA	1800
4	25	15	d	2	620	1800	59	1800	625	1800	62	1800	NA	1800	NA	1800
4	25	15	d	3	564	1800	51	1800	626	1800	51	1800	NA	1800	NA	1800
4	25	15	d	4	555	1800	61	1800	568	1800	62	1800	NA	1800	NA	1800
4	25	15	d	5	569	1800	48	1800	579	1800	61	1800	NA	1800	NA	1800
4	25	15	d	6	690	1800	72	1800	721	1800	84	1800	NA	1800	NA	1800
4	25	15	d	7	510	1800	56	1800	641	1800	55	1800	NA	1800	NA	1800
4	25	15	d	8	650	1800	53	1800	597	1800	65	1800	NA	1800	NA	1800
4	25	15	d	9	534	1800	56	1800	506	1800	60	1800	NA	1800	NA	1800
4	25	15	d	10	643	1800	63	1800	713	1800	111	1800	NA	1800	NA	1800
4	25	20	s	1	364	1800	40	1800	355	1800	43	1800	NA	1800	NA	1800
4	25	20	s	2	415	1800	49	1800	423	1800	39	1800	NA	1800	NA	1800
4	25	20	s	3	385	1800	45	1800	377	1800	40	1800	NA	1800	NA	1800
4	25	20	s	4	388	1800	45	1800	428	1800	37	1800	NA	1800	NA	1800
4	25	20	s	5	337	1800	42	1800	342	1800	35	1800	NA	1800	NA	1800
4	25	20	s	6	360	1800	37	1800	342	1800	34	1800	NA	1800	NA	1800
4	25	20	s	7	434	1800	30	1800	358	1800	32	1800	NA	1800	NA	1800
4	25	20	s	8	440	1800	44	1800	408	1800	42	1800	NA	1800	NA	1800
4	25	20	s	9	418	1800	42	1800	390	1800	39	1800	NA	1800	NA	1800
4	25	20	s	10	398	1800	52	1800	384	1800	35	1800	NA	1800	NA	1800
4	25	20	d	1	813	1800	61	1800	773	1800	67	1800	NA	1800	NA	1800
4	25	20	d	2	961	1800	69	1800	906	1800	81	1800	NA	1800	NA	1800
4	25	20	d	3	966	1800	78	1800	736	1800	90	1800	NA	1800	NA	1800
4	25	20	d	4	1077	1800	79	1800	837	1800	69	1800	NA	1800	NA	1800
4	25	20	d	5	1071	1800	74	1800	843	1800	93	1800	NA	1800	NA	1800
4	25	20	d	6	928	1800	74	1800	858	1800	93	1800	NA	1800	NA	1800
4	25	20	d	7	819	1800	71	1800	753	1800	88	1800	NA	1800	NA	1800
4	25	20	d	8	741	1800	84	1800	760	1800	85	1800	NA	1800	NA	1800
4	25	20	d	9	946	1800	76	1800	855	1800	100	1800	NA	1800	NA	1800
4	25	20	d	10	996	1800	67	1800	748	1800	79	1800	NA	1800	NA	1800

Table A.3. Overall results of the heuristics for each problem instance.

M	J	T	D	V	IEACT tft	IEACT fmax	IEACT time(s)	ILS tft	ILS tft time(s)	ILS fmax	ILS fmax time(s)
2	5	10	s	1	36	15	0.01	32	11.55	12	11.43
2	5	10	s	2	44	18	0.02	44	11.65	18	11.60
2	5	10	s	3	36	16	0.00	36	11.63	16	11.59
2	5	10	s	4	39	14	0.03	39	11.58	14	11.40
2	5	10	s	5	39	17	0.00	39	11.53	17	11.59
2	5	10	s	6	22	8	0.00	22	11.71	8	11.68
2	5	10	s	7	50	20	0.00	44	11.77	17	11.50
2	5	10	s	8	47	19	0.01	45	11.55	19	11.56
2	5	10	s	9	19	7	0.00	19	11.64	7	11.48
2	5	10	s	10	30	13	0.00	30	11.54	13	11.50
2	5	10	d	1	59	22	0.01	49	12.10	22	11.81
2	5	10	d	2	71	34	0.00	71	11.87	28	11.73
2	5	10	d	3	38	15	0.00	38	11.83	15	11.79
2	5	10	d	4	88	39	0.01	88	11.84	36	11.86
2	5	10	d	5	42	20	0.00	36	12.11	20	12.02
2	5	10	d	6	60	24	0.00	58	11.96	24	11.97
2	5	10	d	7	32	17	0.02	32	12.10	17	12.02
2	5	10	d	8	63	25	0.00	63	12.23	25	12.24
2	5	10	d	9	45	21	0.00	43	11.85	19	11.80
2	5	10	d	10	64	34	0.02	58	12.17	28	11.72
2	5	15	s	1	42	16	0.02	40	11.64	16	11.47
2	5	15	s	2	33	12	0.00	31	11.93	12	11.84
2	5	15	s	3	28	12	0.00	28	11.84	12	11.80
2	5	15	s	4	37	13	0.01	29	11.72	13	11.64
2	5	15	s	5	28	14	0.00	28	11.89	14	11.70
2	5	15	s	6	36	20	0.00	33	11.80	17	11.72
2	5	15	s	7	35	17	0.01	35	11.94	17	11.59
2	5	15	s	8	39	16	0.00	39	11.87	16	11.53
2	5	15	s	9	38	14	0.00	38	11.78	14	11.86
2	5	15	s	10	31	13	0.01	28	11.70	11	11.67
2	5	15	d	1	47	24	0.00	47	11.96	20	11.64
2	5	15	d	2	70	29	0.00	68	11.80	26	11.81
2	5	15	d	3	66	33	0.02	59	12.01	26	11.69
2	5	15	d	4	56	25	0.00	56	11.92	25	11.70
2	5	15	d	5	38	14	0.00	38	11.59	14	11.71
2	5	15	d	6	39	20	0.02	36	11.98	16	11.60
2	5	15	d	7	58	26	0.00	55	11.86	24	11.75
2	5	15	d	8	55	25	0.00	47	11.97	21	11.75
2	5	15	d	9	49	27	0.02	47	12.34	22	11.64
2	5	15	d	10	60	29	0.00	52	12.22	22	11.83
2	10	10	s	1	124	27	0.01	118	17.13	27	15.38
2	10	10	s	2	130	28	0.05	114	18.97	28	15.91
2	10	10	s	3	91	28	0.00	85	15.59	24	14.94
2	10	10	s	4	71	15	0.02	67	17.38	15	15.11
2	10	10	s	5	149	40	0.03	129	18.73	29	14.97
2	10	10	s	6	110	25	0.03	109	15.39	25	15.04
2	10	10	s	7	107	30	0.02	105	16.29	28	15.68
2	10	10	s	8	112	25	0.01	98	18.62	25	15.26
2	10	10	s	9	120	31	0.04	120	15.23	31	15.38
2	10	10	s	10	106	30	0.01	101	15.43	25	14.69

Table A.3. (Continued)

M	J	T	D	V	IEACT tft	IEACT fmax	IEACT time(s)	ILS tft	ILS tft time(s)	ILS fmax	ILS fmax time(s)
2	10	10	d	1	274	66	0.02	247	22.27	59	19.96
2	10	10	d	2	307	78	0.05	282	25.39	66	23.59
2	10	10	d	3	247	58	0.02	247	17.20	58	17.31
2	10	10	d	4	237	53	0.01	230	22.42	50	19.72
2	10	10	d	5	212	46	0.03	194	19.25	46	17.01
2	10	10	d	6	245	49	0.04	230	20.30	49	17.77
2	10	10	d	7	231	49	0.01	228	21.97	47	18.30
2	10	10	d	8	252	62	0.01	246	19.84	62	19.75
2	10	10	d	9	189	40	0.02	189	16.54	40	18.27
2	10	10	d	10	181	41	0.02	164	20.69	37	17.78
2	10	15	s	1	109	34	0.03	109	20.93	30	17.00
2	10	15	s	2	149	40	0.02	148	21.83	37	16.25
2	10	15	s	3	136	33	0.02	136	20.20	33	15.92
2	10	15	s	4	131	36	0.01	123	19.19	36	16.10
2	10	15	s	5	132	34	0.01	124	20.02	34	16.37
2	10	15	s	6	184	48	0.03	173	17.78	43	15.80
2	10	15	s	7	124	35	0.02	118	16.34	35	16.75
2	10	15	s	8	167	43	0.02	160	20.84	40	16.63
2	10	15	s	9	153	41	0.03	146	18.62	34	16.34
2	10	15	s	10	156	40	0.02	130	20.23	34	16.83
2	10	15	d	1	325	79	0.03	284	22.93	69	20.52
2	10	15	d	2	322	81	0.01	322	22.66	81	18.87
2	10	15	d	3	205	45	0.02	193	21.99	45	17.58
2	10	15	d	4	296	68	0.03	296	23.08	59	20.84
2	10	15	d	5	343	86	0.01	336	24.03	82	20.53
2	10	15	d	6	244	58	0.01	227	23.42	49	19.62
2	10	15	d	7	245	54	0.02	240	20.91	50	18.89
2	10	15	d	8	386	93	0.02	351	20.10	80	20.91
2	10	15	d	9	330	78	0.03	329	22.80	78	19.81
2	10	15	d	10	380	97	0.02	377	22.69	93	24.33
2	15	15	s	1	367	55	0.03	302	50.14	53	32.44
2	15	15	s	2	257	40	0.03	254	46.28	40	28.83
2	15	15	s	3	316	51	0.03	279	60.04	51	30.36
2	15	15	s	4	282	47	0.03	256	54.94	46	29.95
2	15	15	s	5	273	54	0.05	258	43.04	46	28.61
2	15	15	s	6	298	48	0.03	295	45.87	48	27.58
2	15	15	s	7	297	48	0.03	276	47.43	48	29.69
2	15	15	s	8	401	70	0.03	348	55.72	56	28.76
2	15	15	s	9	328	53	0.03	293	43.37	50	29.85
2	15	15	s	10	349	55	0.03	324	43.10	52	30.51
2	15	15	d	1	509	82	0.03	459	67.58	68	42.15
2	15	15	d	2	483	81	0.04	428	58.02	64	38.21
2	15	15	d	3	433	72	0.04	381	52.22	66	38.72
2	15	15	d	4	523	84	0.05	434	55.11	74	40.29
2	15	15	d	5	534	81	0.04	476	55.81	68	40.20
2	15	15	d	6	542	80	0.03	515	48.03	70	42.12
2	15	15	d	7	585	84	0.03	501	59.97	74	41.68
2	15	15	d	8	566	85	0.03	451	55.08	71	41.51
2	15	15	d	9	513	89	0.03	431	53.82	71	39.21
2	15	15	d	10	488	74	0.03	423	55.65	62	38.91

Table A.3. (Continued)

M	J	T	D	V	IEACT tft	IEACT fmax	IEACT time(s)	ILS tft	ILS tft time(s)	ILS fmax	ILS fmax time(s)
3	15	15	s	1	149	26	0.05	135	26.19	26	20.39
3	15	15	s	2	157	32	0.03	126	23.00	28	20.92
3	15	15	s	3	179	27	0.03	165	31.68	27	21.47
3	15	15	s	4	171	30	0.03	141	26.79	28	21.12
3	15	15	s	5	177	31	0.03	155	35.62	28	23.15
3	15	15	s	6	152	37	0.05	133	29.03	29	20.78
3	15	15	s	7	195	37	0.05	183	26.78	35	22.09
3	15	15	s	8	165	29	0.04	155	27.34	29	21.44
3	15	15	s	9	205	34	0.05	191	26.28	27	21.61
3	15	15	s	10	159	31	0.05	144	30.03	26	20.94
3	15	15	d	1	350	69	0.03	336	31.18	55	25.63
3	15	15	d	2	352	63	0.05	350	39.42	59	36.71
3	15	15	d	3	396	75	0.08	366	40.11	60	25.25
3	15	15	d	4	383	62	0.04	374	40.41	61	26.50
3	15	15	d	5	339	52	0.03	339	32.98	52	29.58
3	15	15	d	6	344	57	0.03	343	31.35	55	26.07
3	15	15	d	7	415	74	0.04	415	38.30	68	32.03
3	15	15	d	8	306	51	0.05	304	32.00	46	24.86
3	15	15	d	9	380	55	0.05	344	37.63	52	26.06
3	15	15	d	10	363	63	0.03	347	38.90	57	30.64
3	25	15	s	1	506	53	0.11	459	100.42	51	61.88
3	25	15	s	2	426	45	0.10	395	119.18	45	64.47
3	25	15	s	3	494	54	0.10	457	122.10	47	64.20
3	25	15	s	4	391	56	0.12	336	102.53	43	58.17
3	25	15	s	5	450	49	0.11	412	115.14	45	61.88
3	25	15	s	6	544	60	0.10	492	155.52	52	62.56
3	25	15	s	7	411	47	0.10	380	108.93	39	64.50
3	25	15	s	8	446	56	0.09	412	121.75	44	66.08
3	25	15	s	9	480	50	0.11	422	94.05	45	62.80
3	25	15	s	10	568	59	0.09	502	107.40	54	64.36
3	25	15	d	1	770	80	0.11	634	138.63	62	97.91
3	25	15	d	2	930	79	0.11	812	151.22	73	95.44
3	25	15	d	3	845	84	0.11	805	135.96	75	96.18
3	25	15	d	4	777	74	0.10	663	153.97	64	96.11
3	25	15	d	5	778	72	0.12	680	115.81	67	97.01
3	25	15	d	6	784	79	0.11	705	153.73	66	94.91
3	25	15	d	7	894	92	0.11	833	110.52	73	92.66
3	25	15	d	8	845	90	0.09	776	180.82	74	98.13
3	25	15	d	9	744	81	0.09	663	163.75	65	106.79
3	25	15	d	10	771	75	0.10	709	145.05	67	99.35
4	25	15	s	1	451	50	0.10	400	118.80	42	53.39
4	25	15	s	2	379	43	0.10	360	77.75	43	52.10
4	25	15	s	3	369	40	0.10	357	80.33	40	53.08
4	25	15	s	4	385	36	0.11	316	92.48	36	54.25
4	25	15	s	5	390	41	0.09	349	97.06	37	54.41
4	25	15	s	6	296	35	0.09	270	85.39	34	49.28
4	25	15	s	7	279	34	0.09	262	94.26	29	52.48
4	25	15	s	8	380	42	0.11	353	96.23	34	58.47
4	25	15	s	9	326	36	0.10	297	86.43	35	63.47
4	25	15	s	10	381	42	0.10	370	75.47	36	54.36

Table A.3. (Continued)

M	J	T	D	V	IEACT tft	IEACT fmax	IEACT time(s)	ILS tft	ILS tft time(s)	ILS fmax	ILS fmax time(s)
4	25	15	d	1	642	58	0.10	600	85.87	56	62.36
4	25	15	d	2	637	63	0.09	608	88.53	56	78.19
4	25	15	d	3	543	47	0.10	497	86.81	46	69.06
4	25	15	d	4	556	61	0.08	527	70.22	53	75.36
4	25	15	d	5	603	55	0.11	549	85.11	52	65.64
4	25	15	d	6	674	68	0.11	650	110.57	58	68.97
4	25	15	d	7	565	57	0.11	513	101.45	52	61.17
4	25	15	d	8	578	61	0.11	534	106.80	50	79.28
4	25	15	d	9	513	52	0.10	474	110.71	47	67.72
4	25	15	d	10	673	67	0.10	653	100.20	60	63.00
4	25	20	s	1	399	40	0.10	375	83.54	40	53.39
4	25	20	s	2	378	41	0.12	367	86.94	41	51.67
4	25	20	s	3	390	42	0.10	353	97.81	37	54.03
4	25	20	s	4	359	40	0.11	343	87.68	37	63.20
4	25	20	s	5	321	33	0.11	313	87.55	33	52.35
4	25	20	s	6	328	38	0.10	304	83.89	34	52.44
4	25	20	s	7	348	39	0.11	307	108.36	32	52.18
4	25	20	s	8	363	39	0.11	358	99.87	38	50.61
4	25	20	s	9	390	41	0.10	375	81.90	39	53.42
4	25	20	s	10	331	34	0.10	315	93.27	33	51.40
4	25	20	d	1	659	68	0.10	619	101.97	58	69.53
4	25	20	d	2	737	73	0.11	665	101.09	59	66.75
4	25	20	d	3	787	74	0.10	774	84.91	72	57.17
4	25	20	d	4	710	74	0.11	692	85.08	67	69.37
4	25	20	d	5	850	84	0.11	817	101.53	76	80.20
4	25	20	d	6	723	72	0.11	706	113.15	67	67.89
4	25	20	d	7	707	70	0.10	678	109.45	67	60.88
4	25	20	d	8	743	75	0.09	698	101.48	66	68.12
4	25	20	d	9	773	79	0.11	753	89.32	77	73.56
4	25	20	d	10	765	71	0.09	753	104.45	66	64.36

**Table A.4. Results obtained by the Wilcoxon Signed-Rank Test comparing the computation times of all observations solved to optimality.**

Measured Value	Objective	Methods compared	Sample Size	Z-value	Significantly different at *p = 0.05?
time (s)	tft	(prb, tib)	31	-4.86	yes
time (s)	tft	(pob, tib)	31	-4.86	yes
time (s)	tft	(prb, pob)	58	-1.96	no
time (s)	fmax	(prb, tib)	31	-4.86	yes
time (s)	fmax	(pob, tib)	31	-4.86	yes
time (s)	fmax	(prb, pob)	67	-5.49	yes

**Table A.5. Results obtained by the Wilcoxon Signed-Rank Test comparing the computation times of all observations solved to optimality at various problem types (M | J | T).**

Problem Type	Measured Value	Objective	Methods compared	Sample Size	Z-value	Significantly different at *p = 0.05?
2 05 10	time (s)	tft	(prb, pob)	17	-2.13	yes
2 05 10	time (s)	fmax	(prb, pob)	19	-0.02	no
2 05 15	time (s)	tft	(prb, pob)	20	-1.70	no
2 05 15	time (s)	fmax	(prb, pob)	19	-2.35	yes
2 10 10	time (s)	tft	(prb, pob)	19	-3.50	yes
2 10 10	time (s)	fmax	(prb, pob)	19	-3.82	yes

**Table A.6. Results obtained by the Wilcoxon Signed-Rank Test comparing the computation times of all observations solved to optimality at various methods.**

Method	Measured Value	Objective	Density compared	Sample Size	Z-value	Significantly different at *p = 0.05?
prb	time (s)	tft	(s, d)	30	-1.29	no
prb	time (s)	fmax	(s, d)	27	-1.89	no
pob	time (s)	tft	(s, d)	39	-2.00	yes
pob	time (s)	fmax	(s, d)	38	-3.24	yes
tib	time (s)	tft	(s, d)	11	-2.93	yes
tib	time (s)	fmax	(s, d)	13	-2.90	yes

**Table A.7. Results obtained by the Wilcoxon Signed-Rank Test comparing the objective values at various numbers of machines.**

M	Measured Objective	Methods compared	Sample Size	Z-value	Significantly different at *p = 0.05?
2	tft	(prb, pob)	20	-3.10	yes
2	tft	(prb, ILS)	60	-5.61	yes
2	tft	(pob, ILS)	60	-6.70	yes
2	fmax	(prb, pob)	15	-1.19	no
2	fmax	(prb, ILS)	58	-6.17	yes
2	fmax	(pob, ILS)	55	-5.84	yes
3	tft	(prb, pob)	33	-1.92	no
3	tft	(prb, ILS)	39	-1.30	no
3	tft	(pob, ILS)	40	-1.64	no
3	fmax	(prb, pob)	28	-0.38	no
3	fmax	(prb, ILS)	32	-0.23	no
3	fmax	(pob, ILS)	37	-0.38	no
4	tft	(prb, pob)	40	-1.47	no
4	tft	(prb, ILS)	40	-5.11	yes
4	tft	(pob, ILS)	40	-4.88	yes
4	fmax	(prb, pob)	39	-0.78	no
4	fmax	(prb, ILS)	39	-4.74	yes
4	fmax	(pob, ILS)	36	-3.98	yes

## Appendix B: Results of Study 4

The following tables contain the results of study 4 (Section V). The following identifiers are used due to space restrictions (Table B.1). Table B.2 and Table B.3 to shows the results of the construction heuristics for the data sets SSP-NPM-I and SSP-NPM-II, respectively. Table B.4 and Table B.5 provide the results of the local search for the data sets SSP-NPM-I and SSP-NPM-II, respectively. Tables B.6 to B.8 provide the results of the pre-study of the random perturbation scheme (P.2) for different objectives with respect to different values of  $\beta$ ,  $\beta \in \{0.2, 0.4, 0.6, 0.8\}$ . The results of the statistical evaluation are provided shown in Table B.9. Table B.10 shows the results of the best combinations of the combined perturbation scheme (P.3) obtained for each objective of the pre-study, with respect to different values of  $\beta$  and  $\gamma$ ,  $\beta \in \{0.2, 0.4, 0.6, 0.8\}$ ,  $\gamma \in \{0.05, 0.1, 0.25, 0.5\}$ . Table B.11 subsequently provides the statistical evaluation. Table B.12 shows the results of the MIP model and the different ILS methods applied to data set SSP-NPM-I for the computation time limit of 600 seconds. Table B.13 provides the results of the different ILS methods applied to data set SSP-NPM-II for the computation time limit of 600 seconds. Table B.14 presents the results of the statistical evaluation of the comparison between the mathematical model and the ILS methods of SSP-NPM-I. Lastly, Table B.15 shows the statistical results of the comparison of different ILS methods for SSP-NPM-II.

**Table B.1. Column identifiers of Appendix B.**

<b>M</b>	number of machines	<b>RPD</b>	relative percentage deviation
<b>J</b>	number of jobs	<b>IEACT</b>	iterated-earliest-artificial-completion-time heuristic
<b>T</b>	number of tools	<b>IGI</b>	iterated-greatest-intersection heuristic
<b>D (s/d)</b>	density (sparse/dense)	<b>MSR</b>	multi-start-random heuristic
<b>sw (l/h)</b>	switching time (low/high)	<b>LS</b>	local-search heuristic
<b>V</b>	instance number per problem type	<b>ILS</b>	iterated-local-search heuristic
<b>ts</b>	total number of tool switches	<b>P.1 (a/ b)</b>	problem-specific perturbation
<b>tft</b>	total flowtime	<b>P.2</b>	random perturbation
<b>fmax</b>	makespan	<b>P.3</b>	combined perturbation
<b>time(s)</b>	computation time (seconds)	<b>MIP</b>	mixed-integer linear program



Table B.2. Overall results of the construction heuristics for SSP-NPM-I.

M	J	T	V	IEACT				IGI				MSR			
				ts	tft	fmax	time(s)	ts	tft	fmax	time(s)	ts	tft	fmax	time(s)
2	10	10	1	8	162	48	0.01	8	260	47	0.01	5	162	37	4.19
2	10	10	2	11	167	42	0.02	5	224	42	0.00	4	163	32	3.94
2	10	10	3	8	145	34	0.02	4	187	38	0.01	3	147	30	3.87
2	10	10	4	8	107	35	0.01	5	240	41	0.00	5	123	28	3.77
2	10	10	5	6	140	32	0.03	3	133	31	0.00	3	117	27	3.86
2	10	10	6	8	123	37	0.03	5	153	33	0.02	4	118	26	3.99
2	10	10	7	10	169	43	0.02	7	221	37	0.03	2	190	42	6.56
2	10	10	8	10	160	43	0.02	9	222	43	0.02	7	162	32	3.93
2	10	10	9	11	155	36	0.03	8	217	46	0.01	1	188	41	6.33
2	10	10	10	8	148	40	0.03	9	211	45	0.00	2	289	55	6.47
2	10	10	11	11	180	42	0.02	10	236	45	0.00	1	260	47	6.47
2	10	10	12	12	220	57	0.03	12	288	56	0.00	4	246	49	6.64
2	10	10	13	8	110	30	0.01	8	210	37	0.02	7	141	30	3.95
2	10	10	14	12	194	47	0.01	14	220	52	0.02	3	284	53	6.46
2	10	10	15	10	173	41	0.04	6	237	42	0.01	4	175	37	3.90
2	10	10	16	10	154	33	0.01	7	241	43	0.02	5	142	29	3.90
2	10	10	17	11	180	39	0.01	9	230	49	0.00	5	171	32	3.81
2	10	10	18	7	123	31	0.03	9	174	37	0.00	4	127	26	3.89
2	10	10	19	10	159	43	0.02	8	259	47	0.00	5	151	32	3.83
2	10	10	20	9	136	38	0.02	7	192	31	0.02	2	207	51	6.45
2	15	10	1	13	303	54	0.03	9	428	59	0.01	10	375	49	5.6
2	15	10	2	16	413	64	0.04	11	443	68	0.02	6	519	64	9.25
2	15	10	3	16	315	55	0.03	12	469	74	0.02	11	306	49	5.71
2	15	10	4	12	329	52	0.06	11	417	61	0.03	9	466	61	9.55
2	15	10	5	9	304	59	0.05	10	444	61	0.01	11	366	52	5.64
2	15	10	6	13	355	55	0.05	10	543	62	0.02	7	555	78	9.58
2	15	10	7	16	298	57	0.04	12	401	62	0.02	7	462	58	9.57
2	15	10	8	14	277	48	0.05	14	374	54	0.02	5	386	58	9.46
2	15	10	9	13	258	45	0.09	14	493	71	0.01	13	310	43	5.69
2	15	10	10	14	355	64	0.04	11	473	74	0.01	9	407	68	5.67
2	15	10	11	14	331	56	0.03	9	407	62	0.01	9	380	53	5.55
2	15	10	12	17	399	65	0.03	13	460	69	0.00	7	651	84	9.36
2	15	10	13	19	402	72	0.03	13	469	64	0.01	8	628	87	9.61
2	15	10	14	15	397	74	0.03	13	489	76	0.04	5	481	73	9.49
2	15	10	15	16	410	75	0.05	14	487	68	0.01	8	588	90	9.56
2	15	10	16	13	287	55	0.03	13	417	59	0.02	8	473	64	9.61
2	15	10	17	10	359	55	0.04	11	582	80	0.01	5	459	69	9.36
2	15	10	18	15	403	72	0.05	13	624	79	0.01	7	607	69	9.58
2	15	10	19	14	246	46	0.03	14	323	53	0.02	8	429	65	9.57
2	15	10	20	14	393	65	0.03	13	488	75	0.02	10	515	74	9.75

Table B.2. (Continued).

M	J	T	V	IEACT				IGI				MSR			
				ts	tft	fmax	time(s)	ts	tft	fmax	time(s)	ts	tft	fmax	time(s)
2	10	15	1	12	222	44	0.03	13	294	58	0.00	9	230	42	4.04
2	10	15	2	13	194	51	0.02	11	255	51	0.03	9	198	40	4.08
2	10	15	3	16	160	43	0.01	11	237	43	0.00	10	163	37	4.06
2	10	15	4	15	178	44	0.05	12	278	57	0.00	9	164	37	4.08
2	10	15	5	10	184	39	0.01	9	218	37	0.00	7	168	37	4.03
2	10	15	6	12	206	47	0.04	10	239	49	0.02	8	200	38	3.97
2	10	15	7	12	151	38	0.01	9	234	50	0.01	9	144	33	4.03
2	10	15	8	17	187	43	0.01	13	249	58	0.02	6	293	66	6.59
2	10	15	9	13	186	46	0.02	13	236	46	0.02	10	173	37	4.04
2	10	15	10	13	177	47	0.02	10	177	52	0.01	8	174	39	4.00
2	10	15	11	11	162	40	0.01	13	264	50	0.02	8	181	37	3.95
2	10	15	12	14	191	52	0.02	11	210	46	0.00	9	176	38	4.08
2	10	15	13	11	167	42	0.01	11	267	49	0.00	8	168	36	4.03
2	10	15	14	14	215	44	0.01	15	307	71	0.00	11	222	44	4.08
2	10	15	15	12	185	41	0.03	15	273	54	0.00	7	262	51	6.69
2	10	15	16	12	203	46	0.00	11	262	58	0.00	9	191	37	4.03
2	10	15	17	8	149	36	0.02	10	186	43	0.02	8	136	29	4.00
2	10	15	18	14	175	46	0.01	10	275	57	0.01	9	199	41	4.09
2	10	15	19	12	192	47	0.01	11	248	54	0.02	9	196	40	4.10
2	10	15	20	14	216	53	0.03	13	254	53	0.01	9	204	45	4.11
2	15	15	1	20	341	62	0.03	21	557	77	0.00	13	643	86	9.87
2	15	15	2	20	432	63	0.03	16	533	75	0.01	18	455	62	5.89
2	15	15	3	21	362	60	0.03	16	469	70	0.02	16	373	52	5.94
2	15	15	4	24	386	69	0.04	21	597	79	0.02	18	408	60	5.99
2	15	15	5	18	355	57	0.03	15	539	70	0.01	14	381	59	5.90
2	15	15	6	22	444	78	0.05	17	582	76	0.02	9	622	83	9.95
2	15	15	7	15	403	67	0.05	15	435	78	0.01	21	509	72	5.99
2	15	15	8	25	404	72	0.06	19	484	73	0.01	19	427	63	5.97
2	15	15	9	15	395	67	0.05	12	478	69	0.02	13	420	61	5.78
2	15	15	10	23	371	65	0.04	20	502	75	0.01	19	394	57	5.95
2	15	15	11	27	452	69	0.03	18	485	67	0.02	16	753	104	9.92
2	15	15	12	21	367	57	0.03	18	408	69	0.01	18	370	55	5.89
2	15	15	13	22	490	77	0.03	19	626	83	0.01	19	549	82	5.93
2	15	15	14	17	392	59	0.03	16	432	70	0.02	19	443	60	5.89
2	15	15	15	18	412	69	0.03	15	503	71	0.01	14	445	63	5.83
2	15	15	16	19	385	70	0.03	18	444	68	0.02	17	395	58	5.92
2	15	15	17	18	392	64	0.03	23	509	77	0.01	21	435	61	5.90
2	15	15	18	21	411	68	0.04	16	458	64	0.02	16	431	58	5.83
2	15	15	19	21	432	76	0.06	17	616	80	0.00	19	512	74	5.89
2	15	15	20	26	415	78	0.04	22	552	79	0.02	20	465	67	5.86

Table B.2. (Continued).

M	J	T	V	IEACT				IGI				MSR			
				ts	tft	fmax	time(s)	ts	tft	fmax	time(s)	ts	tft	fmax	time(s)
3	15	15	1	13	221	43	0.04	13	304	53	0.03	9	244	36	5.41
3	15	15	2	16	185	39	0.03	12	348	50	0.02	11	235	34	5.43
3	15	15	3	13	265	49	0.03	14	391	68	0.03	8	257	37	5.39
3	15	15	4	14	200	41	0.04	13	268	49	0.01	11	197	29	5.45
3	15	15	5	15	204	50	0.05	12	261	46	0.01	9	214	34	5.41
3	15	15	6	14	210	39	0.03	13	299	49	0.02	10	241	36	5.42
3	15	15	7	14	200	35	0.03	11	294	43	0.01	10	221	34	5.38
3	15	15	8	16	271	46	0.03	18	474	79	0.02	9	298	39	5.47
3	15	15	9	16	249	48	0.05	10	337	43	0.01	9	240	35	5.39
3	15	15	10	14	238	44	0.05	12	290	43	0.01	9	234	35	5.40
3	15	15	11	11	200	40	0.03	16	351	56	0.02	8	219	33	5.47
3	15	15	12	18	219	44	0.05	12	313	55	0.01	10	219	33	5.56
3	15	15	13	13	198	44	0.04	12	326	57	0.04	11	252	41	5.47
3	15	15	14	18	210	42	0.03	19	392	64	0.01	12	253	38	5.53
3	15	15	15	15	196	45	0.03	17	286	43	0.02	9	205	30	5.50
3	15	15	16	16	233	40	0.03	12	371	50	0.01	9	215	34	5.39
3	15	15	17	13	212	40	0.05	12	310	52	0.01	9	238	37	5.42
3	15	15	18	14	199	38	0.06	11	254	39	0.02	8	210	31	5.42
3	15	15	19	16	219	52	0.03	12	293	51	0.01	9	220	30	5.42
3	15	15	20	16	184	42	0.05	10	375	59	0.02	9	211	32	5.44
3	20	15	1	19	373	51	0.07	21	568	63	0.03	15	438	49	7.14
3	20	15	2	21	311	52	0.07	17	544	60	0.01	16	374	45	7.28
3	20	15	3	24	404	63	0.06	17	557	75	0.01	21	510	56	7.28
3	20	15	4	22	344	63	0.08	15	545	64	0.02	16	438	53	7.24
3	20	15	5	23	424	70	0.07	19	601	78	0.03	18	478	56	7.25
3	20	15	6	19	375	57	0.06	14	491	56	0.01	17	496	55	7.24
3	20	15	7	24	427	65	0.08	16	543	62	0.03	16	489	55	7.23
3	20	15	8	22	351	55	0.06	19	441	59	0.02	18	364	45	7.16
3	20	15	9	21	353	53	0.06	21	624	77	0.02	18	409	51	7.19
3	20	15	10	16	315	47	0.08	18	507	64	0.02	17	393	44	7.19
3	20	15	11	22	381	59	0.06	15	558	76	0.02	17	486	55	7.21
3	20	15	12	23	422	58	0.08	24	641	82	0.03	19	513	57	7.19
3	20	15	13	22	401	55	0.06	22	602	74	0.03	18	470	56	7.24
3	20	15	14	20	337	53	0.08	20	495	68	0.02	17	396	50	7.20
3	20	15	15	16	315	52	0.06	17	571	68	0.02	16	435	50	7.14
3	20	15	16	14	338	52	0.06	15	523	61	0.02	18	445	55	7.20
3	20	15	17	19	346	48	0.08	16	481	55	0.01	16	420	47	7.19
3	20	15	18	21	445	63	0.06	15	598	72	0.01	15	517	56	7.16
3	20	15	19	25	436	61	0.05	20	569	71	0.01	16	493	50	7.25
3	20	15	20	18	340	55	0.06	16	530	74	0.04	17	440	56	7.18

Table B.2. (Continued).

M	J	T	V	IEACT				IGI				MSR			
				ts	tft	fmax	time(s)	ts	tft	fmax	time(s)	ts	tft	fmax	time(s)
3	15	20	1	22	299	59	0.05	25	440	70	0.01	20	323	49	5.80
3	15	20	2	25	222	48	0.03	17	342	44	0.01	13	236	37	5.72
3	15	20	3	20	232	45	0.05	19	322	47	0.00	15	254	38	5.65
3	15	20	4	19	181	41	0.05	19	287	58	0.02	16	242	36	5.78
3	15	20	5	23	250	50	0.04	24	403	67	0.01	19	283	42	5.75
3	15	20	6	16	203	44	0.05	19	329	57	0.02	17	266	41	5.86
3	15	20	7	17	252	46	0.05	19	326	64	0.01	13	269	39	5.79
3	15	20	8	26	309	65	0.04	16	412	53	0.01	18	312	45	5.77
3	15	20	9	21	248	44	0.05	18	323	66	0.02	13	230	35	5.75
3	15	20	10	24	275	64	0.05	21	377	71	0.01	17	273	42	5.69
3	15	20	11	22	267	51	0.04	22	434	61	0.02	16	296	43	5.75
3	15	20	12	17	198	36	0.04	17	290	44	0.03	13	218	34	5.69
3	15	20	13	19	229	48	0.03	10	270	41	0.01	13	241	37	5.80
3	15	20	14	22	301	52	0.03	23	372	66	0.02	19	281	45	5.84
3	15	20	15	22	273	49	0.03	19	394	65	0.02	14	308	43	5.80
3	15	20	16	21	257	51	0.03	17	379	50	0.01	17	281	38	5.78
3	15	20	17	18	218	47	0.03	21	276	60	0.02	15	227	33	5.67
3	15	20	18	18	232	51	0.05	17	356	61	0.01	16	247	41	5.72
3	15	20	19	23	309	58	0.04	20	380	65	0.02	18	293	47	5.77
3	15	20	20	22	241	44	0.05	17	351	46	0.02	14	269	39	5.72
3	20	20	1	31	506	69	0.08	36	713	89	0.05	29	605	71	7.65
3	20	20	2	30	506	71	0.06	28	744	88	0.02	26	542	66	7.68
3	20	20	3	29	461	61	0.06	28	644	79	0.02	26	523	59	7.76
3	20	20	4	33	419	62	0.08	25	641	82	0.03	30	562	68	7.74
3	20	20	5	32	462	76	0.06	27	645	79	0.03	30	569	67	7.70
3	20	20	6	25	504	72	0.08	25	675	85	0.03	26	610	71	7.56
3	20	20	7	28	445	67	0.08	22	452	58	0.02	24	517	56	7.61
3	20	20	8	32	462	73	0.06	26	618	79	0.02	27	533	62	7.67
3	20	20	9	32	441	67	0.08	27	686	87	0.02	30	540	66	7.66
3	20	20	10	35	457	67	0.07	28	648	87	0.01	27	586	64	7.67
3	20	20	11	30	423	66	0.06	23	627	78	0.01	24	540	61	7.59
3	20	20	12	30	381	60	0.07	25	555	63	0.03	27	495	57	7.71
3	20	20	13	35	464	64	0.08	27	718	89	0.03	28	596	64	7.66
3	20	20	14	24	391	55	0.06	23	637	76	0.04	25	549	62	7.68
3	20	20	15	36	433	66	0.08	29	654	90	0.03	28	524	61	7.72
3	20	20	16	28	447	68	0.08	22	614	73	0.01	25	543	64	7.64
3	20	20	17	29	422	59	0.06	27	647	87	0.01	30	521	57	7.76
3	20	20	18	26	461	68	0.06	28	575	72	0.02	26	566	63	7.72
3	20	20	19	35	511	76	0.08	26	666	91	0.02	28	552	63	7.66
3	20	20	20	28	423	56	0.08	20	695	76	0.04	25	566	62	7.56

Table B.3. Overall results of the construction heuristics for SSP-NPM-II.

M	J	T	V	sw	D	IEACT				IGI				MSR			
						ts	tft	fmax	time (s)	ts	tft	fmax	time (s)	ts	tft	fmax	time (s)
4	40	60	1	l	s	59	1517	107	0.27	57	2097	141	0.07	62	1800	112	18.06
4	40	60	2	l	s	65	1616	120	0.25	57	2146	162	0.07	59	1940	126	17.87
4	40	60	3	l	s	55	1434	121	0.27	53	1828	145	0.08	54	1754	113	17.99
4	40	60	4	l	s	57	1435	115	0.26	53	1786	139	0.08	58	1797	126	17.92
4	40	60	5	l	s	56	1257	114	0.25	58	1930	140	0.08	58	1690	109	17.89
4	40	60	6	l	s	60	1255	91	0.26	65	2022	132	0.08	63	1780	123	17.88
4	40	60	7	l	s	63	1253	90	0.29	61	1852	133	0.09	63	1666	107	17.94
4	40	60	8	l	s	62	1657	126	0.27	60	2142	150	0.10	63	2083	132	17.83
4	40	60	9	l	s	65	1439	132	0.28	59	1916	134	0.08	58	1688	112	17.68
4	40	60	10	l	s	64	1604	132	0.34	63	2208	135	0.08	65	2080	131	17.85
4	40	60	11	l	s	60	1447	121	0.25	55	1814	121	0.08	61	1811	124	17.71
4	40	60	12	l	s	56	1422	136	0.25	54	1995	138	0.06	58	1851	126	17.69
4	40	60	13	l	s	56	1519	128	0.26	53	1841	128	0.09	63	1993	134	17.70
4	40	60	14	l	s	54	1519	124	0.25	57	2103	143	0.10	65	2202	139	17.88
4	40	60	15	l	s	59	1342	110	0.25	53	2179	123	0.06	58	1747	116	17.78
4	40	60	16	l	s	66	1457	128	0.25	59	1919	140	0.08	66	1930	121	18.00
4	40	60	17	l	s	63	1324	107	0.25	61	1920	146	0.08	60	1795	118	17.84
4	40	60	18	l	s	68	1641	145	0.30	59	2142	150	0.08	58	1823	116	17.70
4	40	60	19	l	s	55	1322	114	0.25	49	1988	138	0.06	58	1865	119	17.69
4	40	60	20	l	s	65	1651	139	0.23	55	1933	141	0.07	63	2047	139	17.76
4	40	60	1	l	d	406	8799	567	0.26	384	8688	531	0.10	362	12301	886	54.83
4	40	60	2	l	d	402	7849	464	0.27	390	8230	495	0.07	353	11027	761	54.64
4	40	60	3	l	d	407	9011	556	0.25	409	9212	555	0.06	375	15601	1163	53.96
4	40	60	4	l	d	375	8632	506	0.26	366	9051	512	0.08	346	13491	966	54.23
4	40	60	5	l	d	393	8453	544	0.25	401	8968	543	0.08	342	12366	845	54.38
4	40	60	6	l	d	371	7299	527	0.26	360	8020	490	0.07	345	11652	874	54.39
4	40	60	7	l	d	395	7822	497	0.25	382	8151	484	0.08	352	11477	707	54.44
4	40	60	8	l	d	369	7778	420	0.25	351	8220	435	0.08	339	10537	659	54.48
4	40	60	9	l	d	376	8804	508	0.25	355	9191	456	0.08	337	11192	725	55.18
4	40	60	10	l	d	379	7935	456	0.33	376	8372	448	0.08	362	10849	636	54.44
4	40	60	11	l	d	408	9137	602	0.25	379	9212	525	0.08	367	13219	893	54.26
4	40	60	12	l	d	364	7374	443	0.27	355	7821	414	0.06	363	11137	775	54.66
4	40	60	13	l	d	379	7836	465	0.25	383	8011	452	0.10	340	11183	719	54.36
4	40	60	14	l	d	389	8829	616	0.25	390	8901	612	0.09	364	15553	1150	54.24
4	40	60	15	l	d	398	8012	437	0.26	389	8542	471	0.08	344	10937	781	54.91
4	40	60	16	l	d	368	8377	497	0.25	373	8673	519	0.07	358	12155	805	54.75
4	40	60	17	l	d	368	6967	418	0.27	338	7688	433	0.08	315	10268	675	55.23
4	40	60	18	l	d	379	7896	427	0.32	367	8120	455	0.11	339	10534	818	55.01
4	40	60	19	l	d	385	9061	598	0.26	392	9548	569	0.08	363	15197	1124	54.52
4	40	60	20	l	d	378	7510	414	0.27	388	8535	498	0.06	324	11094	771	55.05
4	40	60	1	h	s	63	2839	214	0.24	63	3086	214	0.07	62	2977	213	17.75
4	40	60	2	h	s	56	1820	166	0.28	50	2320	186	0.08	54	2290	168	17.75
4	40	60	3	h	s	57	2333	201	0.23	59	2792	222	0.08	59	2753	194	17.94
4	40	60	4	h	s	59	2276	214	0.27	62	2814	201	0.08	61	2645	197	17.81
4	40	60	5	h	s	57	2324	200	0.25	48	2649	190	0.06	60	2803	212	17.89
4	40	60	6	h	s	55	2106	188	0.25	59	2978	232	0.08	58	2457	178	17.8
4	40	60	7	h	s	57	2174	197	0.25	53	2457	186	0.08	54	2463	167	17.58
4	40	60	8	h	s	62	2554	236	0.26	56	2806	223	0.07	58	2641	186	17.89
4	40	60	9	h	s	52	2104	201	0.27	52	2523	190	0.08	54	2667	185	17.83
4	40	60	10	h	s	55	2113	171	0.27	54	2396	172	0.09	58	2202	155	17.67
4	40	60	11	h	s	54	1964	179	0.27	46	2147	163	0.08	52	2416	170	17.53
4	40	60	12	h	s	53	1894	170	0.25	43	2220	178	0.08	56	2409	169	17.64
4	40	60	13	h	s	58	1999	184	0.26	53	2095	145	0.10	56	2493	179	17.78
4	40	60	14	h	s	59	2184	175	0.25	54	2880	219	0.07	59	2607	191	17.83
4	40	60	15	h	s	60	2120	183	0.27	46	2428	175	0.08	56	2335	180	17.84
4	40	60	16	h	s	58	2092	186	0.27	54	2414	215	0.08	59	2514	175	17.77
4	40	60	17	h	s	53	2130	168	0.25	55	2675	250	0.10	52	2552	184	17.72
4	40	60	18	h	s	54	2038	175	0.25	55	2317	173	0.07	59	2568	185	17.91
4	40	60	19	h	s	58	2443	200	0.25	58	3052	223	0.08	54	2771	198	17.75
4	40	60	20	h	s	52	2176	176	0.25	49	2566	232	0.08	57	2585	196	17.84

















Table B.4. Overall results of the local search for SSP-NPM-I.

M	J	T	V	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
2	10	10	1	7	0.14	161	0.17	48	0.14
2	10	10	2	5	0.15	158	0.25	36	0.20
2	10	10	3	4	0.16	135	0.21	30	0.17
2	10	10	4	5	0.16	98	0.19	29	0.16
2	10	10	5	3	0.15	133	0.18	32	0.16
2	10	10	6	5	0.14	114	0.21	35	0.18
2	10	10	7	6	0.16	159	0.22	41	0.19
2	10	10	8	8	0.17	157	0.21	43	0.17
2	10	10	9	7	0.16	153	0.17	35	0.16
2	10	10	10	8	0.18	139	0.24	38	0.20
2	10	10	11	9	0.20	177	0.20	40	0.17
2	10	10	12	10	0.19	210	0.21	53	0.19
2	10	10	13	8	0.17	110	0.15	30	0.15
2	10	10	14	11	0.22	178	0.17	45	0.17
2	10	10	15	6	0.16	157	0.25	35	0.25
2	10	10	16	7	0.22	140	0.21	33	0.18
2	10	10	17	9	0.18	155	0.25	35	0.19
2	10	10	18	6	0.18	123	0.18	31	0.17
2	10	10	19	8	0.17	152	0.23	39	0.22
2	10	10	20	7	0.16	130	0.23	34	0.20
2	15	10	1	9	0.31	283	0.75	52	0.40
2	15	10	2	9	0.44	357	0.58	60	0.48
2	15	10	3	11	0.45	270	0.72	49	0.37
2	15	10	4	10	0.34	318	0.36	48	0.34
2	15	10	5	10	0.30	287	0.61	59	0.28
2	15	10	6	9	0.36	315	0.56	55	0.29
2	15	10	7	12	0.30	285	0.31	51	0.42
2	15	10	8	8	0.48	243	0.89	44	0.33
2	15	10	9	13	0.42	240	0.55	41	0.40
2	15	10	10	10	0.34	339	0.31	60	0.36
2	15	10	11	8	0.39	318	0.40	52	0.31
2	15	10	12	13	0.30	332	0.80	63	0.32
2	15	10	13	10	0.42	345	1.11	66	0.36
2	15	10	14	12	0.38	384	0.53	72	0.30
2	15	10	15	13	0.37	397	0.40	71	0.32
2	15	10	16	9	0.44	263	0.44	51	0.32
2	15	10	17	9	0.29	356	0.32	55	0.27
2	15	10	18	9	0.38	386	0.72	72	0.31
2	15	10	19	12	0.35	234	0.61	42	0.44
2	15	10	20	12	0.34	352	0.61	63	0.38

Table B.4. (Continued).

M	J	T	V	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
2	10	15	1	12	0.17	216	0.18	44	0.15
2	10	15	2	11	0.16	185	0.20	45	0.17
2	10	15	3	10	0.14	150	0.16	39	0.17
2	10	15	4	11	0.20	165	0.27	44	0.17
2	10	15	5	9	0.17	181	0.19	39	0.16
2	10	15	6	10	0.16	188	0.25	45	0.16
2	10	15	7	8	0.19	138	0.22	36	0.16
2	10	15	8	12	0.19	157	0.22	41	0.15
2	10	15	9	12	0.19	184	0.20	44	0.23
2	10	15	10	10	0.16	175	0.17	45	0.17
2	10	15	11	12	0.18	161	0.16	38	0.15
2	10	15	12	11	0.17	190	0.19	48	0.17
2	10	15	13	11	0.19	163	0.26	40	0.19
2	10	15	14	14	0.17	215	0.15	44	0.16
2	10	15	15	14	0.17	185	0.16	41	0.16
2	10	15	16	10	0.20	183	0.25	40	0.21
2	10	15	17	10	0.19	143	0.22	36	0.15
2	10	15	18	9	0.20	175	0.19	44	0.19
2	10	15	19	11	0.16	190	0.19	45	0.20
2	10	15	20	11	0.16	215	0.17	53	0.17
2	15	15	1	20	0.36	325	0.49	60	0.46
2	15	15	2	14	0.50	402	0.58	63	0.29
2	15	15	3	13	0.50	348	0.67	54	0.47
2	15	15	4	19	0.33	358	0.55	65	0.50
2	15	15	5	13	0.53	332	0.64	57	0.30
2	15	15	6	17	0.32	422	0.45	72	0.36
2	15	15	7	15	0.31	399	0.50	67	0.30
2	15	15	8	18	0.44	352	0.87	60	0.53
2	15	15	9	11	0.42	361	0.65	63	0.43
2	15	15	10	18	0.31	348	0.72	59	0.47
2	15	15	11	17	0.31	426	0.75	61	0.52
2	15	15	12	18	0.31	348	0.36	55	0.36
2	15	15	13	18	0.39	459	0.79	71	0.39
2	15	15	14	15	0.37	392	0.29	59	0.29
2	15	15	15	15	0.33	399	0.34	67	0.31
2	15	15	16	17	0.29	346	0.76	64	0.36
2	15	15	17	23	0.30	378	0.54	60	0.53
2	15	15	18	15	0.32	404	0.54	66	0.31
2	15	15	19	16	0.38	416	0.50	72	0.36
2	15	15	20	18	0.50	397	0.39	74	0.36

Table B.4. (Continued).

M	J	T	V	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
3	15	15	1	12	0.25	213	0.30	41	0.21
3	15	15	2	11	0.25	182	0.23	33	0.25
3	15	15	3	13	0.23	261	0.27	47	0.23
3	15	15	4	12	0.21	186	0.31	39	0.24
3	15	15	5	12	0.22	193	0.31	44	0.27
3	15	15	6	11	0.25	204	0.32	35	0.25
3	15	15	7	10	0.22	192	0.32	35	0.23
3	15	15	8	16	0.31	251	0.31	42	0.25
3	15	15	9	10	0.22	231	0.37	44	0.27
3	15	15	10	12	0.23	227	0.29	42	0.22
3	15	15	11	12	0.28	198	0.25	40	0.23
3	15	15	12	12	0.23	195	0.36	42	0.24
3	15	15	13	12	0.25	193	0.28	40	0.22
3	15	15	14	19	0.24	204	0.28	42	0.22
3	15	15	15	12	0.34	189	0.28	41	0.22
3	15	15	16	11	0.20	220	0.25	40	0.24
3	15	15	17	12	0.20	208	0.26	40	0.22
3	15	15	18	11	0.23	189	0.28	36	0.21
3	15	15	19	12	0.22	209	0.30	46	0.25
3	15	15	20	10	0.21	171	0.28	36	0.25
3	20	15	1	20	0.49	340	0.89	51	0.43
3	20	15	2	17	0.38	287	0.81	50	0.37
3	20	15	3	15	0.52	393	0.67	61	0.56
3	20	15	4	14	0.47	304	0.80	55	0.50
3	20	15	5	18	0.37	395	0.93	62	0.64
3	20	15	6	14	0.36	359	0.87	53	0.42
3	20	15	7	16	0.38	407	1.04	61	0.68
3	20	15	8	16	0.83	313	0.6	53	0.42
3	20	15	9	20	0.44	314	0.72	47	0.64
3	20	15	10	14	0.63	308	0.58	47	0.39
3	20	15	11	15	0.35	330	0.91	51	0.42
3	20	15	12	22	0.83	383	0.47	52	0.56
3	20	15	13	19	0.73	375	0.66	53	0.47
3	20	15	14	20	0.39	336	0.39	49	0.42
3	20	15	15	16	0.51	299	0.86	52	0.34
3	20	15	16	14	0.43	324	0.40	48	0.52
3	20	15	17	16	0.41	315	0.71	44	0.44
3	20	15	18	15	0.36	416	0.93	55	0.45
3	20	15	19	18	0.46	424	0.62	49	0.80
3	20	15	20	14	0.46	329	0.64	55	0.37

Table B.4. (Continued).

M	J	T	V	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
3	15	20	1	25	0.24	296	0.24	59	0.21
3	15	20	2	17	0.21	219	0.35	46	0.31
3	15	20	3	18	0.28	222	0.38	45	0.23
3	15	20	4	19	0.20	178	0.22	39	0.25
3	15	20	5	22	0.35	241	0.30	48	0.26
3	15	20	6	19	0.23	193	0.33	44	0.20
3	15	20	7	18	0.25	249	0.25	42	0.31
3	15	20	8	16	0.22	301	0.24	63	0.22
3	15	20	9	17	0.23	235	0.31	44	0.22
3	15	20	10	21	0.22	262	0.32	58	0.27
3	15	20	11	20	0.30	261	0.26	47	0.22
3	15	20	12	16	0.24	197	0.25	36	0.20
3	15	20	13	10	0.21	215	0.25	42	0.26
3	15	20	14	23	0.22	283	0.36	52	0.23
3	15	20	15	18	0.27	265	0.28	45	0.33
3	15	20	16	17	0.22	247	0.29	45	0.28
3	15	20	17	20	0.22	211	0.28	45	0.22
3	15	20	18	17	0.20	230	0.26	47	0.25
3	15	20	19	19	0.28	296	0.33	54	0.26
3	15	20	20	17	0.22	233	0.35	42	0.27
3	20	20	1	30	0.68	473	0.81	65	0.55
3	20	20	2	24	0.64	487	0.69	71	0.42
3	20	20	3	28	0.41	431	0.90	57	0.61
3	20	20	4	24	0.50	400	0.74	62	0.42
3	20	20	5	27	0.41	428	0.81	70	0.55
3	20	20	6	19	0.59	496	0.64	72	0.39
3	20	20	7	22	0.39	439	0.70	65	0.53
3	20	20	8	26	0.42	439	0.89	67	0.55
3	20	20	9	27	0.38	438	0.56	67	0.42
3	20	20	10	23	0.55	435	0.56	61	0.54
3	20	20	11	23	0.39	392	0.95	56	0.78
3	20	20	12	25	0.37	359	0.89	56	0.61
3	20	20	13	27	0.39	441	1.04	58	0.64
3	20	20	14	20	0.49	376	0.74	53	0.53
3	20	20	15	29	0.41	416	0.86	62	0.52
3	20	20	16	22	0.37	421	0.62	64	0.53
3	20	20	17	27	0.42	391	0.77	55	0.49
3	20	20	18	27	0.51	439	0.68	66	0.49
3	20	20	19	26	0.41	480	0.83	68	0.59
3	20	20	20	19	0.47	408	0.71	50	0.52



Table B.5. Overall results of the local search for SSP-NPM-II.

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
4	40	60	1	l	s	56	2.43	1300	15.48	101	2.35
4	40	60	2	l	s	57	1.98	1395	19.27	120	2.13
4	40	60	3	l	s	53	1.92	1251	16.43	121	2.00
4	40	60	4	l	s	53	1.87	1250	17.63	115	2.02
4	40	60	5	l	s	58	2.00	1098	12.32	114	1.99
4	40	60	6	l	s	65	2.05	1083	15.51	91	2.08
4	40	60	7	l	s	61	2.05	1075	12.37	90	2.09
4	40	60	8	l	s	60	2.02	1493	14.47	126	2.13
4	40	60	9	l	s	59	2.08	1269	13.68	132	2.06
4	40	60	10	l	s	63	2.07	1352	15.59	132	2.13
4	40	60	11	l	s	55	1.97	1249	15.02	121	2.09
4	40	60	12	l	s	54	2.01	1334	11.47	136	2.06
4	40	60	13	l	s	53	2.08	1403	10.67	128	2.02
4	40	60	14	l	s	57	1.95	1330	13.13	124	2.05
4	40	60	15	l	s	52	2.00	1248	10.01	110	2.05
4	40	60	16	l	s	58	2.05	1355	12.16	116	2.23
4	40	60	17	l	s	61	2.05	1189	13.96	107	2.14
4	40	60	18	l	s	57	2.85	1405	11.93	127	2.45
4	40	60	19	l	s	49	1.97	1115	13.68	114	2.02
4	40	60	20	l	s	55	2.04	1486	15.29	139	2.08
4	40	60	1	l	d	373	3.32	8228	8.73	555	2.55
4	40	60	2	l	d	368	5.22	7464	9.47	444	2.77
4	40	60	3	l	d	396	4.96	8723	6.32	552	2.82
4	40	60	4	l	d	354	4.91	8182	6.98	490	3.31
4	40	60	5	l	d	386	3.91	8212	5.99	540	3.00
4	40	60	6	l	d	357	3.28	7221	5.07	511	3.13
4	40	60	7	l	d	368	5.33	7463	9.17	446	7.83
4	40	60	8	l	d	343	4.76	7172	7.92	402	2.98
4	40	60	9	l	d	329	6.55	8122	7.93	508	2.26
4	40	60	10	l	d	362	5.42	7703	8.78	440	2.78
4	40	60	11	l	d	377	2.70	8672	7.41	570	3.27
4	40	60	12	l	d	347	3.01	7081	6.64	431	2.58
4	40	60	13	l	d	365	3.25	7437	4.87	455	2.54
4	40	60	14	l	d	375	6.04	8567	7.75	616	2.36
4	40	60	15	l	d	365	5.39	7689	4.75	426	2.47
4	40	60	16	l	d	357	6.12	8009	5.86	489	3.13
4	40	60	17	l	d	325	6.62	6721	7.52	398	3.00
4	40	60	18	l	d	362	3.48	7689	7.77	427	2.21
4	40	60	19	l	d	387	2.94	8949	8.14	594	2.47
4	40	60	20	l	d	355	9.09	7154	5.66	414	2.22
4	40	60	1	h	s	63	2.00	2296	22.92	214	2.03
4	40	60	2	h	s	50	2.00	1594	14.96	166	1.92
4	40	60	3	h	s	59	1.97	1853	19.32	201	2.03
4	40	60	4	h	s	62	2.08	1958	16.94	214	1.95
4	40	60	5	h	s	48	1.88	2035	16.99	200	2.05
4	40	60	6	h	s	59	1.98	1853	14.97	188	2.00
4	40	60	7	h	s	53	1.95	1879	15.26	197	2.08
4	40	60	8	h	s	56	1.98	2040	18.22	236	2.04
4	40	60	9	h	s	52	1.95	1767	16.67	201	1.99
4	40	60	10	h	s	54	1.96	1668	17.06	171	2.01
4	40	60	11	h	s	46	2.00	1727	17.83	179	2.05
4	40	60	12	h	s	43	1.83	1594	16.28	170	1.94
4	40	60	13	h	s	53	2.05	1850	11.83	184	2.01
4	40	60	14	h	s	54	2.02	1766	21.53	175	2.11
4	40	60	15	h	s	46	2.05	1709	19.02	183	2.02
4	40	60	16	h	s	54	1.94	1663	16.44	186	1.96
4	40	60	17	h	s	55	2.00	1705	19.25	168	2.07
4	40	60	18	h	s	55	2.02	1718	16.53	175	2.07
4	40	60	19	h	s	58	1.97	1902	22.28	200	2.08
4	40	60	20	h	s	49	1.94	1713	18.50	176	1.97

Table B.5. (Continued).

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
4	40	60	1	h	d	371	3.84	14057	5.77	903	2.21
4	40	60	2	h	d	353	4.48	14001	5.23	839	3.67
4	40	60	3	h	d	343	5.26	12238	6.38	719	2.31
4	40	60	4	h	d	364	5.42	15414	3.05	1087	2.42
4	40	60	5	h	d	373	3.52	14882	6.36	834	2.36
4	40	60	6	h	d	373	4.28	14521	10.46	1014	3.98
4	40	60	7	h	d	342	4.71	13549	5.85	998	3.02
4	40	60	8	h	d	368	7.83	13106	11.72	738	3.33
4	40	60	9	h	d	356	4.06	13208	7.13	784	2.56
4	40	60	10	h	d	346	3.34	13068	7.06	761	3.18
4	40	60	11	h	d	375	4.42	14984	7.94	1122	8.19
4	40	60	12	h	d	367	3.25	13627	3.89	750	2.25
4	40	60	13	h	d	362	4.21	12684	4.47	710	2.82
4	40	60	14	h	d	336	4.82	11404	9.32	641	2.98
4	40	60	15	h	d	319	5.50	11893	5.81	687	3.07
4	40	60	16	h	d	374	3.00	12514	9.81	742	2.24
4	40	60	17	h	d	360	4.86	12929	6.95	855	2.93
4	40	60	18	h	d	348	5.37	12499	13.04	731	3.42
4	40	60	19	h	d	331	4.49	12310	5.38	688	3.08
4	40	60	20	h	d	408	2.17	13937	7.82	811	2.69
4	60	60	1	l	s	89	10.56	3342	76.61	177	11.72
4	60	60	2	l	s	81	7.16	2921	96.47	157	7.44
4	60	60	3	l	s	84	9.86	3253	104.98	172	7.05
4	60	60	4	l	s	83	8.25	3151	142.44	170	8.57
4	60	60	5	l	s	86	7.72	3283	101.39	187	8.01
4	60	60	6	l	s	84	7.41	3087	103.73	171	10.41
4	60	60	7	l	s	84	9.48	3120	105.42	183	8.17
4	60	60	8	l	s	82	8.99	3465	114.56	176	8.53
4	60	60	9	l	s	90	7.33	3307	96.49	164	8.01
4	60	60	10	l	s	79	6.49	2725	98.62	164	7.33
4	60	60	11	l	s	82	8.25	3051	97.43	178	7.36
4	60	60	12	l	s	89	8.72	3110	82.75	161	7.37
4	60	60	13	l	s	82	8.17	3200	95.64	192	8.65
4	60	60	14	l	s	92	13.89	3517	87.69	187	9.68
4	60	60	15	l	s	88	15.39	3706	85.09	197	9.88
4	60	60	16	l	s	83	9.94	3213	70.26	172	8.40
4	60	60	17	l	s	81	7.89	3199	82.70	182	8.54
4	60	60	18	l	s	91	8.61	2860	93.14	147	8.75
4	60	60	19	l	s	87	7.06	2942	115.74	150	11.73
4	60	60	20	l	s	79	8.31	3486	100.21	180	8.92
4	60	60	1	l	d	570	10.57	18311	24.06	641	11.44
4	60	60	2	l	d	573	18.56	19997	19.78	735	16.29
4	60	60	3	l	d	559	19.25	16594	18.94	646	8.85
4	60	60	4	l	d	543	19.09	17078	46.15	624	8.26
4	60	60	5	l	d	517	16.46	15132	38.10	589	7.89
4	60	60	6	l	d	545	16.15	17435	25.11	654	9.91
4	60	60	7	l	d	545	21.92	17139	35.00	621	12.95
4	60	60	8	l	d	554	19.00	19331	34.50	706	8.80
4	60	60	9	l	d	542	18.52	14850	30.13	538	10.64
4	60	60	10	l	d	554	20.53	16762	30.50	646	8.65
4	60	60	11	l	d	582	15.91	20016	28.63	767	12.86
4	60	60	12	l	d	553	14.44	17550	47.49	695	9.28
4	60	60	13	l	d	543	25.50	17565	45.44	628	10.19
4	60	60	14	l	d	534	19.79	15777	32.29	585	9.04
4	60	60	15	l	d	576	25.09	15881	19.86	614	7.85
4	60	60	16	l	d	602	16.95	17643	34.59	673	8.36
4	60	60	17	l	d	575	19.59	18587	23.83	875	13.02
4	60	60	18	l	d	549	23.13	16911	26.81	656	8.45
4	60	60	19	l	d	550	18.48	19082	25.23	749	7.66
4	60	60	20	l	d	554	15.41	18750	40.00	909	7.98

Table B.5. (Continued).

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
4	60	60	1	h	s	96	7.33	4938	106.50	309	8.70
4	60	60	2	h	s	80	7.61	4499	151.00	282	8.72
4	60	60	3	h	s	93	9.69	4996	107.21	288	10.48
4	60	60	4	h	s	87	6.78	4715	124.30	275	11.70
4	60	60	5	h	s	90	14.64	4975	83.55	280	10.97
4	60	60	6	h	s	90	10.78	5030	146.92	286	9.81
4	60	60	7	h	s	87	10.49	4876	105.53	311	8.04
4	60	60	8	h	s	85	7.64	4992	138.95	314	7.32
4	60	60	9	h	s	85	8.10	4417	105.87	258	7.92
4	60	60	10	h	s	86	8.48	4805	88.57	279	8.36
4	60	60	11	h	s	75	7.67	4441	114.74	272	8.01
4	60	60	12	h	s	92	12.09	5344	75.85	264	8.58
4	60	60	13	h	s	89	10.41	4888	128.87	297	8.70
4	60	60	14	h	s	91	7.47	4586	127.81	287	7.52
4	60	60	15	h	s	80	7.48	4420	103.61	309	7.19
4	60	60	16	h	s	86	8.13	4981	124.66	283	11.24
4	60	60	17	h	s	88	10.02	4977	71.31	255	8.42
4	60	60	18	h	s	91	10.25	4118	104.36	246	7.94
4	60	60	19	h	s	86	11.37	5102	88.64	312	7.55
4	60	60	20	h	s	87	12.22	4625	116.06	247	8.96
4	60	60	1	h	d	586	20.36	32133	37.96	1297	9.43
4	60	60	2	h	d	588	17.87	29054	44.79	1223	11.96
4	60	60	3	h	d	572	20.58	32822	46.84	1494	15.49
4	60	60	4	h	d	551	15.43	33421	27.72	1210	8.87
4	60	60	5	h	d	552	15.13	30481	16.69	1094	8.55
4	60	60	6	h	d	556	25.61	29865	38.78	1179	7.84
4	60	60	7	h	d	563	10.33	31744	30.61	1266	10.93
4	60	60	8	h	d	545	22.31	30878	41.22	1104	7.58
4	60	60	9	h	d	560	28.34	32169	28.66	1187	8.61
4	60	60	10	h	d	571	8.45	33573	36.47	1384	9.92
4	60	60	11	h	d	520	16.13	28835	49.72	1143	9.38
4	60	60	12	h	d	549	22.22	29847	18.92	1140	7.65
4	60	60	13	h	d	534	13.31	31807	22.11	1188	11.04
4	60	60	14	h	d	570	17.03	28715	36.43	1215	8.68
4	60	60	15	h	d	561	25.45	31136	36.79	1160	9.26
4	60	60	16	h	d	566	16.90	32220	19.03	1217	10.92
4	60	60	17	h	d	510	19.67	29530	34.61	1138	13.28
4	60	60	18	h	d	545	18.64	30093	36.60	1108	9.76
4	60	60	19	h	d	533	15.45	31931	26.82	1177	9.77
4	60	60	20	h	d	552	14.25	31292	29.06	1080	14.50
4	40	120	1	l	s	126	2.20	2203	21.84	191	2.25
4	40	120	2	l	s	120	2.22	2195	14.49	205	2.30
4	40	120	3	l	s	123	2.17	1898	17.95	161	2.25
4	40	120	4	l	s	113	2.15	2049	10.30	167	2.20
4	40	120	5	l	s	123	2.19	2470	19.45	196	2.28
4	40	120	6	l	s	126	2.19	1888	21.55	155	2.32
4	40	120	7	l	s	127	2.20	2172	19.64	186	2.27
4	40	120	8	l	s	126	2.29	2424	11.58	184	2.29
4	40	120	9	l	s	127	2.16	2434	12.96	191	2.24
4	40	120	10	l	s	126	2.23	2436	11.42	203	2.30
4	40	120	11	l	s	132	2.25	2090	14.09	179	2.21
4	40	120	12	l	s	136	2.24	2329	23.70	173	2.39
4	40	120	13	l	s	127	2.17	2014	18.74	163	2.32
4	40	120	14	l	s	132	2.30	2025	15.63	168	2.28
4	40	120	15	l	s	119	2.19	1996	18.60	175	2.28
4	40	120	16	l	s	126	2.22	2358	13.23	193	2.25
4	40	120	17	l	s	113	2.18	2268	21.45	188	2.32
4	40	120	18	l	s	129	2.36	2567	18.50	195	2.30
4	40	120	19	l	s	127	2.18	2442	20.44	225	2.26
4	40	120	20	l	s	115	2.28	2445	17.16	192	2.27

Table B.5. (Continued).

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
4	40	120	1	l	d	587	7.02	11604	6.12	633	3.31
4	40	120	2	l	d	674	3.91	12782	7.00	860	3.68
4	40	120	3	l	d	608	5.32	12061	5.34	777	3.54
4	40	120	4	l	d	621	3.27	11108	5.83	850	3.47
4	40	120	5	l	d	643	4.17	12353	5.09	758	3.81
4	40	120	6	l	d	698	5.88	14025	9.63	943	6.66
4	40	120	7	l	d	653	4.43	14275	5.58	985	2.44
4	40	120	8	l	d	671	5.43	15087	6.72	970	3.22
4	40	120	9	l	d	651	2.72	11768	5.60	800	2.24
4	40	120	10	l	d	600	5.02	11976	6.83	746	4.80
4	40	120	11	l	d	676	2.51	14577	2.25	972	3.31
4	40	120	12	l	d	675	3.48	14990	6.15	1266	4.78
4	40	120	13	l	d	655	7.40	14211	5.64	930	2.55
4	40	120	14	l	d	652	6.62	12342	10.33	854	3.99
4	40	120	15	l	d	672	3.20	13726	3.36	991	2.57
4	40	120	16	l	d	643	3.19	16305	2.69	1280	4.18
4	40	120	17	l	d	614	3.53	13342	6.04	698	3.50
4	40	120	18	l	d	644	4.27	12836	6.56	974	4.32
4	40	120	19	l	d	643	4.25	13374	4.42	802	2.72
4	40	120	20	l	d	672	4.18	14140	4.72	888	3.48
4	40	120	1	h	s	129	2.22	3361	20.70	297	2.33
4	40	120	2	h	s	121	2.11	3371	19.23	307	2.21
4	40	120	3	h	s	121	2.12	4026	20.33	373	2.28
4	40	120	4	h	s	124	2.22	3703	16.42	313	2.24
4	40	120	5	h	s	130	2.18	3969	13.51	343	2.23
4	40	120	6	h	s	104	2.06	3104	20.46	285	2.28
4	40	120	7	h	s	131	2.20	3598	12.80	314	2.23
4	40	120	8	h	s	122	2.17	3426	16.52	300	2.17
4	40	120	9	h	s	128	2.17	3977	12.71	324	2.28
4	40	120	10	h	s	115	2.15	3058	16.93	286	2.14
4	40	120	11	h	s	117	2.16	3650	13.82	312	2.28
4	40	120	12	h	s	128	2.29	3999	21.04	297	2.31
4	40	120	13	h	s	124	2.14	3882	14.67	301	2.21
4	40	120	14	h	s	118	2.19	4011	19.63	316	2.27
4	40	120	15	h	s	121	2.16	3301	16.38	328	2.18
4	40	120	16	h	s	125	2.24	3380	25.64	302	2.31
4	40	120	17	h	s	110	2.17	2918	16.19	270	2.20
4	40	120	18	h	s	128	2.12	3343	15.50	328	2.17
4	40	120	19	h	s	121	2.11	3418	21.98	291	2.26
4	40	120	20	h	s	129	2.25	3710	18.02	318	2.29
4	40	120	1	h	d	673	7.90	26762	9.37	1887	5.75
4	40	120	2	h	d	665	2.87	25881	3.62	1840	2.47
4	40	120	3	h	d	661	4.13	24462	7.76	1772	4.36
4	40	120	4	h	d	667	3.57	25057	6.69	2018	2.98
4	40	120	5	h	d	683	6.26	28328	18.37	2189	2.95
4	40	120	6	h	d	647	2.75	23139	5.03	1860	3.33
4	40	120	7	h	d	659	2.56	25479	5.75	1847	2.31
4	40	120	8	h	d	645	4.85	23895	6.51	1675	2.77
4	40	120	9	h	d	567	4.00	20165	4.38	1132	2.90
4	40	120	10	h	d	613	3.21	21240	5.85	1164	2.47
4	40	120	11	h	d	643	3.72	26034	5.98	1690	2.81
4	40	120	12	h	d	665	3.11	24046	5.36	1647	2.36
4	40	120	13	h	d	629	4.75	22957	5.36	1425	2.35
4	40	120	14	h	d	608	4.75	22253	4.47	1388	2.19
4	40	120	15	h	d	664	2.78	24626	3.42	1721	3.05
4	40	120	16	h	d	649	4.72	23869	6.92	1802	2.82
4	40	120	17	h	d	683	3.58	26234	5.01	1700	2.75
4	40	120	18	h	d	597	4.89	21153	7.45	1195	2.89
4	40	120	19	h	d	675	2.57	23894	3.29	1508	2.90
4	40	120	20	h	d	620	3.61	22060	11.94	1524	3.26

Table B.5. (Continued).

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
4	60	120	1	l	s	201	8.18	6012	102.34	308	8.94
4	60	120	2	l	s	183	8.92	5976	113.00	277	8.02
4	60	120	3	l	s	200	7.77	5475	118.44	255	8.12
4	60	120	4	l	s	196	7.75	5189	96.56	254	8.20
4	60	120	5	l	s	183	9.19	5021	80.70	243	12.95
4	60	120	6	l	s	193	7.86	5794	117.11	295	8.82
4	60	120	7	l	s	200	8.20	6027	73.22	284	8.36
4	60	120	8	l	s	176	9.80	5717	148.00	303	8.11
4	60	120	9	l	s	180	7.70	4702	137.64	236	7.77
4	60	120	10	l	s	189	7.97	5260	142.58	271	8.69
4	60	120	11	l	s	190	9.80	5085	101.92	233	8.05
4	60	120	12	l	s	185	7.61	5931	120.28	303	7.98
4	60	120	13	l	s	204	9.33	6256	109.61	283	8.18
4	60	120	14	l	s	184	8.02	5567	133.49	249	9.61
4	60	120	15	l	s	199	11.50	6106	132.31	294	8.89
4	60	120	16	l	s	196	8.09	4540	123.06	221	7.97
4	60	120	17	l	s	186	8.01	5437	111.23	253	8.02
4	60	120	18	l	s	204	10.03	6630	90.29	315	9.54
4	60	120	19	l	s	182	9.65	5358	114.80	250	8.14
4	60	120	20	l	s	202	8.43	5437	102.31	244	8.05
4	60	120	1	l	d	991	13.70	29697	22.81	1167	10.61
4	60	120	2	l	d	1010	8.37	32379	23.21	1383	7.61
4	60	120	3	l	d	998	16.94	33054	34.48	1612	22.51
4	60	120	4	l	d	1047	8.86	30257	32.69	1444	14.43
4	60	120	5	l	d	961	17.97	32176	30.37	1232	9.92
4	60	120	6	l	d	983	19.79	28443	22.35	1104	8.78
4	60	120	7	l	d	987	15.69	25644	14.26	1020	9.89
4	60	120	8	l	d	991	14.46	27382	29.20	1191	11.17
4	60	120	9	l	d	1011	10.01	33112	23.87	1499	20.01
4	60	120	10	l	d	928	27.38	23935	12.16	824	10.28
4	60	120	11	l	d	1036	16.06	28961	39.10	1236	18.30
4	60	120	12	l	d	911	17.82	24602	47.40	927	7.72
4	60	120	13	l	d	1014	23.26	32606	25.18	1642	9.11
4	60	120	14	l	d	995	25.69	29086	17.86	1379	10.55
4	60	120	15	l	d	1017	20.50	34247	22.30	1836	11.34
4	60	120	16	l	d	894	10.74	24883	17.25	888	10.56
4	60	120	17	l	d	1018	12.06	33145	32.97	1543	10.17
4	60	120	18	l	d	985	10.85	29137	41.63	1020	8.98
4	60	120	19	l	d	1012	12.14	28305	29.47	1322	7.81
4	60	120	20	l	d	1040	19.72	36000	42.49	1937	21.92
4	60	120	1	h	s	188	11.09	9622	145.92	441	8.01
4	60	120	2	h	s	199	8.22	9819	141.31	494	10.89
4	60	120	3	h	s	199	7.86	10235	127.86	475	8.30
4	60	120	4	h	s	184	8.36	9138	128.94	464	8.02
4	60	120	5	h	s	197	8.90	10243	108.59	516	7.97
4	60	120	6	h	s	193	10.39	9856	143.74	454	10.20
4	60	120	7	h	s	195	12.45	8877	111.58	448	9.55
4	60	120	8	h	s	192	8.35	9217	143.17	452	7.96
4	60	120	9	h	s	190	10.22	8652	120.68	416	9.68
4	60	120	10	h	s	187	9.46	9526	126.25	446	9.33
4	60	120	11	h	s	181	7.72	9258	131.33	432	8.74
4	60	120	12	h	s	177	12.62	9013	140.40	452	8.26
4	60	120	13	h	s	185	8.57	8455	114.61	421	7.84
4	60	120	14	h	s	192	8.23	8978	88.45	407	12.91
4	60	120	15	h	s	185	8.82	10406	117.42	464	9.34
4	60	120	16	h	s	193	7.58	9363	120.31	469	7.93
4	60	120	17	h	s	191	7.57	9141	169.25	457	8.96
4	60	120	18	h	s	194	9.50	9223	144.17	445	8.53
4	60	120	19	h	s	182	7.50	9190	106.75	436	7.98
4	60	120	20	h	s	191	8.87	9558	137.98	462	8.99

Table B.5. (Continued).

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
4	60	120	1	h	d	1001	8.72	59605	12.36	2772	9.25
4	60	120	2	h	d	1016	20.80	54665	22.30	2350	7.89
4	60	120	3	h	d	984	16.19	50107	23.72	2164	12.19
4	60	120	4	h	d	1014	9.86	51769	9.75	2148	7.89
4	60	120	5	h	d	943	27.34	51393	19.94	1835	7.89
4	60	120	6	h	d	1032	9.13	67196	38.37	3787	9.21
4	60	120	7	h	d	1054	14.70	55654	22.56	2699	8.79
4	60	120	8	h	d	1038	25.97	54883	28.75	2089	9.75
4	60	120	9	h	d	949	13.26	48949	17.92	2067	7.69
4	60	120	10	h	d	967	13.46	53925	18.41	1972	11.48
4	60	120	11	h	d	996	14.78	57573	20.66	2497	12.29
4	60	120	12	h	d	988	17.89	51739	33.83	1978	8.36
4	60	120	13	h	d	1008	15.29	56371	16.72	2506	7.74
4	60	120	14	h	d	992	20.59	55243	20.70	2409	10.23
4	60	120	15	h	d	1025	10.89	58848	20.93	2995	10.89
4	60	120	16	h	d	1016	14.60	55503	46.75	2396	9.34
4	60	120	17	h	d	971	18.16	51202	36.57	1932	7.60
4	60	120	18	h	d	1010	12.65	54208	41.39	2720	12.14
4	60	120	19	h	d	1014	15.56	56887	21.43	2574	12.59
4	60	120	20	h	d	952	14.53	50057	20.86	2101	7.83
6	80	120	1	l	s	268	14.89	6503	172.85	260	15.64
6	80	120	2	l	s	245	13.39	6148	253.10	256	13.19
6	80	120	3	l	s	251	16.83	5813	153.69	233	14.68
6	80	120	4	l	s	238	12.23	6425	220.46	275	14.28
6	80	120	5	l	s	252	16.79	6421	148.90	240	14.83
6	80	120	6	l	s	256	14.84	6288	158.67	254	17.82
6	80	120	7	l	s	249	12.73	6065	183.05	249	15.45
6	80	120	8	l	s	262	16.28	7453	156.62	285	12.86
6	80	120	9	l	s	246	12.90	5490	172.68	243	16.02
6	80	120	10	l	s	255	12.92	6014	230.03	255	12.84
6	80	120	11	l	s	258	14.79	6493	149.03	277	12.84
6	80	120	12	l	s	259	14.64	6390	170.09	258	19.66
6	80	120	13	l	s	264	12.74	6434	174.25	267	12.86
6	80	120	14	l	s	216	15.64	6479	166.35	309	15.68
6	80	120	15	l	s	242	15.77	6072	144.76	297	12.94
6	80	120	16	l	s	243	14.28	5593	169.82	257	12.52
6	80	120	17	l	s	250	18.91	6356	196.98	267	15.05
6	80	120	18	l	s	268	15.02	7121	139.92	306	13.34
6	80	120	19	l	s	267	13.43	5825	209.18	248	14.64
6	80	120	20	l	s	257	12.72	6567	127.56	254	13.27
6	80	120	1	l	d	1630	27.45	39604	33.48	1068	14.61
6	80	120	2	l	d	1556	36.23	40420	52.21	1100	14.90
6	80	120	3	l	d	1691	34.86	43444	27.20	1313	15.00
6	80	120	4	l	d	1647	31.56	40066	53.97	1145	20.34
6	80	120	5	l	d	1608	32.01	42270	67.73	1121	14.53
6	80	120	6	l	d	1648	28.51	39606	57.24	1455	17.81
6	80	120	7	l	d	1517	25.74	41357	45.98	1209	14.61
6	80	120	8	l	d	1487	26.88	38561	83.68	1123	14.55
6	80	120	9	l	d	1650	34.16	37242	53.24	1215	13.11
6	80	120	10	l	d	1604	33.14	39249	53.97	1052	15.50
6	80	120	11	l	d	1691	30.91	47583	36.75	1404	12.02
6	80	120	12	l	d	1585	21.53	39557	24.44	1368	14.06
6	80	120	13	l	d	1586	31.66	43218	73.03	1380	15.46
6	80	120	14	l	d	1611	30.38	43416	38.51	1659	13.09
6	80	120	15	l	d	1546	21.34	39741	35.40	1087	15.04
6	80	120	16	l	d	1514	23.03	38621	54.68	1132	16.35
6	80	120	17	l	d	1628	40.64	40915	36.95	1111	14.10
6	80	120	18	l	d	1559	32.94	41998	69.58	1119	12.56
6	80	120	19	l	d	1583	25.22	40258	53.19	1071	12.89
6	80	120	20	l	d	1669	25.86	45454	47.83	1565	17.89

Table B.5. (Continued).

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
6	80	120	1	h	s	265	14.41	9952	222.86	441	14.36
6	80	120	2	h	s	255	14.61	10602	231.42	446	14.56
6	80	120	3	h	s	254	13.57	10772	213.28	448	17.11
6	80	120	4	h	s	258	13.47	10872	223.84	469	12.94
6	80	120	5	h	s	244	12.89	10286	186.32	431	14.76
6	80	120	6	h	s	267	15.81	10812	154.47	498	12.85
6	80	120	7	h	s	255	14.96	11202	185.09	445	13.01
6	80	120	8	h	s	262	12.34	10730	188.53	433	14.70
6	80	120	9	h	s	240	12.33	9778	207.61	418	14.97
6	80	120	10	h	s	265	20.13	11142	156.65	448	12.85
6	80	120	11	h	s	243	18.22	10208	159.63	390	13.26
6	80	120	12	h	s	265	11.84	11150	258.67	511	13.01
6	80	120	13	h	s	252	16.34	9868	177.98	442	13.41
6	80	120	14	h	s	270	13.17	10034	198.01	443	15.26
6	80	120	15	h	s	265	12.61	10846	182.58	466	13.94
6	80	120	16	h	s	244	19.26	10827	210.41	468	13.47
6	80	120	17	h	s	247	15.69	10315	169.37	455	14.89
6	80	120	18	h	s	246	17.14	10523	194.70	446	12.72
6	80	120	19	h	s	251	13.53	10047	216.49	461	12.58
6	80	120	20	h	s	228	18.19	10987	199.43	500	15.08
6	80	120	1	h	d	1597	23.19	74934	31.99	2169	16.59
6	80	120	2	h	d	1618	30.98	74507	44.66	2057	13.55
6	80	120	3	h	d	1581	30.45	74756	23.64	2159	12.61
6	80	120	4	h	d	1599	19.36	75722	54.51	2040	14.17
6	80	120	5	h	d	1665	17.85	80299	24.47	2327	14.64
6	80	120	6	h	d	1572	26.42	78576	42.50	2334	12.41
6	80	120	7	h	d	1665	32.22	80805	48.66	2838	19.36
6	80	120	8	h	d	1650	37.71	78015	75.82	2590	17.03
6	80	120	9	h	d	1559	35.53	75031	40.91	2011	17.11
6	80	120	10	h	d	1582	28.75	74724	74.19	2169	17.25
6	80	120	11	h	d	1608	38.87	77771	30.22	2304	12.40
6	80	120	12	h	d	1669	31.56	81707	51.45	2638	15.41
6	80	120	13	h	d	1673	32.78	81195	39.71	2720	20.44
6	80	120	14	h	d	1539	25.34	73682	53.70	2045	21.25
6	80	120	15	h	d	1684	26.89	80424	38.72	2825	27.17
6	80	120	16	h	d	1544	31.16	69906	32.38	1846	15.68
6	80	120	17	h	d	1539	28.64	70272	41.19	1917	14.46
6	80	120	18	h	d	1605	20.22	79761	26.80	2140	12.03
6	80	120	19	h	d	1527	26.12	70066	55.93	1886	16.23
6	80	120	20	h	d	1568	32.54	77266	38.30	2335	13.26
6	120	120	1	l	s	392	64.59	15711	952.70	419	44.92
6	120	120	2	l	s	387	93.92	15890	566.61	392	43.62
6	120	120	3	l	s	383	84.44	18184	803.76	472	59.97
6	120	120	4	l	s	409	94.20	17219	756.23	445	62.31
6	120	120	5	l	s	388	77.28	16107	729.33	416	69.27
6	120	120	6	l	s	369	82.61	15891	1170.14	448	53.44
6	120	120	7	l	s	398	93.81	16604	835.14	442	55.45
6	120	120	8	l	s	399	100.35	18040	787.56	463	59.42
6	120	120	9	l	s	394	100.73	16980	886.16	449	60.82
6	120	120	10	l	s	405	111.71	16246	916.19	424	50.61
6	120	120	11	l	s	401	141.02	17628	943.88	444	49.83
6	120	120	12	l	s	390	98.28	17810	962.93	510	43.25
6	120	120	13	l	s	394	154.62	16086	900.44	450	47.72
6	120	120	14	l	s	396	77.47	16798	926.45	487	51.03
6	120	120	15	l	s	412	74.39	18199	936.03	526	50.95
6	120	120	16	l	s	379	157.37	17372	863.29	441	64.11
6	120	120	17	l	s	398	100.44	18259	663.56	484	55.37
6	120	120	18	l	s	358	120.70	15877	736.85	421	50.16
6	120	120	19	l	s	396	154.75	17344	841.70	437	62.14
6	120	120	20	l	s	393	130.84	17182	959.44	444	55.17

Table B.5. (Continued).

M	J	T	V	sw	D	ts	ts time(s)	tft	tft time(s)	fmax	fmax time(s)
6	120	120	1	l	d	2406	99.58	97225	319.98	2243	47.97
6	120	120	2	l	d	2346	120.55	93074	287.10	1685	43.35
6	120	120	3	l	d	2417	72.19	96005	337.35	1809	57.39
6	120	120	4	l	d	2451	102.52	101130	203.96	1833	50.52
6	120	120	5	l	d	2420	75.30	94598	220.56	1678	60.26
6	120	120	6	l	d	2574	80.88	108712	201.44	2388	56.13
6	120	120	7	l	d	2501	89.79	107127	152.25	2210	54.72
6	120	120	8	l	d	2465	93.96	95626	307.32	1656	71.14
6	120	120	9	l	d	2431	108.83	93044	269.81	1676	44.77
6	120	120	10	l	d	2409	124.28	96928	265.01	1753	58.39
6	120	120	11	l	d	2431	108.43	92393	290.75	2118	43.78
6	120	120	12	l	d	2453	109.05	89740	234.08	2397	76.09
6	120	120	13	l	d	2577	95.79	93617	98.23	1900	42.89
6	120	120	14	l	d	2481	76.67	95299	228.78	1687	44.02
6	120	120	15	l	d	2626	81.45	112012	125.33	2198	57.94
6	120	120	16	l	d	2395	85.16	92418	338.51	1651	75.95
6	120	120	17	l	d	2538	88.42	103235	226.85	2067	45.77
6	120	120	18	l	d	2471	99.82	93451	325.98	1918	44.45
6	120	120	19	l	d	2539	101.11	103356	195.49	2212	61.10
6	120	120	20	l	d	2535	95.87	88666	250.07	2119	51.44
6	120	120	1	h	s	407	83.50	30153	854.97	812	56.57
6	120	120	2	h	s	411	105.09	29544	691.58	759	61.38
6	120	120	3	h	s	418	96.76	30272	695.45	842	53.37
6	120	120	4	h	s	399	102.93	28476	1036.53	791	60.67
6	120	120	5	h	s	391	95.92	28327	962.97	835	64.48
6	120	120	6	h	s	399	93.57	29128	977.71	754	69.99
6	120	120	7	h	s	410	117.91	29185	925.55	799	43.83
6	120	120	8	h	s	391	119.86	30087	825.92	732	52.58
6	120	120	9	h	s	364	92.75	27534	884.16	702	49.72
6	120	120	10	h	s	408	95.27	28625	1017.13	833	68.97
6	120	120	11	h	s	400	118.83	27446	745.89	725	56.07
6	120	120	12	h	s	384	98.41	29783	996.61	790	50.02
6	120	120	13	h	s	393	137.17	28988	743.48	801	43.93
6	120	120	14	h	s	406	98.25	27972	834.67	760	56.06
6	120	120	15	h	s	417	103.99	30009	931.69	841	44.39
6	120	120	16	h	s	396	116.46	26949	764.96	741	52.72
6	120	120	17	h	s	413	82.09	28045	774.59	792	44.74
6	120	120	18	h	s	406	143.40	29125	961.45	801	48.06
6	120	120	19	h	s	392	93.20	26699	1029.80	737	53.34
6	120	120	20	h	s	393	88.27	31748	714.70	878	47.80
6	120	120	1	h	d	2315	89.98	169448	236.14	3112	50.87
6	120	120	2	h	d	2353	109.92	164314	247.31	2956	48.19
6	120	120	3	h	d	2452	78.03	171371	268.79	3501	62.39
6	120	120	4	h	d	2360	131.23	163336	297.49	3074	51.58
6	120	120	5	h	d	2414	82.67	172931	258.59	3248	43.55
6	120	120	6	h	d	2483	119.05	181893	247.92	3718	42.92
6	120	120	7	h	d	2347	142.78	166820	362.51	3024	56.55
6	120	120	8	h	d	2339	103.76	169888	303.39	3033	55.14
6	120	120	9	h	d	2435	177.05	167024	220.70	2941	55.70
6	120	120	10	h	d	2322	92.72	165576	370.28	3018	43.67
6	120	120	11	h	d	2426	115.31	174364	284.64	3248	55.81
6	120	120	12	h	d	2485	93.20	182761	189.10	3186	43.36
6	120	120	13	h	d	2495	89.55	178488	207.75	3180	54.64
6	120	120	14	h	d	2358	115.08	168386	265.99	2952	62.17
6	120	120	15	h	d	2428	130.51	174073	289.38	3364	61.24
6	120	120	16	h	d	2600	128.78	178565	204.18	4058	42.63
6	120	120	17	h	d	2471	134.04	177087	272.54	3159	49.09
6	120	120	18	h	d	2414	117.86	178676	185.91	3548	62.76
6	120	120	19	h	d	2500	183.32	186794	228.44	3211	45.33
6	120	120	20	h	d	2447	84.67	177722	200.20	3234	49.69



**Table B.6. Overall results of the ILS (perturbation P.2) for 100 iterations and different values of  $\beta$  for the objective of minimizing the number of tool switches.**

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD
2	10	10	1	4	19.98	0.33	4	20.43	0.33	3	19.67	0.00	4	20.00	0.33
2	10	10	2	4	19.41	1.00	4	19.23	1.00	2	19.18	0.00	4	19.06	1.00
2	10	10	3	3	18.36	0.00	3	19.51	0.00	3	18.75	0.00	3	19.09	0.00
2	10	10	4	3	18.55	0.00	3	18.41	0.00	3	19.01	0.00	3	18.55	0.00
2	10	10	5	2	18.73	0.00	3	19.41	0.50	3	18.92	0.50	2	18.45	0.00
2	10	10	6	3	18.76	0.00	3	18.64	0.00	3	20.42	0.00	3	19.54	0.00
2	10	10	7	4	19.49	0.00	4	19.99	0.00	4	19.85	0.00	4	19.69	0.00
2	10	10	8	4	20.41	0.00	5	21.08	0.25	4	20.83	0.00	5	19.95	0.25
2	10	10	9	3	19.59	0.00	4	19.56	0.33	4	20.09	0.33	4	19.51	0.33
2	10	10	10	4	20.27	0.00	4	20.17	0.00	4	20.56	0.00	4	20.56	0.00
2	10	10	11	4	20.23	0.33	3	19.96	0.00	4	20.11	0.33	4	20.37	0.33
2	10	10	12	5	19.78	0.00	5	20.47	0.00	6	20.50	0.20	5	20.71	0.00
2	10	10	13	4	21.46	0.00	4	20.49	0.00	5	20.38	0.25	4	20.03	0.00
2	10	10	14	8	20.29	1.00	6	20.53	0.50	4	20.74	0.00	4	21.72	0.00
2	10	10	15	2	19.34	0.00	3	18.97	0.50	3	18.63	0.50	3	19.64	0.50
2	10	10	16	4	19.22	0.33	3	19.36	0.00	3	19.13	0.00	3	19.25	0.00
2	10	10	17	3	19.79	0.00	4	19.06	0.33	3	19.55	0.00	4	19.23	0.33
2	10	10	18	5	19.60	1.50	2	19.64	0.00	3	19.56	0.50	3	19.22	0.50
2	10	10	19	5	18.95	0.67	5	19.54	0.67	3	19.20	0.00	3	19.64	0.00
2	10	10	20	3	20.15	0.00	4	20.49	0.33	3	19.94	0.00	4	20.11	0.33
2	15	10	1	6	48.25	0.20	6	47.42	0.20	7	47.46	0.40	5	48.33	0.00
2	15	10	2	6	49.77	0.00	7	48.23	0.17	6	46.78	0.00	6	48.03	0.00
2	15	10	3	8	47.84	0.14	9	47.42	0.29	8	51.79	0.14	7	47.83	0.00
2	15	10	4	8	49.89	0.14	7	46.98	0.00	8	48.14	0.14	7	48.84	0.00
2	15	10	5	7	48.08	0.17	6	48.75	0.00	7	45.83	0.17	7	47.82	0.17
2	15	10	6	8	49.77	0.14	7	51.15	0.00	7	50.07	0.00	7	48.44	0.00
2	15	10	7	8	48.49	0.33	8	48.55	0.33	6	49.05	0.00	6	48.78	0.00
2	15	10	8	6	48.80	0.00	6	50.07	0.00	7	49.62	0.17	7	48.22	0.17
2	15	10	9	9	46.97	0.29	7	49.43	0.00	7	47.13	0.00	7	47.86	0.00
2	15	10	10	5	49.00	0.00	8	48.84	0.60	8	49.42	0.60	5	49.68	0.00
2	15	10	11	6	47.01	0.20	5	48.14	0.00	6	47.92	0.20	6	47.00	0.20
2	15	10	12	8	50.05	0.33	6	49.72	0.00	7	50.29	0.17	8	46.95	0.33
2	15	10	13	8	47.88	0.00	9	49.50	0.13	8	50.44	0.00	9	48.44	0.13
2	15	10	14	6	49.71	0.00	6	47.16	0.00	6	48.40	0.00	8	47.87	0.33
2	15	10	15	8	48.30	0.14	7	49.14	0.00	7	50.95	0.00	8	49.56	0.14
2	15	10	16	7	47.70	0.00	8	48.79	0.14	7	47.84	0.00	8	47.47	0.14
2	15	10	17	5	42.64	0.00	5	44.57	0.00	6	45.49	0.20	5	45.83	0.00
2	15	10	18	8	47.60	0.14	7	47.50	0.00	9	48.81	0.29	7	48.89	0.00
2	15	10	19	7	47.40	0.00	7	48.30	0.00	8	46.95	0.14	7	47.54	0.00
2	15	10	20	8	51.03	0.14	7	50.17	0.00	9	50.76	0.29	9	52.53	0.29

Table B.6. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD
2	10	15	1	10	20.03	0.25	8	20.77	0.00	8	20.51	0.00	8	20.73	0.00
2	10	15	2	8	19.46	0.14	7	19.59	0.00	7	19.80	0.00	7	19.81	0.00
2	10	15	3	8	20.02	0.14	8	20.31	0.14	7	20.27	0.00	9	20.34	0.29
2	10	15	4	9	19.74	0.29	8	19.72	0.14	7	19.22	0.00	8	19.50	0.14
2	10	15	5	6	20.25	0.20	5	20.20	0.00	6	20.00	0.20	5	20.18	0.00
2	10	15	6	7	20.34	0.40	6	19.92	0.20	5	19.88	0.00	6	20.67	0.20
2	10	15	7	7	19.72	0.17	8	19.29	0.33	6	19.55	0.00	6	19.70	0.00
2	10	15	8	10	21.52	0.11	9	21.2	0.00	10	21.67	0.11	9	21.42	0.00
2	10	15	9	10	20.24	0.25	8	20.37	0.00	9	20.48	0.13	9	20.92	0.13
2	10	15	10	7	20.06	0.00	7	19.72	0.00	7	20.03	0.00	7	19.22	0.00
2	10	15	11	8	19.83	0.14	7	19.29	0.00	7	19.78	0.00	8	19.10	0.14
2	10	15	12	8	19.97	0.14	8	20.59	0.14	8	19.91	0.14	7	20.89	0.00
2	10	15	13	8	20.20	0.33	7	20.58	0.17	8	20.54	0.33	6	20.91	0.00
2	10	15	14	8	20.92	0.00	8	20.47	0.00	9	21.18	0.13	9	20.68	0.13
2	10	15	15	9	20.72	0.00	11	21.42	0.22	10	20.94	0.11	9	21.44	0.00
2	10	15	16	8	19.51	0.33	7	20.8	0.17	8	20.13	0.33	6	20.75	0.00
2	10	15	17	7	20.03	0.17	6	19.77	0.00	7	20.31	0.17	6	20.43	0.00
2	10	15	18	8	20.64	0.14	8	20.48	0.14	7	20.90	0.00	7	20.37	0.00
2	10	15	19	9	21.20	0.29	9	20.40	0.29	8	20.00	0.14	7	20.41	0.00
2	10	15	20	8	19.98	0.00	8	19.80	0.00	8	19.87	0.00	8	20.11	0.00
2	15	15	1	13	51.82	0.00	14	55.41	0.08	14	54.64	0.08	13	52.55	0.00
2	15	15	2	14	50.30	0.00	14	51.47	0.00	15	51.17	0.07	14	51.14	0.00
2	15	15	3	12	48.01	0.00	13	48.5	0.08	12	50.45	0.00	13	50.30	0.08
2	15	15	4	16	52.59	0.14	14	53.53	0.00	15	50.72	0.07	14	52.93	0.00
2	15	15	5	11	49.61	0.00	13	51.5	0.18	11	50.86	0.00	11	49.73	0.00
2	15	15	6	12	51.65	0.09	13	50.83	0.18	11	53.03	0.00	14	52.03	0.27
2	15	15	7	14	53.98	0.08	14	54.3	0.08	13	54.66	0.00	14	53.41	0.08
2	15	15	8	16	52.44	0.14	15	54.67	0.07	15	54.72	0.07	14	53.48	0.00
2	15	15	9	10	47.73	0.25	10	48.29	0.25	8	48.85	0.00	9	49.92	0.13
2	15	15	10	16	49.74	0.14	15	52.59	0.07	14	52.47	0.00	14	49.02	0.00
2	15	15	11	17	54.64	0.06	16	56.83	0.00	17	56.59	0.06	17	53.01	0.06
2	15	15	12	12	49.91	0.00	14	52.58	0.17	14	53.40	0.17	13	51.15	0.08
2	15	15	13	16	52.22	0.23	13	53.78	0.00	15	53.89	0.15	15	50.60	0.15
2	15	15	14	13	50.93	0.18	13	51.64	0.18	11	51.15	0.00	15	53.05	0.36
2	15	15	15	9	51.06	0.00	11	49.53	0.22	10	50.74	0.11	10	50.11	0.11
2	15	15	16	9	50.81	0.00	12	51.19	0.33	12	51.77	0.33	11	53.10	0.22
2	15	15	17	17	56.39	0.13	15	56.33	0.00	16	53.84	0.07	16	53.10	0.07
2	15	15	18	14	55.07	0.27	13	53.06	0.18	13	53.03	0.18	11	54.49	0.00
2	15	15	19	15	54.83	0.07	15	53.86	0.07	15	54.50	0.07	14	54.67	0.00
2	15	15	20	16	52.07	0.07	15	52.27	0.00	17	53.14	0.13	15	52.85	0.00

Table B.6. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD
3	15	15	1	5	28.39	0.00	6	28.22	0.20	6	30.12	0.20	6	28.39	0.20
3	15	15	2	6	29.37	0.20	5	29.11	0.00	7	30.04	0.40	5	29.83	0.00
3	15	15	3	5	28.58	0.00	5	29.17	0.00	5	27.81	0.00	6	28.31	0.20
3	15	15	4	6	29.04	1.00	7	27.92	1.33	3	29.03	0.00	5	29.21	0.67
3	15	15	5	5	29.73	0.00	6	30.31	0.20	7	28.21	0.40	5	29.10	0.00
3	15	15	6	5	31.20	0.25	4	28.23	0.00	5	27.74	0.25	4	28.54	0.00
3	15	15	7	6	26.80	0.00	7	27.85	0.17	7	28.47	0.17	6	28.81	0.00
3	15	15	8	7	29.40	0.40	6	29.12	0.20	5	29.42	0.00	5	30.50	0.00
3	15	15	9	5	29.06	0.00	7	31.25	0.40	6	28.28	0.20	6	29.50	0.20
3	15	15	10	6	28.68	0.00	6	29.03	0.00	7	27.85	0.17	6	29.16	0.00
3	15	15	11	5	29.57	0.25	4	29.02	0.00	5	28.67	0.25	6	28.00	0.50
3	15	15	12	5	30.21	1.50	2	28.31	0.00	7	28.73	2.50	2	29.55	0.00
3	15	15	13	8	28.53	0.60	5	30.58	0.00	5	29.83	0.00	6	29.28	0.20
3	15	15	14	7	29.77	0.40	7	29.17	0.40	5	29.52	0.00	5	28.89	0.00
3	15	15	15	4	28.57	0.00	6	28.93	0.50	5	28.25	0.25	5	28.11	0.25
3	15	15	16	3	28.50	0.50	6	27.52	2.00	2	29.81	0.00	5	28.51	1.50
3	15	15	17	6	29.73	0.50	6	28.89	0.50	4	28.83	0.00	6	28.36	0.50
3	15	15	18	5	29.81	0.00	6	28.03	0.20	6	27.53	0.20	5	28.78	0.00
3	15	15	19	4	27.77	0.00	7	28.87	0.75	6	28.31	0.50	6	28.03	0.50
3	15	15	20	6	28.02	0.20	5	29.56	0.00	6	29.25	0.20	6	29.11	0.20
3	20	15	1	10	62.45	1.00	5	58.60	0.00	7	58.09	0.40	10	58.30	1.00
3	20	15	2	6	59.58	0.00	7	62.36	0.17	10	57.69	0.67	9	60.95	0.50
3	20	15	3	10	68.42	0.00	10	65.59	0.00	10	67.50	0.00	11	64.65	0.10
3	20	15	4	12	56.95	0.71	9	62.78	0.29	7	60.81	0.00	10	62.27	0.43
3	20	15	5	9	61.95	0.00	11	63.48	0.22	11	63.33	0.22	10	64.07	0.11
3	20	15	6	7	59.83	0.00	11	62.72	0.57	9	62.44	0.29	11	60.30	0.57
3	20	15	7	10	64.29	0.25	8	59.19	0.00	8	64.09	0.00	11	62.17	0.38
3	20	15	8	9	61.61	0.13	9	64.73	0.13	8	63.06	0.00	9	61.70	0.13
3	20	15	9	7	63.91	0.00	8	61.92	0.14	8	62.63	0.14	9	62.62	0.29
3	20	15	10	7	62.71	0.00	8	63.36	0.14	8	61.89	0.14	8	61.08	0.14
3	20	15	11	12	60.41	0.20	12	63.81	0.20	10	64.81	0.00	10	63.06	0.00
3	20	15	12	11	62.31	0.10	11	63.13	0.10	12	63.39	0.20	10	60.43	0.00
3	20	15	13	13	66.77	0.44	9	61.98	0.00	11	60.24	0.22	10	65.93	0.11
3	20	15	14	10	63.37	0.67	9	61.28	0.50	9	60.17	0.50	6	63.72	0.00
3	20	15	15	9	64.31	0.00	12	60.39	0.33	9	59.15	0.00	12	62.35	0.33
3	20	15	16	9	60.09	0.13	9	67.74	0.13	10	60.87	0.25	8	64.00	0.00
3	20	15	17	10	59.19	0.67	11	62.39	0.83	6	62.77	0.00	10	60.59	0.67
3	20	15	18	6	59.32	0.00	10	59.48	0.67	8	60.85	0.33	8	59.80	0.33
3	20	15	19	8	62.10	0.00	10	65.88	0.25	8	62.25	0.00	13	64.18	0.63
3	20	15	20	9	64.42	0.29	8	61.69	0.14	8	58.16	0.14	7	59.16	0.00

Table B.6. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD	ts	time(s)	RPD
3	15	20	1	17	31.74	0.13	16	31.72	0.07	15	35.40	0.00	15	32.91	0.00
3	15	20	2	10	31.89	0.00	13	30.14	0.30	11	29.87	0.10	10	30.68	0.00
3	15	20	3	12	31.40	0.20	12	30.36	0.20	11	30.93	0.10	10	30.17	0.00
3	15	20	4	12	30.61	0.09	11	30.97	0.00	13	29.86	0.18	11	30.23	0.00
3	15	20	5	14	30.59	0.17	12	32.78	0.00	17	33.31	0.42	14	32.88	0.17
3	15	20	6	10	32.42	0.00	13	29.55	0.30	10	30.49	0.00	13	31.40	0.30
3	15	20	7	11	29.33	0.00	12	30.25	0.09	12	30.47	0.09	12	30.26	0.09
3	15	20	8	13	31.71	0.18	16	32.33	0.45	14	32.26	0.27	11	32.68	0.00
3	15	20	9	13	30.38	0.44	13	29.79	0.44	10	29.60	0.11	9	31.31	0.00
3	15	20	10	13	31.81	0.30	10	31.28	0.00	11	34.00	0.10	10	32.27	0.00
3	15	20	11	12	30.28	0.20	10	31.41	0.00	10	30.73	0.00	11	31.16	0.10
3	15	20	12	10	29.94	0.00	11	29.57	0.10	11	30.44	0.10	11	30.33	0.10
3	15	20	13	10	28.97	0.00	10	28.13	0.00	10	29.33	0.00	10	29.29	0.00
3	15	20	14	12	32.42	0.00	15	32.88	0.25	15	31.73	0.25	14	31.38	0.17
3	15	20	15	15	29.77	0.36	11	30.89	0.00	13	31.08	0.18	11	29.99	0.00
3	15	20	16	15	31.08	0.36	12	32.11	0.09	13	30.73	0.18	11	31.17	0.00
3	15	20	17	10	31.84	0.00	10	32.34	0.00	12	32.39	0.20	11	29.74	0.10
3	15	20	18	12	30.81	0.33	12	30.81	0.33	9	31.8	0.00	11	31.67	0.22
3	15	20	19	14	29.96	0.08	13	31.36	0.00	13	32.22	0.00	13	32.25	0.00
3	15	20	20	9	28.97	0.00	12	29.94	0.33	14	30.98	0.56	11	31.11	0.22
3	20	20	1	17	70.70	0.00	19	71.17	0.12	20	69.25	0.18	21	71.57	0.24
3	20	20	2	18	66.40	0.13	21	68.64	0.31	19	69.22	0.19	16	69.54	0.00
3	20	20	3	19	70.28	0.06	19	68.41	0.06	19	68.70	0.06	18	66.67	0.00
3	20	20	4	20	69.84	0.18	22	73.69	0.29	20	70.40	0.18	17	71.70	0.00
3	20	20	5	16	69.94	0.00	21	70.74	0.31	20	70.10	0.25	20	70.14	0.25
3	20	20	6	17	67.49	0.00	18	70.55	0.06	17	70.42	0.00	18	66.19	0.06
3	20	20	7	20	71.95	0.18	18	65.99	0.06	19	68.57	0.12	17	66.11	0.00
3	20	20	8	21	72.67	0.11	22	73.00	0.16	19	70.50	0.00	19	70.43	0.00
3	20	20	9	19	66.59	0.12	17	72.88	0.00	18	70.72	0.06	22	70.37	0.29
3	20	20	10	16	70.87	0.00	18	70.53	0.13	20	67.92	0.25	19	69.22	0.19
3	20	20	11	19	67.64	0.19	16	68.13	0.00	19	66.23	0.19	20	68.06	0.25
3	20	20	12	20	69.79	0.67	12	68.36	0.00	22	72.98	0.83	17	68.09	0.42
3	20	20	13	20	70.92	0.25	19	69.83	0.19	16	71.68	0.00	19	72.06	0.19
3	20	20	14	16	71.64	0.00	19	71.05	0.19	18	68.90	0.13	19	72.47	0.19
3	20	20	15	20	72.50	0.18	17	72.05	0.00	19	70.12	0.12	18	73.50	0.06
3	20	20	16	20	66.37	0.43	19	67.08	0.36	14	68.47	0.00	17	65.86	0.21
3	20	20	17	21	72.25	0.17	19	71.63	0.06	19	69.58	0.06	18	75.45	0.00
3	20	20	18	19	69.55	0.19	17	68.53	0.06	16	71.53	0.00	19	69.25	0.19
3	20	20	19	17	69.11	0.00	18	68.01	0.06	19	72.89	0.12	18	69.27	0.06
3	20	20	20	19	66.89	0.27	19	64.91	0.27	15	69.48	0.00	15	72.15	0.00

**Table B.7. Overall results of the ILS (perturbation P.2) for 100 iterations and different values of  $\beta$  for the objective of minimizing the total flowtime.**

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD
2	10	10	1	146	23.25	0.04	150	23.67	0.07	140	23.30	0.00	146	23.25	0.04
2	10	10	2	152	22.09	0.01	152	22.42	0.01	157	22.71	0.05	152	22.09	0.01
2	10	10	3	135	22.28	0.00	137	22.14	0.01	135	22.91	0.00	135	22.28	0.00
2	10	10	4	98	21.88	0.00	98	23.3	0.00	98	22.16	0.00	98	21.88	0.00
2	10	10	5	106	22.60	0.00	110	22.42	0.04	108	22.60	0.02	106	22.60	0.00
2	10	10	6	122	23.61	0.15	121	23.51	0.14	106	23.44	0.00	122	23.61	0.15
2	10	10	7	141	23.31	0.09	129	24.06	0.00	135	23.59	0.05	141	23.31	0.09
2	10	10	8	150	23.07	0.07	151	23.67	0.08	141	23.53	0.01	150	23.07	0.07
2	10	10	9	134	23.06	0.00	141	23.72	0.05	134	23.61	0.00	134	23.06	0.00
2	10	10	10	141	23.72	0.01	141	23.81	0.01	139	23.84	0.00	141	23.72	0.01
2	10	10	11	155	23.97	0.00	165	23.28	0.06	157	23.27	0.01	155	23.97	0.00
2	10	10	12	169	23.21	0.00	173	24.15	0.02	171	23.91	0.01	169	23.21	0.00
2	10	10	13	110	23.59	0.00	110	23.99	0.00	110	23.24	0.00	110	23.59	0.00
2	10	10	14	155	24.47	0.00	158	24.27	0.02	161	24.75	0.04	155	24.47	0.00
2	10	10	15	158	23.83	0.02	155	22.92	0.00	155	22.05	0.00	158	23.83	0.02
2	10	10	16	133	23.10	0.06	125	22.86	0.00	129	22.78	0.03	133	23.10	0.06
2	10	10	17	155	22.79	0.00	157	24.09	0.01	156	24.2	0.01	155	22.79	0.00
2	10	10	18	113	22.75	0.14	117	23.31	0.18	112	22.85	0.13	113	22.75	0.14
2	10	10	19	148	23.16	0.04	148	22.59	0.04	142	22.69	0.00	148	23.16	0.04
2	10	10	20	131	24.35	0.07	122	23.42	0.00	133	23.83	0.09	131	24.35	0.07
2	15	10	1	291	60.45	0.00	301	61.93	0.03	299	60.59	0.03	291	60.45	0.00
2	15	10	2	338	60.12	0.02	333	60.72	0.00	343	63.64	0.03	338	60.12	0.02
2	15	10	3	293	68.55	0.00	292	62.81	0.00	292	63.58	0.00	293	68.55	0.00
2	15	10	4	302	63.97	0.02	306	62.83	0.03	296	60.97	0.00	302	63.97	0.02
2	15	10	5	259	63.04	0.00	296	60.37	0.14	289	61.45	0.12	259	63.04	0.00
2	15	10	6	327	65.20	0.07	345	62.03	0.13	306	63.62	0.00	327	65.20	0.07
2	15	10	7	252	61.03	0.00	285	62.81	0.13	285	63.8	0.13	252	61.03	0.00
2	15	10	8	234	63.12	0.06	233	64.23	0.05	238	64.9	0.08	234	63.12	0.06
2	15	10	9	245	61.92	0.02	245	61.98	0.02	240	64.31	0.00	245	61.92	0.02
2	15	10	10	339	61.61	0.12	303	61.3	0.00	331	60.54	0.09	339	61.61	0.12
2	15	10	11	316	64.92	0.07	318	59.64	0.07	314	59.01	0.06	316	64.92	0.07
2	15	10	12	312	62.59	0.02	326	66.14	0.06	314	63.91	0.02	312	62.59	0.02
2	15	10	13	340	67.09	0.07	365	65.42	0.15	318	62.56	0.00	340	67.09	0.07
2	15	10	14	309	65.25	0.00	315	63.03	0.02	325	62.48	0.05	309	65.25	0.00
2	15	10	15	361	68.64	0.02	353	69.86	0.00	370	68.26	0.05	361	68.64	0.02
2	15	10	16	255	62.72	0.06	250	65.48	0.04	240	63.45	0.00	255	62.72	0.06
2	15	10	17	352	62.84	0.05	335	62.97	0.00	355	63.20	0.06	352	62.84	0.05
2	15	10	18	352	62.00	0.07	342	65.94	0.04	363	64.69	0.10	352	62.00	0.07
2	15	10	19	221	65.74	0.00	242	65.3	0.10	242	65.59	0.10	221	65.74	0.00
2	15	10	20	329	66.74	0.00	366	67.78	0.11	346	67.32	0.05	329	66.74	0.00

Table B.7. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD
2	10	15	1	215	23.62	0.00	215	24.34	0.00	220	24.76	0.02	215	23.62	0.00
2	10	15	2	185	23.69	0.05	185	23.75	0.05	177	23.55	0.00	185	23.69	0.05
2	10	15	3	147	24.39	0.04	150	23.77	0.06	150	23.81	0.06	147	24.39	0.04
2	10	15	4	150	23.59	0.01	158	25.07	0.07	148	24.25	0.00	150	23.59	0.01
2	10	15	5	162	23.42	0.01	161	23.61	0.00	171	24.75	0.06	162	23.42	0.01
2	10	15	6	193	23.66	0.03	193	23.86	0.03	188	23.42	0.01	193	23.66	0.03
2	10	15	7	138	23.27	0.00	138	23.47	0.00	142	23.83	0.03	138	23.27	0.00
2	10	15	8	171	25.02	0.04	175	24.68	0.07	164	25.08	0.00	171	25.02	0.04
2	10	15	9	169	24.20	0.06	166	24.83	0.04	159	24.29	0.00	169	24.20	0.06
2	10	15	10	171	23.46	0.14	164	23.47	0.09	150	23.93	0.00	171	23.46	0.14
2	10	15	11	157	23.97	0.00	161	22.79	0.03	158	23.69	0.01	157	23.97	0.00
2	10	15	12	170	23.71	0.04	165	24.89	0.01	174	23.96	0.07	170	23.71	0.04
2	10	15	13	166	24.42	0.09	152	25.94	0.00	166	24.69	0.09	166	24.42	0.09
2	10	15	14	209	24.11	0.00	209	24.44	0.00	210	24.81	0.00	209	24.11	0.00
2	10	15	15	185	24.61	0.01	183	25.01	0.00	185	25.08	0.01	185	24.61	0.01
2	10	15	16	192	24.19	0.11	191	24.33	0.10	189	25.02	0.09	192	24.19	0.11
2	10	15	17	127	23.13	0.07	119	24.30	0.00	131	24.56	0.10	127	23.13	0.07
2	10	15	18	175	24.00	0.04	169	24.56	0.00	175	24.81	0.04	175	24.00	0.04
2	10	15	19	186	24.22	0.04	183	23.57	0.03	178	24.20	0.00	186	24.22	0.04
2	10	15	20	187	25.32	0.00	193	24.43	0.03	191	23.71	0.02	187	25.32	0.00
2	15	15	1	325	68.17	0.00	325	71.20	0.00	325	70.86	0.00	325	68.17	0.00
2	15	15	2	389	66.32	0.02	392	67.45	0.02	383	68.56	0.00	389	66.32	0.02
2	15	15	3	319	65.20	0.00	324	67.92	0.02	325	66.55	0.02	319	65.20	0.00
2	15	15	4	369	69.33	0.00	376	69.53	0.02	376	67.00	0.02	369	69.33	0.00
2	15	15	5	351	66.87	0.02	345	64.57	0.00	353	68.74	0.02	351	66.87	0.02
2	15	15	6	394	68.57	0.01	391	69.67	0.00	397	66.52	0.02	394	68.57	0.01
2	15	15	7	399	68.43	0.00	399	69.14	0.00	399	66.33	0.00	399	68.43	0.00
2	15	15	8	376	69.06	0.00	384	66.64	0.02	389	66.82	0.03	376	69.06	0.00
2	15	15	9	365	61.79	0.00	379	64.91	0.04	372	67.31	0.02	365	61.79	0.00
2	15	15	10	337	66.47	0.00	348	67.00	0.03	356	68.83	0.06	337	66.47	0.00
2	15	15	11	404	67.68	0.00	428	68.43	0.06	437	67.91	0.08	404	67.68	0.00
2	15	15	12	349	66.47	0.02	341	66.75	0.00	354	67.33	0.04	349	66.47	0.02
2	15	15	13	459	67.20	0.03	462	65.67	0.04	458	67.75	0.03	459	67.20	0.03
2	15	15	14	368	67.23	0.03	373	65.89	0.04	379	67.75	0.06	368	67.23	0.03
2	15	15	15	343	64.76	0.00	366	66.02	0.07	378	66.79	0.10	343	64.76	0.00
2	15	15	16	330	67.98	0.00	352	64.68	0.07	363	66.92	0.10	330	67.98	0.00
2	15	15	17	381	65.33	0.02	383	66.95	0.02	385	68.07	0.03	381	65.33	0.02
2	15	15	18	386	68.59	0.00	397	67.83	0.03	391	68.17	0.01	386	68.59	0.00
2	15	15	19	420	68.84	0.04	420	65.89	0.04	420	64.78	0.04	420	68.84	0.04
2	15	15	20	390	68.92	0.00	398	63.89	0.02	406	64.76	0.04	390	68.92	0.00

Table B.7. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD
3	15	15	1	217	39.89	0.01	214	39.12	0.00	214	38.22	0.00	217	39.89	0.01
3	15	15	2	182	36.73	0.14	182	38.04	0.14	182	38.34	0.14	182	36.73	0.14
3	15	15	3	223	37.36	0.00	245	39.67	0.10	235	37.77	0.05	223	37.36	0.00
3	15	15	4	159	37.66	0.01	165	38.11	0.05	157	38.86	0.00	159	37.66	0.01
3	15	15	5	197	36.78	0.14	176	38.82	0.02	173	37.84	0.00	197	36.78	0.14
3	15	15	6	205	35.72	0.00	205	37.55	0.00	205	36.33	0.00	205	35.72	0.00
3	15	15	7	194	37.44	0.12	173	37.83	0.00	194	37.92	0.12	194	37.44	0.12
3	15	15	8	262	38.53	0.06	253	39.42	0.02	262	39.89	0.06	262	38.53	0.06
3	15	15	9	235	38.30	0.02	235	37.33	0.02	231	38.85	0.00	235	38.30	0.02
3	15	15	10	208	38.53	0.00	222	39.27	0.07	225	36.81	0.08	208	38.53	0.00
3	15	15	11	197	38.13	0.06	191	37.2	0.03	199	37.19	0.07	197	38.13	0.06
3	15	15	12	193	37.27	0.14	206	39.42	0.21	170	38.44	0.00	193	37.27	0.14
3	15	15	13	193	37.31	0.00	193	37.61	0.00	193	38.81	0.00	193	37.31	0.00
3	15	15	14	206	39.96	0.01	206	40.06	0.01	203	38.17	0.00	206	39.96	0.01
3	15	15	15	185	38.28	0.06	189	39.75	0.08	189	38.55	0.08	185	38.28	0.06
3	15	15	16	213	39.34	0.11	215	36.61	0.12	192	37.41	0.00	213	39.34	0.11
3	15	15	17	205	37.73	0.04	197	38.47	0.00	209	39.67	0.06	205	37.73	0.04
3	15	15	18	190	36.84	0.04	190	38.25	0.04	183	38.15	0.00	190	36.84	0.04
3	15	15	19	212	35.35	0.02	210	37.63	0.01	208	37.75	0.00	212	35.35	0.02
3	15	15	20	172	38.93	0.00	172	38.95	0.00	172	37.27	0.00	172	38.93	0.00
3	20	15	1	360	88.40	0.00	360	85.59	0.00	360	86.31	0.00	360	88.40	0.00
3	20	15	2	277	88.05	0.00	277	86.19	0.00	303	88.67	0.09	277	88.05	0.00
3	20	15	3	394	84.42	0.00	394	90.67	0.00	394	89.61	0.00	394	84.42	0.00
3	20	15	4	324	80.46	0.00	333	86.91	0.03	333	84.18	0.03	324	80.46	0.00
3	20	15	5	413	90.20	0.08	383	85.47	0.00	413	84.48	0.08	413	90.20	0.08
3	20	15	6	371	87.25	0.00	371	84.3	0.00	371	87.45	0.00	371	87.25	0.00
3	20	15	7	418	83.44	0.04	418	88.31	0.04	414	86.24	0.03	418	83.44	0.04
3	20	15	8	307	85.75	0.13	272	87.81	0.00	293	85.44	0.08	307	85.75	0.13
3	20	15	9	322	83.35	0.00	339	90.92	0.05	332	88.53	0.03	322	83.35	0.00
3	20	15	10	312	86.83	0.08	314	82.06	0.09	314	85.57	0.09	312	86.83	0.08
3	20	15	11	299	86.63	0.00	365	92.00	0.22	353	87.98	0.18	299	86.63	0.00
3	20	15	12	399	87.56	0.01	399	87.33	0.01	399	86.14	0.01	399	87.56	0.01
3	20	15	13	381	89.06	0.00	381	88.75	0.00	385	86.16	0.01	381	89.06	0.00
3	20	15	14	336	92.63	0.00	336	82.83	0.00	336	86.52	0.00	336	92.63	0.00
3	20	15	15	311	86.50	0.00	311	82.95	0.00	311	86.48	0.00	311	86.50	0.00
3	20	15	16	324	85.18	0.00	324	85.79	0.00	324	88.01	0.00	324	85.18	0.00
3	20	15	17	322	84.28	0.05	308	85.26	0.00	322	85.47	0.05	322	84.28	0.05
3	20	15	18	435	84.03	0.04	419	86.18	0.00	432	85.82	0.03	435	84.03	0.04
3	20	15	19	427	80.81	0.07	400	86.04	0.00	417	84.55	0.04	427	80.81	0.07
3	20	15	20	329	87.86	0.00	336	85.81	0.02	334	84.95	0.02	329	87.86	0.00

Table B.7. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD	tft	time(s)	RPD
3	15	20	1	296	42.27	0.00	296	43.6	0.00	296	40.28	0.00	296	42.27	0.00
3	15	20	2	219	40.81	0.00	219	41.9	0.00	219	42.35	0.00	219	40.81	0.00
3	15	20	3	221	41.98	0.00	223	40.2	0.01	223	39.99	0.01	221	41.98	0.00
3	15	20	4	178	40.95	0.00	178	40.45	0.00	178	40.73	0.00	178	40.95	0.00
3	15	20	5	239	40.53	0.00	241	42.63	0.01	241	39.92	0.01	239	40.53	0.00
3	15	20	6	200	42.25	0.00	200	41.83	0.00	200	40.56	0.00	200	42.25	0.00
3	15	20	7	249	39.14	0.14	219	41.22	0.00	241	42.00	0.10	249	39.14	0.14
3	15	20	8	301	41.92	0.10	281	41.6	0.03	299	42.24	0.10	301	41.92	0.10
3	15	20	9	209	42.99	0.00	214	40.81	0.02	210	40.23	0.00	209	42.99	0.00
3	15	20	10	251	42.63	0.05	239	41.03	0.00	247	41.75	0.03	251	42.63	0.05
3	15	20	11	261	37.92	0.01	261	41.05	0.01	259	40.05	0.00	261	37.92	0.01
3	15	20	12	197	41.16	0.00	197	40.58	0.00	197	41.36	0.00	197	41.16	0.00
3	15	20	13	219	40.33	0.00	219	40.08	0.00	219	40.58	0.00	219	40.33	0.00
3	15	20	14	281	43.2	0.14	247	40.96	0.00	262	42.84	0.06	281	43.2	0.14
3	15	20	15	265	40.94	0.00	265	40.75	0.00	265	41.91	0.00	265	40.94	0.00
3	15	20	16	251	41.05	0.00	252	40.88	0.00	252	41.63	0.00	251	41.05	0.00
3	15	20	17	206	42.28	0.00	211	41.76	0.02	211	40.33	0.02	206	42.28	0.00
3	15	20	18	230	41.70	0.04	224	40.83	0.01	226	39.95	0.02	230	41.70	0.04
3	15	20	19	274	40.02	0.00	282	40.88	0.03	280	40.77	0.02	274	40.02	0.00
3	15	20	20	228	39.36	0.08	235	37.92	0.11	212	42.23	0.00	228	39.36	0.08
3	20	20	1	497	92.28	0.00	497	94.74	0.00	497	99.98	0.00	497	92.28	0.00
3	20	20	2	494	98.28	0.06	500	100.94	0.07	468	96.47	0.00	494	98.28	0.06
3	20	20	3	443	99.14	0.00	443	99.22	0.00	443	102.42	0.00	443	99.14	0.00
3	20	20	4	417	90.89	0.02	417	96.25	0.02	409	96.72	0.00	417	90.89	0.02
3	20	20	5	452	90.59	0.00	452	97.66	0.00	452	96.02	0.00	452	90.59	0.00
3	20	20	6	499	92.52	0.00	499	94.40	0.00	499	95.86	0.00	499	92.52	0.00
3	20	20	7	411	96.69	0.00	417	95.73	0.01	440	93.92	0.07	411	96.69	0.00
3	20	20	8	454	97.28	0.00	454	97.83	0.00	454	99.83	0.00	454	97.28	0.00
3	20	20	9	439	103.10	0.00	439	99.41	0.00	439	97.22	0.00	439	103.10	0.00
3	20	20	10	441	92.62	0.00	441	99.43	0.00	441	95.48	0.00	441	92.62	0.00
3	20	20	11	410	93.39	0.00	410	95.82	0.00	410	94.22	0.00	410	93.39	0.00
3	20	20	12	378	97.57	0.00	378	94.94	0.00	378	95.78	0.00	378	97.57	0.00
3	20	20	13	454	94.74	0.00	454	94.07	0.00	454	96.61	0.00	454	94.74	0.00
3	20	20	14	380	92.19	0.00	380	90.85	0.00	380	99.38	0.00	380	92.19	0.00
3	20	20	15	429	97.74	0.00	429	97.00	0.00	429	94.03	0.00	429	97.74	0.00
3	20	20	16	433	95.94	0.02	433	95.44	0.02	433	93.42	0.02	433	95.94	0.02
3	20	20	17	396	98.33	0.00	396	99.61	0.00	396	95.68	0.00	396	98.33	0.00
3	20	20	18	451	103.71	0.00	451	95.65	0.00	451	93.50	0.00	451	103.71	0.00
3	20	20	19	415	93.32	0.00	496	94.67	0.20	458	96.67	0.10	415	93.32	0.00
3	20	20	20	414	94.52	0.00	414	97.03	0.00	414	101.07	0.00	414	94.52	0.00



**Table B.8. Overall results of the ILS (perturbation P.2) for 100 iterations and different values of  $\beta$  for the objective of minimizing the makespan.**

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				fmax	time(s)	RPD	fmax	time(s)	RPD	fmax	time(s)	RPD	fmax	time(s)	RPD
2	10	10	1	37	18.67	0.03	37	19.24	0.03	37	19.00	0.03	36	19.47	0.00
2	10	10	2	32	19.70	0.03	33	18.53	0.06	31	19.14	0.00	33	18.95	0.06
2	10	10	3	32	20.53	0.00	32	18.97	0.00	32	18.17	0.00	32	18.12	0.00
2	10	10	4	30	18.09	0.20	25	17.73	0.00	28	18.25	0.12	28	18.52	0.12
2	10	10	5	27	18.32	0.00	27	18.11	0.00	28	17.77	0.04	29	18.74	0.07
2	10	10	6	29	19.62	0.07	27	19.09	0.00	27	19.62	0.00	29	19.42	0.07
2	10	10	7	33	19.50	0.00	33	20.00	0.00	35	19.82	0.06	33	19.69	0.00
2	10	10	8	35	20.39	0.13	31	19.84	0.00	33	20.08	0.06	31	19.58	0.00
2	10	10	9	33	19.19	0.03	33	19.38	0.03	32	19.39	0.00	33	19.20	0.03
2	10	10	10	34	18.49	0.06	37	19.56	0.16	32	19.63	0.00	33	19.29	0.03
2	10	10	11	35	20.11	0.00	37	19.11	0.06	35	19.49	0.00	36	19.28	0.03
2	10	10	12	39	19.92	0.03	39	19.42	0.03	38	19.42	0.00	39	20.71	0.03
2	10	10	13	30	20.36	0.20	25	19.89	0.00	29	20.19	0.16	29	19.47	0.16
2	10	10	14	34	20.66	0.00	35	19.85	0.03	34	20.33	0.00	37	19.72	0.09
2	10	10	15	38	18.56	0.12	35	18.34	0.03	35	18.44	0.03	34	18.66	0.00
2	10	10	16	31	18.71	0.07	32	18.75	0.10	33	19.16	0.14	29	18.73	0.00
2	10	10	17	34	18.82	0.03	35	18.39	0.06	34	18.48	0.03	33	19.13	0.00
2	10	10	18	27	19.41	0.00	29	19.31	0.07	28	19.63	0.04	30	18.90	0.11
2	10	10	19	38	19.31	0.09	37	19.33	0.06	35	19.61	0.00	38	19.35	0.09
2	10	10	20	32	18.80	0.03	32	20.35	0.03	33	19.89	0.06	31	19.60	0.00
2	15	10	1	50	41.66	0.09	51	45.34	0.11	46	45.83	0.00	52	45.86	0.13
2	15	10	2	53	44.20	0.00	55	42.27	0.04	54	41.88	0.02	54	41.83	0.02
2	15	10	3	43	42.09	0.00	51	44.22	0.19	48	46.06	0.12	47	44.38	0.09
2	15	10	4	50	44.68	0.06	50	43.18	0.06	47	43.03	0.00	47	43.80	0.00
2	15	10	5	49	44.39	0.07	54	45.05	0.17	51	43.11	0.11	46	46.81	0.00
2	15	10	6	55	44.76	0.06	52	44.50	0.00	55	45.28	0.06	55	45.23	0.06
2	15	10	7	46	44.66	0.15	45	44.64	0.13	46	45.56	0.15	40	45.65	0.00
2	15	10	8	41	44.17	0.05	39	45.70	0.00	42	43.83	0.08	43	44.09	0.10
2	15	10	9	43	45.72	0.10	43	45.19	0.10	39	42.57	0.00	43	44.28	0.10
2	15	10	10	56	48.25	0.00	62	46.97	0.11	57	45.39	0.02	56	42.58	0.00
2	15	10	11	47	42.05	0.00	49	43.67	0.04	51	45.16	0.09	52	45.00	0.11
2	15	10	12	51	46.15	0.00	52	45.63	0.02	53	44.65	0.04	53	46.40	0.04
2	15	10	13	56	44.30	0.08	55	46.47	0.06	52	46.80	0.00	56	44.06	0.08
2	15	10	14	49	44.33	0.00	53	42.75	0.08	50	43.28	0.02	53	45.52	0.08
2	15	10	15	69	47.78	0.15	62	46.31	0.03	60	45.70	0.00	62	46.09	0.03
2	15	10	16	47	42.83	0.04	46	44.33	0.02	45	45.55	0.00	49	43.28	0.09
2	15	10	17	55	40.33	0.00	55	41.35	0.00	55	42.36	0.00	55	42.67	0.00
2	15	10	18	58	45.56	0.00	62	44.08	0.07	61	42.38	0.05	60	44.81	0.03
2	15	10	19	43	43.71	0.00	44	44.70	0.02	44	43.51	0.02	44	43.44	0.02
2	15	10	20	63	45.00	0.07	59	45.49	0.00	62	44.86	0.05	60	47.58	0.02

Table B.8. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				TFT	time(s)	RPD	TFT	time(s)	RPD	TFT	time(s)	RPD	TFT	time(s)	RPD
2	10	15	1	44	19.67	0.02	43	20.24	0.00	44	20.07	0.02	44	19.95	0.02
2	10	15	2	41	19.53	0.03	45	19.52	0.13	40	19.01	0.00	45	19.97	0.13
2	10	15	3	33	20.10	0.00	37	20.00	0.12	39	20.36	0.18	39	20.17	0.18
2	10	15	4	38	19.23	0.06	36	19.54	0.00	41	19.28	0.14	42	19.39	0.17
2	10	15	5	39	19.86	0.08	36	19.21	0.00	38	19.78	0.06	36	20.11	0.00
2	10	15	6	42	20.16	0.05	41	19.80	0.03	44	20.29	0.10	40	19.66	0.00
2	10	15	7	36	19.09	0.16	31	19.36	0.00	36	19.39	0.16	36	19.17	0.16
2	10	15	8	42	20.71	0.11	38	20.28	0.00	42	21.26	0.11	39	20.03	0.03
2	10	15	9	40	20.86	0.11	39	19.83	0.08	36	20.18	0.00	44	20.76	0.22
2	10	15	10	38	18.91	0.03	37	19.36	0.00	38	20.25	0.03	39	19.09	0.05
2	10	15	11	38	20.25	0.00	38	20.14	0.00	38	18.99	0.00	38	19.00	0.00
2	10	15	12	42	20.28	0.17	38	20.01	0.06	36	19.65	0.00	43	20.92	0.19
2	10	15	13	40	19.92	0.05	38	19.90	0.00	39	20.56	0.03	40	19.77	0.05
2	10	15	14	44	20.51	0.00	44	19.91	0.00	44	20.56	0.00	44	19.53	0.00
2	10	15	15	41	19.90	0.00	41	20.67	0.00	41	20.64	0.00	41	20.44	0.00
2	10	15	16	43	19.69	0.10	42	19.59	0.08	40	19.32	0.03	39	20.75	0.00
2	10	15	17	35	20.17	0.13	32	20.21	0.03	31	19.43	0.00	35	19.44	0.13
2	10	15	18	42	19.29	0.14	37	20.78	0.00	41	20.05	0.11	42	20.47	0.14
2	10	15	19	41	20.04	0.00	43	20.36	0.05	41	19.74	0.00	44	20.28	0.07
2	10	15	20	45	20.59	0.10	41	19.47	0.00	44	19.95	0.07	44	19.96	0.07
2	15	15	1	59	47.70	0.00	60	48.55	0.02	60	48.61	0.02	59	46.60	0.00
2	15	15	2	62	46.56	0.00	63	47.33	0.02	62	47.00	0.00	63	46.65	0.02
2	15	15	3	54	47.31	0.04	56	45.16	0.08	56	45.88	0.08	52	48.24	0.00
2	15	15	4	67	48.81	0.05	64	48.36	0.00	66	46.77	0.03	65	48.23	0.02
2	15	15	5	57	45.36	0.06	54	48.86	0.00	56	46.84	0.04	57	50.35	0.06
2	15	15	6	65	47.06	0.03	66	47.24	0.05	63	45.75	0.00	64	46.90	0.02
2	15	15	7	67	49.15	0.00	67	48.31	0.00	67	48.25	0.00	67	47.58	0.00
2	15	15	8	59	50.26	0.00	64	49.00	0.08	59	51.41	0.00	66	47.20	0.12
2	15	15	9	60	43.63	0.00	63	44.67	0.05	64	43.71	0.07	62	43.75	0.03
2	15	15	10	60	44.70	0.09	55	45.76	0.00	57	46.33	0.04	60	46.63	0.09
2	15	15	11	67	46.69	0.00	67	49.22	0.00	67	47.76	0.00	67	50.89	0.00
2	15	15	12	55	45.74	0.00	55	49.47	0.00	55	45.89	0.00	55	47.67	0.00
2	15	15	13	67	49.40	0.02	66	52.53	0.00	73	50.36	0.11	73	47.78	0.11
2	15	15	14	57	46.41	0.06	59	47.89	0.09	56	49.05	0.04	54	50.53	0.00
2	15	15	15	60	44.73	0.15	62	47.16	0.19	59	45.53	0.13	52	46.25	0.00
2	15	15	16	58	48.53	0.04	56	47.89	0.00	57	46.31	0.02	59	47.30	0.05
2	15	15	17	57	46.87	0.00	61	50.76	0.07	62	49.20	0.09	62	49.53	0.09
2	15	15	18	61	48.33	0.02	60	49.67	0.00	60	47.31	0.00	61	48.40	0.02
2	15	15	19	72	48.49	0.07	67	50.20	0.00	67	48.59	0.00	71	48.81	0.06
2	15	15	20	64	46.71	0.03	67	45.61	0.08	63	47.53	0.02	62	46.15	0.00

Table B.8. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				fmax	time(s)	RPD	fmax	time(s)	RPD	fmax	time(s)	RPD	fmax	time(s)	RPD
3	15	15	1	34	26.95	0.03	38	27.33	0.15	37	27.66	0.12	33	27.72	0.00
3	15	15	2	34	29.25	0.06	37	28.45	0.16	32	28.52	0.00	33	28.71	0.03
3	15	15	3	41	29.39	0.03	41	28.46	0.03	40	28.18	0.00	42	27.47	0.05
3	15	15	4	27	27.80	0.00	29	27.75	0.07	31	27.14	0.15	32	28.00	0.19
3	15	15	5	33	28.82	0.06	31	28.35	0.00	32	27.42	0.03	32	28.02	0.03
3	15	15	6	35	28.04	0.00	35	28.11	0.00	35	28.80	0.00	35	27.61	0.00
3	15	15	7	31	27.11	0.03	34	28.40	0.13	30	27.23	0.00	35	27.55	0.17
3	15	15	8	42	27.45	0.00	42	27.11	0.00	43	28.49	0.02	42	28.29	0.00
3	15	15	9	39	28.17	0.05	37	27.95	0.00	39	28.55	0.05	38	26.54	0.03
3	15	15	10	38	27.18	0.09	36	27.17	0.03	35	27.67	0.00	36	27.46	0.03
3	15	15	11	35	27.57	0.06	33	26.78	0.00	35	27.26	0.06	33	26.43	0.00
3	15	15	12	34	27.86	0.03	33	29.28	0.00	34	29.00	0.03	34	28.46	0.03
3	15	15	13	36	30.10	0.06	39	27.87	0.15	34	27.83	0.00	35	28.78	0.03
3	15	15	14	37	27.93	0.00	37	28.21	0.00	42	29.00	0.14	38	27.80	0.03
3	15	15	15	32	27.66	0.14	34	27.88	0.21	33	27.45	0.18	28	27.47	0.00
3	15	15	16	35	26.53	0.09	33	28.61	0.03	37	28.25	0.16	32	27.13	0.00
3	15	15	17	35	28.45	0.00	38	28.84	0.09	38	28.35	0.09	37	28.72	0.06
3	15	15	18	35	27.19	0.06	34	27.61	0.03	33	28.39	0.00	34	26.86	0.03
3	15	15	19	36	25.69	0.16	34	27.63	0.10	31	27.36	0.00	36	27.40	0.16
3	15	15	20	30	28.55	0.00	38	27.86	0.27	35	28.17	0.17	33	28.22	0.10
3	20	15	1	49	56.38	0.02	50	54.27	0.04	49	51.54	0.02	48	54.00	0.00
3	20	15	2	41	55.20	0.00	44	55.69	0.07	42	54.32	0.02	43	55.25	0.05
3	20	15	3	54	57.60	0.02	53	62.11	0.00	54	56.94	0.02	57	58.97	0.08
3	20	15	4	42	58.44	0.00	52	57.06	0.24	54	58.83	0.29	54	57.98	0.29
3	20	15	5	53	56.17	0.02	54	60.46	0.04	52	59.11	0.00	56	59.19	0.08
3	20	15	6	46	53.08	0.00	53	57.91	0.15	54	58.25	0.17	54	57.82	0.17
3	20	15	7	52	56.87	0.00	53	55.07	0.02	57	55.63	0.10	54	57.92	0.04
3	20	15	8	37	59.11	0.00	38	57.26	0.03	37	56.23	0.00	40	56.95	0.08
3	20	15	9	46	63.10	0.05	44	54.48	0.00	44	55.45	0.00	47	55.41	0.07
3	20	15	10	40	55.47	0.00	43	54.81	0.08	43	55.75	0.08	42	58.31	0.05
3	20	15	11	45	54.75	0.00	47	57.35	0.04	51	57.71	0.13	48	57.08	0.07
3	20	15	12	46	61.19	0.00	52	62.20	0.13	54	57.97	0.17	53	59.86	0.15
3	20	15	13	49	54.81	0.00	52	53.28	0.06	52	56.65	0.06	52	55.19	0.06
3	20	15	14	44	57.92	0.00	48	56.08	0.09	49	58.68	0.11	48	55.71	0.09
3	20	15	15	43	55.55	0.08	44	55.05	0.10	40	53.66	0.00	46	56.91	0.15
3	20	15	16	50	60.92	0.02	49	57.70	0.00	50	56.36	0.02	50	56.91	0.02
3	20	15	17	37	56.63	0.00	40	56.42	0.08	44	56.39	0.19	38	56.01	0.03
3	20	15	18	50	54.51	0.04	52	56.73	0.08	48	55.99	0.00	51	53.19	0.06
3	20	15	19	55	58.14	0.10	51	55.31	0.02	50	57.72	0.00	50	58.08	0.00
3	20	15	20	44	54.19	0.00	45	54.32	0.02	49	56.85	0.11	49	56.68	0.11

Table B.8. (Continued).

M	J	T	V	$\beta$											
				0.2			0.4			0.6			0.8		
				fmax	time(s)	RPD	fmax	time(s)	RPD	fmax	time(s)	RPD	fmax	time(s)	RPD
3	15	20	1	52	33.40	0.16	52	32.71	0.16	45	32.38	0.00	50	30.62	0.11
3	15	20	2	38	28.27	0.09	37	29.47	0.06	35	27.88	0.00	40	29.63	0.14
3	15	20	3	43	29.03	0.08	40	29.35	0.00	43	28.89	0.08	40	28.91	0.00
3	15	20	4	39	28.51	0.05	39	30.14	0.05	39	29.45	0.05	37	29.37	0.00
3	15	20	5	48	31.72	0.12	43	31.66	0.00	44	30.57	0.02	43	30.31	0.00
3	15	20	6	44	31.22	0.13	39	29.86	0.00	44	30.14	0.13	44	30.26	0.13
3	15	20	7	44	28.70	0.13	39	29.66	0.00	40	28.56	0.03	40	27.59	0.03
3	15	20	8	44	29.67	0.02	48	29.71	0.12	43	30.33	0.00	47	29.09	0.09
3	15	20	9	33	30.86	0.00	37	28.97	0.12	38	29.72	0.15	34	29.09	0.03
3	15	20	10	44	28.21	0.07	41	30.72	0.00	44	30.31	0.07	47	30.02	0.15
3	15	20	11	47	27.61	0.07	47	30.14	0.07	44	28.36	0.00	47	30.46	0.07
3	15	20	12	36	28.43	0.00	36	28.52	0.00	36	27.36	0.00	36	29.98	0.00
3	15	20	13	46	29.92	0.12	42	28.26	0.02	41	29.75	0.00	41	28.37	0.00
3	15	20	14	48	32.30	0.17	43	30.27	0.05	43	29.64	0.05	41	29.34	0.00
3	15	20	15	47	27.87	0.00	47	28.54	0.00	47	27.52	0.00	47	28.86	0.00
3	15	20	16	44	30.81	0.00	47	30.44	0.07	47	30.74	0.07	49	30.12	0.11
3	15	20	17	33	28.17	0.00	33	29.75	0.00	40	28.98	0.21	37	30.19	0.12
3	15	20	18	39	29.66	0.00	44	30.93	0.13	39	31.00	0.00	47	29.24	0.21
3	15	20	19	47	30.45	0.09	43	30.61	0.00	47	30.54	0.09	48	30.42	0.12
3	15	20	20	41	28.76	0.05	40	29.91	0.03	42	28.40	0.08	39	29.06	0.00
3	20	20	1	67	66.96	0.10	64	63.88	0.05	66	61.70	0.08	61	62.44	0.00
3	20	20	2	63	60.78	0.00	64	64.36	0.02	66	63.40	0.05	63	64.53	0.00
3	20	20	3	59	68.23	0.00	59	63.56	0.00	59	61.22	0.00	59	64.44	0.00
3	20	20	4	53	63.94	0.04	51	63.64	0.00	57	64.89	0.12	55	64.72	0.08
3	20	20	5	65	68.63	0.07	61	61.87	0.00	61	63.08	0.00	61	63.35	0.00
3	20	20	6	61	63.56	0.00	61	59.28	0.00	64	62.75	0.05	64	62.12	0.05
3	20	20	7	60	61.53	0.05	58	64.67	0.02	57	63.47	0.00	57	59.87	0.00
3	20	20	8	55	61.89	0.00	58	64.51	0.05	60	65.02	0.09	58	60.47	0.05
3	20	20	9	54	65.39	0.00	62	65.36	0.15	54	62.77	0.00	63	62.40	0.17
3	20	20	10	65	61.98	0.08	63	60.20	0.05	60	63.05	0.00	62	62.50	0.03
3	20	20	11	61	57.81	0.03	60	58.42	0.02	59	61.46	0.00	59	62.38	0.00
3	20	20	12	58	65.01	0.00	58	61.18	0.00	58	61.81	0.00	58	63.64	0.00
3	20	20	13	62	64.15	0.00	62	64.56	0.00	62	64.13	0.00	62	62.56	0.00
3	20	20	14	53	64.08	0.00	53	64.83	0.00	53	66.55	0.00	53	64.81	0.00
3	20	20	15	58	63.96	0.05	55	63.37	0.00	58	65.19	0.05	60	63.32	0.09
3	20	20	16	51	63.62	0.00	60	61.32	0.18	62	61.89	0.22	56	63.97	0.10
3	20	20	17	55	65.68	0.00	55	60.22	0.00	55	65.05	0.00	55	67.89	0.00
3	20	20	18	59	61.84	0.00	62	62.81	0.05	62	63.21	0.05	59	61.89	0.00
3	20	20	19	59	61.97	0.00	62	69.01	0.05	60	62.68	0.02	60	62.36	0.02
3	20	20	20	52	60.69	0.00	52	69.53	0.00	52	62.06	0.00	52	56.72	0.00

**Table B.9. Results obtained by the Wilcoxon Signed-Rank Test comparing the objective values of the ILS (perturbation P.2) for 100 iterations at various levels of  $\beta$ .**

Measured Value	Values of $\beta$ Compared	Sample Size	Z-Value	Significantly different at *p = 0.05?
ts	(0.2, 0.4)	116	-0.3733	no
ts	(0.2, 0.6)	118	-1.5898	no
ts	(0.2, 0.8)	119	-2.1692	yes
ts	(0.4, 0.6)	114	-1.3614	no
ts	(0.4, 0.8)	101	-1.7717	no
ts	(0.6, 0.8)	108	-0.7556	no
tft	(0.2, 0.4)	104	-1.3474	no
tft	(0.2, 0.6)	112	-1.1322	no
tft	(0.2, 0.8)	107	-0.2626	no
tft	(0.4, 0.6)	107	-0.5299	no
tft	(0.4, 0.8)	99	-0.7085	no
tft	(0.6, 0.8)	105	-0.5962	no
fmax	(0.2, 0.4)	127	-0.3489	no
fmax	(0.2, 0.6)	115	-0.2944	no
fmax	(0.2, 0.8)	117	-1.6414	no
fmax	(0.4, 0.6)	126	-0.1230	no
fmax	(0.4, 0.8)	120	-1.5242	no
fmax	(0.6, 0.8)	114	-0.8793	no

**Table B.10. Results of the ILS (perturbation P.3) for 100 iterations and for the best combinations of  $\beta$  and  $\gamma$  for each objective.**

M	J	T	V	$\beta / \gamma$								
				0.2 / 0.1			0.2 / 0.05			0.2 / 0.1		
				ts	time(s)	RPD	tft	time(s)	RPD	fmax	time(s)	RPD
2	10	10	1	3	17.75	50	134	21.58	0	35	17.14	9
2	10	10	2	2	17.58	0	156	20.31	4	32	17.47	3
2	10	10	3	2	16.21	0	133	20.93	0	30	17.27	0
2	10	10	4	2	17.25	0	95	19.31	0	24	16.17	0
2	10	10	5	1	15.97	0	107	19.47	3	22	16.51	0
2	10	10	6	3	17.31	50	106	18.31	2	26	17.22	0
2	10	10	7	4	18.86	0	133	19.47	5	33	17.30	6
2	10	10	8	4	18.64	0	144	20.26	7	31	18.24	3
2	10	10	9	4	18.86	100	150	17.86	13	31	16.99	3
2	10	10	10	5	18.42	25	139	20.79	1	32	17.94	0
2	10	10	11	4	19.05	33	154	21.47	5	33	17.57	3
2	10	10	12	5	18.39	25	168	21.50	2	35	17.87	0
2	10	10	13	4	19.25	33	103	20.74	0	25	17.22	0
2	10	10	14	4	18.70	0	168	20.17	10	34	17.64	0
2	10	10	15	2	16.88	0	148	20.61	0	35	17.76	9
2	10	10	16	3	17.95	0	127	19.96	2	29	16.60	4
2	10	10	17	3	17.37	0	150	19.86	1	29	16.86	0
2	10	10	18	2	16.98	0	96	19.08	0	27	17.10	4
2	10	10	19	3	18.47	0	139	21.00	1	33	16.75	3
2	10	10	20	4	19.75	33	122	20.19	0	26	18.69	0
2	15	10	1	4	39.87	0	269	51.22	0	39	35.27	0
2	15	10	2	4	39.91	33	333	47.48	7	52	38.59	11
2	15	10	3	7	42.00	17	260	54.99	0	40	37.38	0
2	15	10	4	6	36.68	100	282	50.16	0	40	33.63	3
2	15	10	5	6	42.39	20	264	52.75	2	45	39.81	2
2	15	10	6	6	40.17	0	285	50.96	0	47	36.88	0
2	15	10	7	6	39.25	20	238	50.17	0	36	37.94	0
2	15	10	8	6	41.23	20	218	57.24	7	35	39.29	0
2	15	10	9	6	46.01	0	211	56.61	0	33	37.72	0
2	15	10	10	6	43.26	50	336	51.32	15	51	36.79	2
2	15	10	11	4	42.25	0	294	45.55	4	43	35.89	0
2	15	10	12	7	46.03	75	286	58.36	3	46	36.50	2
2	15	10	13	8	39.73	14	301	54.43	0	47	34.23	0
2	15	10	14	6	43.94	0	316	54.52	9	53	37.06	13
2	15	10	15	10	35.62	43	360	58.02	4	59	32.64	2
2	15	10	16	6	43.23	0	235	54.41	4	40	38.06	0
2	15	10	17	4	33.37	0	329	51.75	0	54	36.26	0
2	15	10	18	8	45.09	33	338	60.23	3	57	38.41	2
2	15	10	19	6	43.39	0	217	47.76	5	37	35.91	6
2	15	10	20	8	48.00	14	338	51.75	4	58	39.71	7

Table B.10. (Continued).

M	J	T	V	$\beta / \gamma$								
				0.2 / 0.1			0.2 / 0.1			0.2 / 0.1		
				ts	time(s)	RPD	tft	time(s)	RPD	fmax	time(s)	RPD
2	10	15	1	7	19.00	0	210	22.77	0	42	18.28	0
2	10	15	2	7	17.39	0	168	21.24	0	40	16.61	3
2	10	15	3	8	17.83	0	137	21.61	1	31	17.47	0
2	10	15	4	8	17.40	33	148	22.00	0	35	17.81	0
2	10	15	5	6	18.82	20	161	20.87	0	34	17.74	0
2	10	15	6	5	19.82	0	187	20.25	3	40	17.20	8
2	10	15	7	8	17.31	33	138	20.15	0	31	17.05	0
2	10	15	8	10	17.97	0	157	21.65	0	38	18.09	3
2	10	15	9	8	18.58	0	159	20.91	0	36	17.45	0
2	10	15	10	8	16.61	33	144	22.02	0	37	17.34	0
2	10	15	11	8	17.03	33	157	21.69	0	37	17.42	0
2	10	15	12	7	17.45	17	162	20.49	0	36	17.36	0
2	10	15	13	7	17.92	17	149	22.48	0	36	17.30	0
2	10	15	14	10	18.32	25	211	22.17	2	42	17.63	0
2	10	15	15	11	18.91	10	183	22.49	0	40	18.07	0
2	10	15	16	7	17.73	17	173	22.43	1	37	18.03	0
2	10	15	17	6	17.28	0	134	20.81	13	30	17.19	3
2	10	15	18	8	18.43	14	169	23.22	0	41	18.50	11
2	10	15	19	8	17.71	0	172	20.89	0	41	17.83	8
2	10	15	20	8	17.53	14	184	21.98	0	43	17.55	5
2	15	15	1	14	47.94	8	312	60.87	1	54	41.21	0
2	15	15	2	14	45.69	17	383	54.94	7	57	37.00	4
2	15	15	3	11	43.53	10	281	58.24	0	46	39.84	5
2	15	15	4	13	48.42	0	341	56.53	0	54	41.11	0
2	15	15	5	10	45.88	11	321	55.35	2	51	36.97	6
2	15	15	6	11	46.53	0	410	60.48	15	60	37.81	2
2	15	15	7	12	46.01	0	399	53.94	2	64	38.52	5
2	15	15	8	13	47.20	8	342	56.23	1	55	38.33	4
2	15	15	9	9	41.09	13	348	55.00	1	55	35.91	0
2	15	15	10	14	46.62	8	321	63.06	2	53	40.89	8
2	15	15	11	14	46.20	8	417	62.28	10	60	41.19	7
2	15	15	12	13	45.35	18	331	60.80	0	50	41.53	4
2	15	15	13	14	49.20	8	420	63.74	0	65	40.98	5
2	15	15	14	11	45.03	0	344	55.15	7	51	40.69	2
2	15	15	15	8	41.70	0	322	54.21	0	52	37.18	2
2	15	15	16	9	45.60	0	306	56.98	0	51	38.11	2
2	15	15	17	15	48.47	15	361	57.57	4	53	38.69	2
2	15	15	18	12	46.03	20	358	60.25	1	55	40.03	6
2	15	15	19	14	46.23	8	381	57.34	5	57	39.45	4
2	15	15	20	14	46.12	8	379	59.63	1	58	37.61	4

Table B.10. (Continued).

M	J	T	V	$\beta / \gamma$								
				0.2 / 0.1			0.2 / 0.1			0.2 / 0.1		
				ts	time(s)	RPD	tft	time(s)	RPD	fmax	time(s)	RPD
3	15	15	1	1	24.19	0	199	30.40	3	31	24.06	0
3	15	15	2	1	25.47	0	152	31.04	2	26	23.93	4
3	15	15	3	2	23.31	100	186	32.75	3	31	23.14	15
3	15	15	4	2	26.38	100	136	32.75	3	22	23.32	10
3	15	15	5	1	25.44	0	162	27.69	21	27	23.34	17
3	15	15	6	2	25.33	100	172	29.48	0	31	23.42	15
3	15	15	7	1	23.52	0	152	30.74	1	26	23.34	0
3	15	15	8	2	25.14	0	217	31.12	0	34	24.36	0
3	15	15	9	1	24.42	0	216	30.89	10	33	23.08	18
3	15	15	10	2	24.22	100	180	30.48	7	29	22.63	16
3	15	15	11	1	23.20	0	166	29.44	0	27	23.72	4
3	15	15	12	2	24.33	0	165	31.42	4	28	24.71	4
3	15	15	13	2	26.42	100	184	27.25	6	28	22.71	4
3	15	15	14	2	25.86	0	197	27.97	6	33	24.16	6
3	15	15	15	3	23.85	50	153	33.36	4	28	23.33	12
3	15	15	16	2	24.87	100	162	31.06	0	26	23.03	4
3	15	15	17	2	23.52	0	185	35.84	1	31	23.46	7
3	15	15	18	1	25.54	0	152	30.43	2	24	22.52	9
3	15	15	19	3	23.25	200	181	33.56	6	27	24.20	4
3	15	15	20	3	26.83	200	149	31.14	0	26	23.65	0
3	20	15	1	4	57.55	100	303	71.11	0	41	45.72	8
3	20	15	2	3	59.44	50	207	74.25	0	29	41.28	0
3	20	15	3	3	50.99	50	329	67.27	0	39	44.49	0
3	20	15	4	2	54.65	0	282	69.38	7	37	43.45	9
3	20	15	5	3	59.85	50	360	73.32	7	39	44.60	0
3	20	15	6	3	57.95	0	315	74.06	0	42	42.05	8
3	20	15	7	4	54.05	100	370	70.99	6	51	46.50	21
3	20	15	8	3	52.27	50	235	70.50	7	30	46.56	7
3	20	15	9	4	59.47	100	258	75.87	4	34	45.36	6
3	20	15	10	4	54.89	100	289	74.42	17	37	46.31	19
3	20	15	11	3	60.58	0	256	67.63	0	36	45.68	9
3	20	15	12	3	55.81	0	334	65.96	0	43	44.23	5
3	20	15	13	4	60.42	33	344	72.57	7	39	51.45	0
3	20	15	14	3	52.37	50	292	67.03	7	36	44.12	0
3	20	15	15	3	68.07	50	236	66.53	0	31	41.86	0
3	20	15	16	3	50.36	0	308	60.45	4	37	44.38	6
3	20	15	17	2	48.57	0	245	65.25	0	30	44.41	3
3	20	15	18	4	52.89	33	371	71.00	2	43	43.81	0
3	20	15	19	3	63.28	50	324	64.17	0	44	46.07	7
3	20	15	20	4	57.60	100	284	61.81	8	36	41.18	6



Table B.10. (Continued).

M	J	T	V	$\beta / \gamma$								
				0.2 / 0.1			0.2 / 0.1			0.2 / 0.1		
				ts	time(s)	RPD	tft	time(s)	RPD	fmax	time(s)	RPD
3	15	20	1	12	28.55	9	274	35.92	8	42	24.96	5
3	15	20	2	7	23.47	40	208	33.97	16	31	24.44	0
3	15	20	3	11	24.54	120	194	30.42	4	32	25.36	3
3	15	20	4	10	26.37	11	155	33.61	0	37	23.84	32
3	15	20	5	9	26.44	0	225	34.51	0	34	25.25	0
3	15	20	6	10	26.11	11	183	30.50	0	34	24.36	10
3	15	20	7	5	26.04	0	205	31.27	5	37	25.03	12
3	15	20	8	9	27.67	13	249	33.47	2	42	25.83	5
3	15	20	9	10	23.76	43	205	31.98	15	29	24.07	0
3	15	20	10	10	27.00	67	206	36.97	0	40	26.45	11
3	15	20	11	10	27.33	43	240	32.55	9	37	24.81	3
3	15	20	12	7	24.34	40	193	31.52	16	28	23.14	0
3	15	20	13	6	23.39	0	189	31.24	3	30	25.05	0
3	15	20	14	9	28.78	0	224	34.39	5	35	24.95	0
3	15	20	15	9	23.84	13	247	33.15	7	36	23.98	0
3	15	20	16	8	24.97	14	216	34.34	0	34	24.41	0
3	15	20	17	9	25.37	80	186	31.36	13	29	23.22	0
3	15	20	18	9	24.93	50	177	32.90	5	32	23.56	0
3	15	20	19	12	27.34	71	246	30.29	3	39	25.95	3
3	15	20	20	8	24.34	0	195	35.70	0	33	23.92	14
3	20	20	1	17	65.20	21	448	80.02	3	55	48.56	10
3	20	20	2	14	56.75	27	391	80.84	1	49	50.14	4
3	20	20	3	13	58.78	8	367	75.93	2	46	49.30	2
3	20	20	4	17	61.76	31	357	79.80	6	39	47.93	0
3	20	20	5	14	60.12	0	399	78.64	0	55	51.80	12
3	20	20	6	15	62.13	25	451	76.67	0	53	46.84	2
3	20	20	7	12	52.83	9	413	69.68	8	46	48.21	0
3	20	20	8	15	57.61	25	374	76.84	5	46	51.03	10
3	20	20	9	16	54.89	14	422	74.55	15	50	52.92	9
3	20	20	10	13	62.20	30	366	80.11	0	49	49.95	9
3	20	20	11	10	54.08	0	374	82.11	0	48	46.50	7
3	20	20	12	12	59.84	9	338	80.32	2	44	51.22	5
3	20	20	13	15	55.01	36	429	73.56	9	48	49.40	2
3	20	20	14	13	58.71	18	330	77.38	0	44	49.17	0
3	20	20	15	15	56.77	36	370	78.60	6	49	49.10	9
3	20	20	16	13	55.93	18	376	83.63	7	50	50.64	6
3	20	20	17	13	57.29	8	393	82.31	5	50	53.58	6
3	20	20	18	13	54.94	18	362	80.19	0	43	48.70	0
3	20	20	19	14	57.28	17	424	79.39	3	48	53.10	7
3	20	20	20	13	53.45	18	390	79.58	3	49	48.41	0

**Table B.11. Results obtained by the Wilcoxon Signed-Rank Test comparing the objective values of the ILS (perturbation P.3) for 100 iterations at the best levels of  $\beta$  and  $\gamma$ .**

Measured Value	Parameter Values of ( $\beta / \gamma$ ) Compared		Sample Size	Z-Value	Significantly different at *p = 0.05?
	Combination with lowest RPD	Parameters Compared			
ts	(0.2 / 0.10)	(0.2 / 0.05)	92	-0.3563	no
ts	(0.2 / 0.10)	(0.2 / 0.25)	92	-4.1022	yes
ts	(0.2 / 0.10)	(0.2 / 0.50)	117	-7.2755	yes
ts	(0.2 / 0.10)	(0.4 / 0.05)	92	-0.9150	no
ts	(0.2 / 0.10)	(0.4 / 0.10)	93	-1.4522	no
ts	(0.2 / 0.10)	(0.4 / 0.25)	105	-6.0771	yes
ts	(0.2 / 0.10)	(0.4 / 0.50)	120	-8.1591	yes
ts	(0.2 / 0.10)	(0.6 / 0.05)	100	-2.4825	yes
ts	(0.2 / 0.10)	(0.6 / 0.10)	96	-1.7047	no
ts	(0.2 / 0.10)	(0.6 / 0.25)	111	-7.1144	yes
ts	(0.2 / 0.10)	(0.6 / 0.50)	129	-8.6445	yes
ts	(0.2 / 0.10)	(0.8 / 0.05)	93	-2.8909	yes
ts	(0.2 / 0.10)	(0.8 / 0.10)	94	-3.7125	yes
ts	(0.2 / 0.10)	(0.8 / 0.25)	108	-6.8843	yes
ts	(0.2 / 0.10)	(0.8 / 0.50)	127	-8.8415	yes
tft	(0.2 / 0.05)	(0.2 / 0.10)	122	-1.0897	no
tft	(0.2 / 0.05)	(0.2 / 0.25)	128	-2.6671	yes
tft	(0.2 / 0.05)	(0.2 / 0.50)	132	-6.6253	yes
tft	(0.2 / 0.05)	(0.4 / 0.05)	119	-1.9252	no
tft	(0.2 / 0.05)	(0.4 / 0.10)	121	-2.1081	yes
tft	(0.2 / 0.05)	(0.4 / 0.25)	123	-4.2214	yes
tft	(0.2 / 0.05)	(0.4 / 0.50)	122	-7.0275	yes
tft	(0.2 / 0.05)	(0.6 / 0.05)	114	-3.1653	yes
tft	(0.2 / 0.05)	(0.6 / 0.10)	126	-4.2621	yes
tft	(0.2 / 0.05)	(0.6 / 0.25)	128	-5.7135	yes
tft	(0.2 / 0.05)	(0.6 / 0.50)	132	-8.2652	yes
tft	(0.2 / 0.05)	(0.8 / 0.05)	123	-1.8854	yes
tft	(0.2 / 0.05)	(0.8 / 0.10)	121	-3.6859	yes
tft	(0.2 / 0.05)	(0.8 / 0.25)	125	-6.3483	yes
tft	(0.2 / 0.05)	(0.8 / 0.50)	132	-7.7144	yes
fmax	(0.2 / 0.10)	(0.2 / 0.05)	95	-1.2398	no
fmax	(0.2 / 0.10)	(0.2 / 0.25)	105	-4.2869	yes
fmax	(0.2 / 0.10)	(0.2 / 0.50)	117	-7.4550	yes
fmax	(0.2 / 0.10)	(0.4 / 0.05)	96	-1.9879	yes
fmax	(0.2 / 0.10)	(0.4 / 0.10)	106	-2.1354	yes
fmax	(0.2 / 0.10)	(0.4 / 0.25)	105	-4.9806	yes
fmax	(0.2 / 0.10)	(0.4 / 0.50)	125	-8.2271	yes
fmax	(0.2 / 0.10)	(0.6 / 0.05)	100	-2.8297	yes
fmax	(0.2 / 0.10)	(0.6 / 0.10)	97	-2.9631	yes
fmax	(0.2 / 0.10)	(0.6 / 0.25)	109	-5.5839	yes
fmax	(0.2 / 0.10)	(0.6 / 0.50)	121	-8.5073	yes
fmax	(0.2 / 0.10)	(0.8 / 0.05)	101	-2.5898	yes
fmax	(0.2 / 0.10)	(0.8 / 0.10)	109	-4.6966	yes
fmax	(0.2 / 0.10)	(0.8 / 0.25)	117	-7.0593	yes
fmax	(0.2 / 0.10)	(0.8 / 0.50)	124	-8.7877	yes

**Table B.12. Overall results of the MIP model and the ILS methods for SSP-NPM-I given a computation time limit of 600 seconds.**

M	J	T	V	MIP			P.1			P.2			P.3		
				ts	tft	fmax	ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
2	10	10	1	2	134	32	3	134	35	2	134	32	2	134	32
2	10	10	2	2	146	31	2	156	36	2	150	31	2	150	31
2	10	10	3	2	133	30	2	134	30	2	134	30	2	133	30
2	10	10	4	2	95	24	3	95	24	2	95	24	2	95	24
2	10	10	5	1	104	22	2	114	22	1	104	22	1	104	22
2	10	10	6	2	104	26	4	106	26	2	107	26	2	104	26
2	10	10	7	4	127	31	5	127	33	4	127	31	4	127	31
2	10	10	8	3	135	28	4	137	30	4	136	28	3	135	28
2	10	10	9	2	133	30	3	150	31	2	133	30	2	133	30
2	10	10	10	3	137	32	5	139	38	4	137	32	4	137	32
2	10	10	11	3	146	32	5	146	33	4	146	32	4	146	32
2	10	10	12	4	165	35	4	168	35	4	165	37	4	168	35
2	10	10	13	3	103	25	4	103	25	4	103	25	3	103	25
2	10	10	14	4	153	34	6	178	43	4	153	34	4	153	34
2	10	10	15	2	146	32	4	148	36	2	148	32	2	148	32
2	10	10	16	3	124	28	3	129	30	3	128	28	3	124	28
2	10	10	17	3	148	29	4	150	29	3	151	29	3	148	29
2	10	10	18	2	96	26	3	110	27	2	99	26	2	96	26
2	10	10	19	3	137	32	3	145	34	3	137	32	3	137	32
2	10	10	20	3	122	26	4	122	26	3	122	27	3	122	26
2	15	10	1	3	275	42	4	269	39	5	296	46	4	268	39
2	15	10	2	3	312	47	6	331	53	5	337	49	4	328	45
2	15	10	3	5	260	41	6	260	43	6	272	46	6	258	40
2	15	10	4	3	273	42	5	282	40	6	286	43	5	281	39
2	15	10	5	4	258	44	6	258	45	5	263	50	5	258	45
2	15	10	6	4	286	48	7	298	47	6	293	51	5	283	47
2	15	10	7	4	240	35	5	238	39	6	251	37	5	238	35
2	15	10	8	4	195	34	7	234	35	5	220	37	5	204	35
2	15	10	9	4	211	33	7	211	34	5	233	38	6	210	33
2	15	10	10	3	308	48	4	336	51	5	302	53	5	292	50
2	15	10	11	4	276	43	5	302	43	5	304	48	4	287	43
2	15	10	12	4	291	44	5	280	47	6	285	50	4	279	44
2	15	10	13	5	302	49	9	317	53	7	316	52	7	301	45
2	15	10	14	4	284	46	9	333	55	6	301	51	5	284	46
2	15	10	15	6	354	58	10	374	60	6	346	60	8	349	58
2	15	10	16	4	240	40	6	229	41	6	235	44	6	226	40
2	15	10	17	3	337	53	5	329	55	4	345	54	4	330	52
2	15	10	18	5	334	55	7	356	57	7	328	58	7	330	56
2	15	10	19	4	235	35	6	228	37	6	228	40	6	219	36
2	15	10	20	5	327	54	8	338	58	5	333	57	6	329	53

Table B.12. (Continued).

M	J	T	V	MIP			P.1			P.2			P.3		
				ts	tft	fmax	ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
2	10	15	1	7	212	42	8	210	43	7	210	42	7	210	42
2	10	15	2	6	168	39	10	184	39	6	168	39	6	168	39
2	10	15	3	6	135	31	10	150	36	7	135	33	7	135	31
2	10	15	4	6	148	35	11	148	35	7	148	35	6	148	35
2	10	15	5	5	161	34	6	168	37	5	161	34	5	161	34
2	10	15	6	5	181	37	6	188	41	6	187	38	5	181	37
2	10	15	7	6	138	31	8	139	31	6	139	31	6	138	31
2	10	15	8	9	157	37	12	157	41	10	157	37	10	157	37
2	10	15	9	7	159	36	8	161	37	8	159	36	8	159	36
2	10	15	10	5	144	37	8	175	42	7	150	37	5	144	37
2	10	15	11	6	157	37	9	157	37	6	157	37	7	157	37
2	10	15	12	6	160	36	7	162	39	6	162	36	6	160	36
2	10	15	13	6	149	36	8	149	36	6	149	36	7	149	36
2	10	15	14	8	210	42	10	211	42	8	207	42	8	207	42
2	10	15	15	8	183	40	10	183	41	9	183	41	9	183	40
2	10	15	16	6	172	37	8	183	37	6	176	38	6	172	37
2	10	15	17	5	121	29	6	134	34	5	119	29	6	119	29
2	10	15	18	6	165	37	8	169	41	6	169	38	7	169	37
2	10	15	19	7	172	38	8	172	41	7	172	38	7	172	38
2	10	15	20	7	184	41	8	202	43	7	184	41	7	191	41
2	15	15	1	10	305	58	13	308	54	12	325	58	11	305	54
2	15	15	2	10	350	56	13	383	63	12	373	60	13	369	56
2	15	15	3	9	285	46	11	314	57	11	309	51	10	284	46
2	15	15	4	11	345	59	15	344	54	13	371	63	12	341	54
2	15	15	5	8	316	49	9	318	51	9	336	50	10	315	48
2	15	15	6	10	345	61	12	416	64	11	370	59	11	356	58
2	15	15	7	11	391	65	12	399	63	13	399	67	12	393	61
2	15	15	8	11	346	55	15	342	57	14	358	62	13	342	55
2	15	15	9	6	347	55	8	348	55	7	360	59	8	346	55
2	15	15	10	11	335	52	13	338	51	13	324	55	13	310	50
2	15	15	11	11	378	55	13	431	63	15	422	62	13	378	56
2	15	15	12	10	330	51	13	338	50	12	337	54	11	332	49
2	15	15	13	9	436	65	12	473	70	13	424	69	12	425	63
2	15	15	14	8	318	50	10	380	55	11	314	55	11	314	49
2	15	15	15	7	324	51	8	331	52	10	329	57	8	322	50
2	15	15	16	7	299	50	10	310	50	9	316	53	8	308	48
2	15	15	17	11	339	54	13	363	53	15	367	57	14	345	50
2	15	15	18	9	378	55	11	356	56	11	380	59	10	352	52
2	15	15	19	11	363	57	14	402	60	13	386	60	13	393	55
2	15	15	20	11	385	60	14	372	56	14	379	62	13	379	57

Table B.12. (Continued).

M	J	T	V	MIP			P.1			P.2			P.3		
				ts	tft	fmax	ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
3	15	15	1	1	187	30	4	207	35	3	210	32	1	195	30
3	15	15	2	1	141	26	2	168	26	5	173	29	1	141	26
3	15	15	3	1	173	29	4	188	37	2	196	35	1	166	27
3	15	15	4	1	130	21	2	138	22	4	151	26	1	131	21
3	15	15	5	1	135	21	1	160	23	2	164	26	1	134	23
3	15	15	6	1	178	29	2	183	26	4	205	33	1	172	26
3	15	15	7	1	147	27	2	153	26	3	179	29	1	147	25
3	15	15	8	1	218	34	2	218	34	3	244	40	1	214	31
3	15	15	9	1	194	26	2	210	36	4	217	36	1	205	28
3	15	15	10	1	165	25	4	180	31	4	198	32	1	168	25
3	15	15	11	0	152	26	3	166	26	4	194	32	0	155	25
3	15	15	12	1	154	26	5	176	28	2	191	28	1	160	26
3	15	15	13	1	190	26	2	189	40	4	193	31	1	174	26
3	15	15	14	1	177	28	3	197	33	4	206	33	1	177	28
3	15	15	15	1	128	23	2	159	32	2	149	29	1	145	23
3	15	15	16	1	149	25	6	148	28	4	175	32	1	149	25
3	15	15	17	1	179	29	2	185	31	3	209	33	2	180	30
3	15	15	18	1	150	22	1	166	27	4	187	28	1	149	22
3	15	15	19	1	161	26	3	194	27	3	185	30	1	161	25
3	15	15	20	1	143	26	2	171	35	4	172	31	1	145	26
3	20	15	1	2	337	37	2	306	37	7	360	45	2	300	35
3	20	15	2	1	214	29	7	223	29	7	299	37	3	204	27
3	20	15	3	2	328	40	6	360	48	7	394	51	3	329	41
3	20	15	4	2	282	38	5	283	39	7	325	46	2	265	33
3	20	15	5	2	337	41	2	341	45	4	411	47	2	333	40
3	20	15	6	1	330	39	4	333	39	7	357	46	3	303	37
3	20	15	7	1	325	41	4	370	51	6	394	49	2	354	43
3	20	15	8	2	250	30	4	254	37	7	286	39	2	218	28
3	20	15	9	2	251	30	4	259	30	8	264	41	3	256	30
3	20	15	10	2	251	34	3	303	39	7	311	41	2	257	31
3	20	15	11	2	267	36	2	316	39	6	358	41	2	270	33
3	20	15	12	2	324	46	3	346	45	8	386	51	2	336	40
3	20	15	13	2	337	42	3	380	51	7	381	50	3	322	38
3	20	15	14	1	271	39	6	292	39	6	323	42	2	287	34
3	20	15	15	2	264	32	2	246	35	6	292	41	2	239	29
3	20	15	16	2	320	43	8	305	41	7	324	46	2	303	34
3	20	15	17	1	233	30	3	315	44	9	311	40	2	242	29
3	20	15	18	1	363	46	4	389	43	8	418	50	2	375	43
3	20	15	19	1	344	42	2	324	48	8	387	49	2	334	40
3	20	15	20	1	260	35	5	291	42	5	332	42	2	259	32

Table B.12. (Continued).

M	J	T	V	MIP			P.1			P.2			P.3		
				ts	tft	fmax	ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
3	15	20	1	7	263	43	13	270	45	11	286	48	9	247	41
3	15	20	2	5	164	30	5	208	36	9	205	37	5	173	29
3	15	20	3	4	185	31	11	218	36	7	223	35	7	186	30
3	15	20	4	4	153	30	13	178	37	9	178	38	7	163	31
3	15	20	5	6	223	39	12	241	34	10	238	41	9	220	34
3	15	20	6	6	182	30	12	188	34	11	197	41	7	182	31
3	15	20	7	4	197	33	7	220	35	9	242	40	6	194	33
3	15	20	8	7	225	40	11	255	44	9	265	45	9	228	38
3	15	20	9	5	162	27	6	210	32	7	196	35	6	164	28
3	15	20	10	5	199	33	7	217	37	10	236	39	5	206	35
3	15	20	11	5	230	38	11	240	39	9	255	42	7	223	32
3	15	20	12	4	155	27	7	197	35	8	182	31	4	164	27
3	15	20	13	5	186	32	8	190	36	7	215	35	6	190	29
3	15	20	14	5	210	39	15	218	39	11	252	41	7	211	36
3	15	20	15	6	229	39	12	247	39	8	265	44	7	230	37
3	15	20	16	5	221	36	13	216	38	8	249	42	7	208	33
3	15	20	17	4	158	28	6	199	33	6	173	34	5	169	27
3	15	20	18	5	176	29	10	187	41	7	213	38	7	168	29
3	15	20	19	6	225	37	8	246	54	11	232	40	6	224	36
3	15	20	20	5	195	32	9	199	33	10	216	36	7	201	31
3	20	20	1	8	456	58	14	455	53	15	498	61	14	432	49
3	20	20	2	7	372	57	15	442	49	17	409	58	12	379	43
3	20	20	3	9	399	48	14	374	45	15	400	53	11	360	44
3	20	20	4	10	400	44	15	376	42	16	401	51	13	341	41
3	20	20	5	8	405	50	14	398	51	17	446	61	12	403	49
3	20	20	6	8	467	54	12	457	63	15	487	62	12	453	50
3	20	20	7	8	363	44	11	415	56	15	440	55	9	381	43
3	20	20	8	8	381	48	12	355	45	16	442	54	11	352	43
3	20	20	9	8	419	50	17	385	50	18	440	49	13	385	45
3	20	20	10	10	399	63	12	423	57	18	441	61	12	350	45
3	20	20	11	7	374	48	11	374	48	14	410	56	10	374	47
3	20	20	12	7	389	48	10	333	43	16	378	53	12	333	39
3	20	20	13	7	421	54	15	395	47	15	454	60	11	422	46
3	20	20	14	9	343	53	12	342	44	16	380	53	12	342	44
3	20	20	15	7	341	49	12	382	42	17	360	54	12	343	42
3	20	20	16	8	396	48	10	379	52	17	413	53	10	377	45
3	20	20	17	7	403	51	15	383	50	17	396	50	12	374	46
3	20	20	18	7	409	48	12	407	42	15	429	52	11	363	43
3	20	20	19	9	434	49	14	395	48	15	421	55	14	389	42
3	20	20	20	7	409	49	14	390	52	16	414	52	10	389	45

**Table B.13. Overall results of the ILS methods for SSP-NPM-II given a computation time limit of 600 seconds.**

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
4	40	60	1	l	s	43	1196	93	48	1390	104	47	1205	93
4	40	60	2	l	s	49	1198	90	55	1378	120	45	1168	94
4	40	60	3	l	s	36	1113	95	50	1413	117	44	1194	93
4	40	60	4	l	s	42	1107	95	53	1293	115	40	1162	94
4	40	60	5	l	s	47	967	92	49	1200	112	43	1004	90
4	40	60	6	l	s	51	1051	89	52	1214	91	51	1064	88
4	40	60	7	l	s	40	962	76	53	1230	90	44	1002	82
4	40	60	8	l	s	39	1496	99	52	1645	126	46	1352	99
4	40	60	9	l	s	37	1102	106	51	1406	117	45	1096	95
4	40	60	10	l	s	42	1240	101	56	1503	132	35	1285	98
4	40	60	11	l	s	43	1216	94	54	1367	121	42	1181	92
4	40	60	12	l	s	41	1154	92	49	1410	121	40	1154	90
4	40	60	13	l	s	47	1272	97	53	1503	127	46	1253	97
4	40	60	14	l	s	45	1270	96	54	1489	124	50	1270	100
4	40	60	15	l	s	44	1098	89	52	1236	107	42	1128	89
4	40	60	16	l	s	45	1219	93	55	1437	113	47	1251	98
4	40	60	17	l	s	45	1155	78	42	1301	107	45	1155	89
4	40	60	18	l	s	51	1244	93	53	1385	113	41	1244	93
4	40	60	19	l	s	43	1054	96	49	1304	114	39	1054	98
4	40	60	20	l	s	36	1291	105	52	1640	134	50	1395	99
4	40	60	1	l	d	349	8228	555	306	8760	559	323	8228	555
4	40	60	2	l	d	363	7322	389	296	7651	449	326	7322	394
4	40	60	3	l	d	384	8817	555	317	8951	552	328	8817	552
4	40	60	4	l	d	352	8075	486	283	8453	494	306	8075	494
4	40	60	5	l	d	347	7996	540	293	8396	540	324	8274	540
4	40	60	6	l	d	336	6882	511	293	7262	523	320	7019	489
4	40	60	7	l	d	378	7428	446	292	7685	494	317	7355	470
4	40	60	8	l	d	341	7148	402	290	7550	412	307	7087	412
4	40	60	9	l	d	328	7655	438	268	8209	508	308	7584	449
4	40	60	10	l	d	352	7735	418	298	7688	440	311	7633	421
4	40	60	11	l	d	367	8604	529	308	9013	590	334	8541	529
4	40	60	12	l	d	342	7027	400	284	7244	435	332	7027	400
4	40	60	13	l	d	351	7305	456	290	7765	461	310	7388	444
4	40	60	14	l	d	373	8514	616	312	8738	616	312	8514	616
4	40	60	15	l	d	349	7369	425	288	7455	434	331	7382	434
4	40	60	16	l	d	348	7629	451	274	8189	493	321	7884	451
4	40	60	17	l	d	334	6440	380	276	6611	401	302	6396	375
4	40	60	18	l	d	355	7642	418	289	7728	427	309	7484	418
4	40	60	19	l	d	375	8870	561	310	9019	594	339	8895	561
4	40	60	20	l	d	346	6945	405	285	7004	414	314	7039	409
4	40	60	1	h	s	43	1802	158	53	2391	189	46	1898	156
4	40	60	2	h	s	47	1381	120	49	1770	166	37	1381	120
4	40	60	3	h	s	39	1578	158	54	2206	191	42	1626	150
4	40	60	4	h	s	51	1838	152	55	2099	179	47	1847	157
4	40	60	5	h	s	39	1621	149	48	2144	173	42	1712	135
4	40	60	6	h	s	38	1713	150	56	1948	182	42	1709	144
4	40	60	7	h	s	39	1544	121	42	1816	167	40	1581	132
4	40	60	8	h	s	37	1729	156	51	2109	171	45	1834	157
4	40	60	9	h	s	36	1538	142	52	2027	176	45	1538	146
4	40	60	10	h	s	43	1509	119	51	1882	163	38	1548	125
4	40	60	11	h	s	39	1472	138	46	1721	155	33	1397	139
4	40	60	12	h	s	31	1506	137	43	1827	159	41	1504	135
4	40	60	13	h	s	38	1538	124	53	1656	170	40	1378	134
4	40	60	14	h	s	40	1622	133	51	1942	175	41	1645	122
4	40	60	15	h	s	46	1413	121	46	1576	164	40	1488	143
4	40	60	16	h	s	35	1548	144	53	1566	168	42	1548	123
4	40	60	17	h	s	39	1456	128	48	2099	168	38	1526	145
4	40	60	18	h	s	43	1607	142	55	1832	167	45	1607	151
4	40	60	19	h	s	49	1840	159	52	2018	186	41	1641	165
4	40	60	20	h	s	38	1532	142	49	1915	171	43	1532	146

Table B.13. (Continued).

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
4	40	60	1	h	d	366	13689	767	302	13717	861	318	13672	801
4	40	60	2	h	d	326	13571	839	290	14456	871	298	13946	839
4	40	60	3	h	d	331	11731	680	257	12140	719	318	11682	680
4	40	60	4	h	d	338	15326	1087	296	15414	1087	323	15326	1087
4	40	60	5	h	d	355	14318	788	287	14902	834	331	13962	788
4	40	60	6	h	d	367	14212	893	304	14827	989	337	14212	999
4	40	60	7	h	d	319	13051	998	290	13509	998	322	13148	954
4	40	60	8	h	d	366	12792	734	305	13331	750	329	13027	734
4	40	60	9	h	d	350	12553	698	294	12596	734	305	12367	771
4	40	60	10	h	d	344	12395	678	285	12582	782	287	12395	678
4	40	60	11	h	d	353	15347	1220	296	15849	1221	345	15347	1176
4	40	60	12	h	d	362	12673	710	288	12682	750	325	12633	710
4	40	60	13	h	d	358	12636	697	287	12800	710	318	12597	701
4	40	60	14	h	d	326	11179	627	281	11046	641	304	10896	627
4	40	60	15	h	d	307	11063	609	268	11568	705	300	11049	630
4	40	60	16	h	d	372	12369	676	304	12965	742	332	12371	710
4	40	60	17	h	d	354	12579	763	286	12675	855	315	12579	763
4	40	60	18	h	d	338	11763	672	283	12529	744	311	11954	672
4	40	60	19	h	d	332	11593	680	273	12143	688	302	11850	680
4	40	60	20	h	d	394	13905	801	316	14673	846	325	13905	801
4	60	60	1	l	s	73	2971	138	80	3786	178	77	3197	158
4	60	60	2	l	s	68	2942	139	81	3345	157	77	2965	139
4	60	60	3	l	s	61	3162	145	89	3450	172	78	3129	140
4	60	60	4	l	s	75	2918	148	86	3581	170	78	3018	148
4	60	60	5	l	s	78	3093	143	88	3797	195	78	3093	150
4	60	60	6	l	s	73	2975	165	74	3545	161	81	2974	165
4	60	60	7	l	s	71	3018	152	91	3257	195	73	3094	152
4	60	60	8	l	s	66	3137	145	79	3656	205	78	3011	154
4	60	60	9	l	s	75	2947	139	92	3681	179	79	3001	143
4	60	60	10	l	s	68	2617	120	79	3062	159	72	2636	139
4	60	60	11	l	s	73	2923	145	85	3549	178	67	2923	145
4	60	60	12	l	s	67	2991	143	89	3284	161	80	2991	147
4	60	60	13	l	s	63	2996	140	83	3575	185	76	2996	154
4	60	60	14	l	s	71	3264	154	84	3589	198	80	3372	159
4	60	60	15	l	s	67	3224	149	91	4185	190	77	3467	160
4	60	60	16	l	s	70	3065	146	84	3434	178	77	3069	138
4	60	60	17	l	s	69	3079	146	81	3593	182	72	3079	161
4	60	60	18	l	s	77	2866	132	86	3252	158	83	2866	135
4	60	60	19	l	s	62	2694	128	81	3192	181	66	2694	128
4	60	60	20	l	s	61	3180	146	82	3782	184	66	3145	157
4	60	60	1	l	d	554	17268	642	442	17976	654	485	17535	642
4	60	60	2	l	d	572	19235	724	477	20110	771	540	19251	733
4	60	60	3	l	d	548	16318	648	464	16997	658	519	16318	648
4	60	60	4	l	d	538	15911	613	463	17203	625	539	16355	613
4	60	60	5	l	d	513	14495	568	454	15299	589	495	14537	589
4	60	60	6	l	d	544	17397	654	461	17850	666	518	17209	666
4	60	60	7	l	d	553	17105	621	470	17128	645	541	17146	631
4	60	60	8	l	d	540	18703	706	469	19132	733	534	18703	706
4	60	60	9	l	d	528	14733	532	464	14697	550	511	14733	532
4	60	60	10	l	d	558	16464	646	464	17172	646	533	16568	646
4	60	60	11	l	d	566	19247	791	481	20227	791	561	19482	791
4	60	60	12	l	d	538	17499	630	466	17893	707	514	17548	646
4	60	60	13	l	d	554	17091	625	445	17523	641	554	17001	625
4	60	60	14	l	d	535	15274	579	478	15598	585	498	15274	579
4	60	60	15	l	d	570	15809	610	446	16111	617	528	15809	610
4	60	60	16	l	d	599	17582	673	486	17792	673	517	17383	673
4	60	60	17	l	d	555	18435	875	439	18695	891	528	18587	875
4	60	60	18	l	d	542	16745	652	461	17296	656	525	16768	652
4	60	60	19	l	d	550	18823	702	472	19321	749	533	18823	705
4	60	60	20	l	d	554	18925	909	472	19630	909	530	18925	909



Table B.13. (Continued).

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
4	60	60	1	h	s	76	4568	221	94	5370	260	85	4703	234
4	60	60	2	h	s	67	4137	209	80	5280	235	70	4135	204
4	60	60	3	h	s	69	4375	219	86	4835	219	78	4547	205
4	60	60	4	h	s	65	4244	203	87	5095	269	79	4244	214
4	60	60	5	h	s	65	4355	216	81	4998	280	80	4539	242
4	60	60	6	h	s	76	4868	221	93	5611	250	76	4964	221
4	60	60	7	h	s	73	4331	198	86	5193	255	75	4331	218
4	60	60	8	h	s	73	4626	230	86	5748	253	73	4626	271
4	60	60	9	h	s	66	3969	193	86	4646	239	77	3969	195
4	60	60	10	h	s	66	4296	202	84	5135	269	77	4296	213
4	60	60	11	h	s	65	4172	234	77	5217	264	73	4172	234
4	60	60	12	h	s	73	4606	208	90	5891	275	82	4606	247
4	60	60	13	h	s	67	4695	238	84	5848	250	78	4756	238
4	60	60	14	h	s	76	4424	227	91	5107	256	77	4424	229
4	60	60	15	h	s	61	4276	210	80	4750	271	72	4276	236
4	60	60	16	h	s	70	4698	221	87	4939	290	74	4789	241
4	60	60	17	h	s	69	4687	235	89	5234	275	73	4836	226
4	60	60	18	h	s	64	3839	208	86	5068	254	86	3839	208
4	60	60	19	h	s	64	4595	216	85	4797	264	75	4755	243
4	60	60	20	h	s	76	4302	203	87	5639	261	81	4440	226
4	60	60	1	h	d	593	31910	1224	488	32622	1297	540	32799	1267
4	60	60	2	h	d	585	28429	1138	478	29451	1230	524	28264	1185
4	60	60	3	h	d	563	32447	1494	484	33830	1557	521	32447	1517
4	60	60	4	h	d	558	32874	1175	478	32863	1210	503	32313	1191
4	60	60	5	h	d	547	29147	1115	463	30634	1115	486	29147	1115
4	60	60	6	h	d	557	29375	1156	453	30230	1179	540	29876	1179
4	60	60	7	h	d	563	31336	1232	456	32129	1273	507	31336	1252
4	60	60	8	h	d	533	29991	1067	447	30747	1104	520	30103	1081
4	60	60	9	h	d	558	31635	1138	459	31872	1194	536	31635	1149
4	60	60	10	h	d	568	33225	1354	463	34343	1384	510	33344	1383
4	60	60	11	h	d	528	28453	1072	451	28460	1143	528	28684	1072
4	60	60	12	h	d	548	29301	1075	471	29220	1140	548	28959	1075
4	60	60	13	h	d	530	31132	1181	466	32127	1195	514	31132	1191
4	60	60	14	h	d	575	28523	1138	465	28570	1215	536	28523	1138
4	60	60	15	h	d	558	30125	1082	480	30849	1160	513	29338	1128
4	60	60	16	h	d	556	30656	1217	463	32303	1225	540	31366	1217
4	60	60	17	h	d	505	28327	1033	468	30154	1110	496	28513	1033
4	60	60	18	h	d	537	29444	1086	469	30923	1136	523	29583	1086
4	60	60	19	h	d	529	30408	1117	453	30999	1184	508	30408	1122
4	60	60	20	h	d	540	29543	1065	469	30785	1098	520	29088	1088
4	40	120	1	l	s	123	2157	177	120	2415	191	117	2192	173
4	40	120	2	l	s	113	2096	172	120	2294	203	113	2096	163
4	40	120	3	l	s	104	1863	161	114	2073	161	113	1872	156
4	40	120	4	l	s	113	2096	147	113	2174	167	113	2061	158
4	40	120	5	l	s	113	2358	181	123	2762	196	119	2392	165
4	40	120	6	l	s	114	1911	148	123	2147	155	116	1911	148
4	40	120	7	l	s	120	2131	172	127	2340	186	114	2132	165
4	40	120	8	l	s	113	2316	164	126	2584	184	118	2300	165
4	40	120	9	l	s	122	2341	176	127	2595	191	113	2375	182
4	40	120	10	l	s	119	2287	174	126	2530	186	119	2303	173
4	40	120	11	l	s	126	2073	165	128	2239	179	124	2073	165
4	40	120	12	l	s	136	2228	167	129	2479	173	121	2240	165
4	40	120	13	l	s	122	1951	146	122	2242	163	119	1964	146
4	40	120	14	l	s	130	1899	139	124	2176	168	119	1934	139
4	40	120	15	l	s	108	1931	147	116	2240	175	113	1982	147
4	40	120	16	l	s	113	2033	168	126	2504	189	119	2210	158
4	40	120	17	l	s	113	2031	156	113	2462	188	112	2053	154
4	40	120	18	l	s	123	2368	182	124	2787	195	116	2404	168
4	40	120	19	l	s	111	2284	171	118	2731	219	112	2249	170
4	40	120	20	l	s	115	2320	175	115	2677	192	115	2389	175

Table B.13. (Continued).

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
4	40	120	1	l	d	592	11424	633	564	11909	633	570	11424	633
4	40	120	2	l	d	681	12727	848	619	13285	866	639	12727	851
4	40	120	3	l	d	607	12162	747	555	12165	809	580	12162	755
4	40	120	4	l	d	623	11231	850	575	11285	874	599	11231	826
4	40	120	5	l	d	638	12434	761	601	12519	791	624	12434	772
4	40	120	6	l	d	697	13908	891	642	14325	970	680	14070	896
4	40	120	7	l	d	653	14175	922	613	14344	985	621	14175	922
4	40	120	8	l	d	672	15147	983	623	15266	1038	638	15184	951
4	40	120	9	l	d	653	11673	773	611	11851	800	637	11673	747
4	40	120	10	l	d	598	11984	700	563	12310	747	564	11984	720
4	40	120	11	l	d	676	14577	936	617	14577	992	642	14577	940
4	40	120	12	l	d	663	14659	1180	614	15043	1270	641	14659	1180
4	40	120	13	l	d	667	14203	925	625	14264	930	630	14203	925
4	40	120	14	l	d	653	12271	793	612	12372	866	631	12385	793
4	40	120	15	l	d	672	13499	866	635	13729	987	655	13617	924
4	40	120	16	l	d	643	16305	1284	604	16305	1280	610	16305	1272
4	40	120	17	l	d	621	13156	702	584	13461	702	597	13206	700
4	40	120	18	l	d	636	12578	880	603	13012	998	617	12578	854
4	40	120	19	l	d	638	13336	789	600	13422	802	631	13439	801
4	40	120	20	l	d	674	13945	798	628	14170	897	643	13945	798
4	40	120	1	h	s	113	3320	262	122	3596	297	115	3335	255
4	40	120	2	h	s	96	3184	263	112	3623	297	107	3214	267
4	40	120	3	h	s	110	3818	293	121	4514	359	116	3709	303
4	40	120	4	h	s	117	3441	249	119	3894	312	110	3518	261
4	40	120	5	h	s	120	3616	283	130	4234	343	130	3570	285
4	40	120	6	h	s	91	2651	229	104	3145	285	100	2784	242
4	40	120	7	h	s	117	3477	280	109	3949	314	114	3473	275
4	40	120	8	h	s	103	3319	255	117	3799	300	109	3319	260
4	40	120	9	h	s	113	3406	257	114	4039	324	117	3408	274
4	40	120	10	h	s	104	2859	241	112	3349	282	110	2859	243
4	40	120	11	h	s	109	3443	286	117	3927	309	112	3461	275
4	40	120	12	h	s	111	3792	283	128	4188	297	119	3800	284
4	40	120	13	h	s	124	3609	290	117	4074	301	113	3778	289
4	40	120	14	h	s	114	3805	290	118	4369	316	115	3722	291
4	40	120	15	h	s	113	3262	284	121	3863	309	117	3262	276
4	40	120	16	h	s	113	3380	288	125	3767	276	121	3336	252
4	40	120	17	h	s	110	2800	251	110	3178	270	110	2780	226
4	40	120	18	h	s	120	3314	269	115	3635	320	118	3321	263
4	40	120	19	h	s	107	3262	259	121	3635	291	117	3347	266
4	40	120	20	h	s	121	3407	261	129	3946	318	128	3466	286
4	40	120	1	h	d	674	26546	1784	621	27386	1922	641	27125	1784
4	40	120	2	h	d	659	25432	1741	617	25881	1840	646	25432	1638
4	40	120	3	h	d	665	24496	1677	617	24969	1802	634	24496	1677
4	40	120	4	h	d	641	25538	2025	605	25890	2025	634	25539	2025
4	40	120	5	h	d	676	27714	1918	644	28597	2189	658	27714	1918
4	40	120	6	h	d	650	23716	1860	611	23716	1874	631	23716	1860
4	40	120	7	h	d	658	25267	1673	611	25685	1855	631	25267	1671
4	40	120	8	h	d	648	23697	1529	599	24092	1766	624	23775	1529
4	40	120	9	h	d	570	20091	1132	554	20470	1181	570	20139	1181
4	40	120	10	h	d	615	20616	1157	570	21434	1206	585	20589	1157
4	40	120	11	h	d	644	25284	1527	615	25582	1690	634	25061	1527
4	40	120	12	h	d	661	23962	1601	603	24356	1609	627	23962	1601
4	40	120	13	h	d	638	22880	1425	595	23177	1425	617	22880	1425
4	40	120	14	h	d	612	21775	1260	558	22429	1388	590	21948	1267
4	40	120	15	h	d	660	24606	1777	608	24676	1777	622	24606	1777
4	40	120	16	h	d	654	23660	1629	616	24166	1792	637	23660	1629
4	40	120	17	h	d	671	26179	1619	630	26412	1714	654	26179	1619
4	40	120	18	h	d	600	21015	1181	575	21658	1195	583	20524	1195
4	40	120	19	h	d	675	23894	1478	633	23894	1508	652	23894	1478
4	40	120	20	h	d	622	22183	1530	577	22482	1530	600	22183	1530

Table B.13. (Continued).

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
4	60	120	1	l	s	192	5936	266	201	6190	308	200	5929	267
4	60	120	2	l	s	169	5893	249	184	6333	277	179	5893	260
4	60	120	3	l	s	196	5433	241	200	5963	255	200	5433	241
4	60	120	4	l	s	172	5171	231	196	5550	254	193	5234	239
4	60	120	5	l	s	175	4780	234	186	5481	261	184	4783	228
4	60	120	6	l	s	193	5577	244	193	6541	288	193	5577	253
4	60	120	7	l	s	197	5809	257	200	6528	288	200	5914	257
4	60	120	8	l	s	165	5525	250	178	6173	272	176	5566	242
4	60	120	9	l	s	176	4615	215	180	5327	236	180	4615	215
4	60	120	10	l	s	173	5180	238	189	5609	271	188	5180	247
4	60	120	11	l	s	180	4776	204	191	5524	233	184	4875	218
4	60	120	12	l	s	180	5862	265	185	6145	303	181	5825	264
4	60	120	13	l	s	190	6111	255	206	6347	283	197	6075	275
4	60	120	14	l	s	170	5336	227	184	5897	257	176	5336	240
4	60	120	15	l	s	192	5951	265	203	7065	294	189	5951	268
4	60	120	16	l	s	182	4551	193	197	5061	221	193	4551	195
4	60	120	17	l	s	179	5401	245	186	5915	253	183	5413	253
4	60	120	18	l	s	196	6570	270	211	7105	301	195	6570	282
4	60	120	19	l	s	182	5285	233	183	5759	250	182	5285	250
4	60	120	20	l	s	185	5307	244	199	5964	244	194	5307	244
4	60	120	1	l	d	1002	29865	1168	946	30020	1176	988	29865	1168
4	60	120	2	l	d	1005	31760	1324	944	32863	1383	990	32117	1329
4	60	120	3	l	d	989	33437	1680	950	33430	1680	989	33394	1680
4	60	120	4	l	d	1043	30263	1452	974	30395	1468	1012	30258	1432
4	60	120	5	l	d	969	31743	1185	919	32336	1248	931	31858	1185
4	60	120	6	l	d	988	28149	1089	947	28807	1104	973	28149	1089
4	60	120	7	l	d	980	25487	972	928	25650	1020	980	25487	972
4	60	120	8	l	d	993	27413	1186	930	27748	1197	974	27413	1186
4	60	120	9	l	d	1012	33243	1447	968	33512	1555	993	33243	1447
4	60	120	10	l	d	932	23440	824	879	23997	824	920	23440	824
4	60	120	11	l	d	1039	28805	1144	989	29553	1263	1025	28805	1144
4	60	120	12	l	d	902	24677	927	884	25300	927	906	24677	927
4	60	120	13	l	d	1009	32301	1512	957	32765	1670	1009	32301	1460
4	60	120	14	l	d	1008	29172	1317	956	29194	1415	990	29133	1317
4	60	120	15	l	d	1020	33572	1702	941	34530	1844	976	34218	1702
4	60	120	16	l	d	904	24512	891	859	25742	891	898	24817	891
4	60	120	17	l	d	1032	33131	1423	972	33299	1531	996	33131	1428
4	60	120	18	l	d	989	29170	1020	942	29254	1020	989	29177	1020
4	60	120	19	l	d	1020	28459	1322	941	28642	1322	995	28459	1322
4	60	120	20	l	d	1036	36559	1953	981	36662	1961	1027	36559	1953
4	60	120	1	h	s	173	9438	424	192	10411	441	179	9438	426
4	60	120	2	h	s	192	9712	448	200	10100	497	198	9712	434
4	60	120	3	h	s	192	9865	414	200	11003	475	186	9793	445
4	60	120	4	h	s	173	9015	388	184	10669	464	179	8911	399
4	60	120	5	h	s	193	10103	460	197	10705	487	197	10063	460
4	60	120	6	h	s	193	9549	405	198	10454	472	191	9549	417
4	60	120	7	h	s	174	8411	373	190	9544	428	196	8412	368
4	60	120	8	h	s	169	9090	385	195	9474	452	184	9100	444
4	60	120	9	h	s	177	8437	369	194	9151	422	186	8437	369
4	60	120	10	h	s	183	9511	413	190	10121	467	185	9511	413
4	60	120	11	h	s	173	9322	397	181	9811	432	180	9322	405
4	60	120	12	h	s	171	8960	416	174	10156	452	176	8989	408
4	60	120	13	h	s	176	8354	365	185	9306	421	185	8354	368
4	60	120	14	h	s	192	8945	388	192	9655	431	192	8976	388
4	60	120	15	h	s	184	9996	442	186	11566	464	184	9909	442
4	60	120	16	h	s	189	9162	415	193	10340	469	177	9344	415
4	60	120	17	h	s	182	9069	401	191	10436	457	191	9069	415
4	60	120	18	h	s	176	9252	386	195	10413	445	192	9252	410
4	60	120	19	h	s	173	8551	397	182	9842	436	178	8735	415
4	60	120	20	h	s	179	9491	411	191	10695	462	185	9479	419

Table B.13. (Continued).

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
4	60	120	1	h	d	1001	59354	2529	973	59675	2786	1001	59393	2587
4	60	120	2	h	d	1021	54952	2291	958	54952	2350	982	54952	2297
4	60	120	3	h	d	977	50569	2072	921	51032	2192	962	50597	2072
4	60	120	4	h	d	1020	51676	2094	960	51815	2148	1009	51676	2148
4	60	120	5	h	d	959	50905	1835	915	51737	1835	950	51188	1835
4	60	120	6	h	d	1030	64282	3495	977	68021	3787	999	64282	3540
4	60	120	7	h	d	1035	55199	2699	970	55886	2755	1042	55199	2690
4	60	120	8	h	d	1043	54427	2089	982	55421	2089	1036	54474	2089
4	60	120	9	h	d	953	49035	1972	918	49035	2067	952	49035	1995
4	60	120	10	h	d	972	53181	1979	928	54330	1979	964	53521	1979
4	60	120	11	h	d	1002	56796	2470	946	57910	2521	982	57350	2439
4	60	120	12	h	d	995	51856	1940	941	53044	1978	978	52008	1940
4	60	120	13	h	d	1013	56046	2409	952	56460	2506	992	56500	2409
4	60	120	14	h	d	1000	54548	2293	965	55333	2423	962	54548	2293
4	60	120	15	h	d	1030	58453	2562	950	58952	2995	990	58453	2674
4	60	120	16	h	d	1021	55005	2339	957	56650	2466	1007	55005	2339
4	60	120	17	h	d	974	50896	1932	923	51717	1932	957	50896	1932
4	60	120	18	h	d	1020	53269	2393	942	55014	2790	986	53474	2444
4	60	120	19	h	d	1016	56852	2390	942	56944	2602	974	57068	2479
4	60	120	20	h	d	957	49234	2053	915	50121	2101	957	49234	2053
6	80	120	1	l	s	250	6257	253	260	6663	270	252	6261	253
6	80	120	2	l	s	226	5981	235	245	7182	256	230	5981	232
6	80	120	3	l	s	235	5568	196	252	6039	239	249	5662	196
6	80	120	4	l	s	230	6314	227	238	7822	276	231	6317	237
6	80	120	5	l	s	245	6005	232	253	7262	240	239	6005	220
6	80	120	6	l	s	229	5977	216	256	6763	271	247	5977	217
6	80	120	7	l	s	228	5832	227	249	6901	273	249	5842	228
6	80	120	8	l	s	238	6754	240	264	8285	285	243	6754	249
6	80	120	9	l	s	242	5275	198	248	6521	252	243	5275	193
6	80	120	10	l	s	233	5880	245	248	6734	255	253	5880	245
6	80	120	11	l	s	246	6302	247	260	6626	260	253	6226	277
6	80	120	12	l	s	248	6123	224	265	7206	290	255	6228	224
6	80	120	13	l	s	246	6252	245	264	7646	267	254	6252	267
6	80	120	14	l	s	213	6208	234	220	7261	272	220	6222	260
6	80	120	15	l	s	233	5764	215	247	7759	273	239	5764	215
6	80	120	16	l	s	226	5499	236	248	6087	257	236	5499	236
6	80	120	17	l	s	235	5905	214	258	7251	279	245	5963	212
6	80	120	18	l	s	257	6940	253	272	7531	293	266	6940	254
6	80	120	19	l	s	239	5604	202	266	6457	248	252	5604	217
6	80	120	20	l	s	235	6327	247	257	6958	259	239	6327	254
6	80	120	1	l	d	1630	39449	1068	1500	40040	1075	1630	39449	1068
6	80	120	2	l	d	1558	40558	1100	1415	41202	1100	1534	40558	1100
6	80	120	3	l	d	1692	43242	1305	1547	43754	1317	1670	43242	1305
6	80	120	4	l	d	1658	40097	1146	1498	40349	1150	1633	40051	1150
6	80	120	5	l	d	1624	41993	1121	1484	42347	1149	1578	42019	1121
6	80	120	6	l	d	1623	39934	1376	1471	41522	1467	1583	39934	1376
6	80	120	7	l	d	1532	40839	1124	1420	41283	1209	1532	40842	1124
6	80	120	8	l	d	1483	38236	1123	1371	38716	1123	1494	38236	1123
6	80	120	9	l	d	1656	37567	1155	1484	38841	1219	1598	37567	1155
6	80	120	10	l	d	1606	39120	1076	1468	39850	1076	1544	39126	1076
6	80	120	11	l	d	1690	47344	1349	1511	48330	1404	1676	47344	1349
6	80	120	12	l	d	1575	39072	1345	1448	40395	1368	1575	39072	1368
6	80	120	13	l	d	1586	42902	1294	1482	44011	1396	1565	42902	1294
6	80	120	14	l	d	1587	42962	1659	1429	42877	1659	1582	42962	1659
6	80	120	15	l	d	1560	39097	1087	1441	40426	1100	1545	39169	1087
6	80	120	16	l	d	1515	38432	1083	1444	39323	1135	1495	38432	1083
6	80	120	17	l	d	1650	40777	1124	1485	41109	1125	1631	40777	1124
6	80	120	18	l	d	1556	41757	1119	1392	42792	1119	1556	41757	1119
6	80	120	19	l	d	1579	39374	1053	1454	39403	1093	1563	39626	1053
6	80	120	20	l	d	1658	45407	1565	1490	46561	1569	1634	45592	1565

Table B.13. (Continued).

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
6	80	120	1	h	s	239	9759	387	262	11855	448	247	9759	402
6	80	120	2	h	s	238	9902	364	259	11268	446	259	9902	377
6	80	120	3	h	s	243	10211	397	254	11831	476	234	10211	390
6	80	120	4	h	s	233	10472	384	259	11326	469	244	10472	425
6	80	120	5	h	s	236	9961	385	244	10536	433	232	9961	376
6	80	120	6	h	s	252	10196	380	271	12376	409	264	10196	416
6	80	120	7	h	s	239	10484	388	262	11191	452	253	10937	388
6	80	120	8	h	s	245	9986	386	262	11718	461	246	9986	361
6	80	120	9	h	s	225	9512	378	234	10479	400	237	9512	381
6	80	120	10	h	s	257	10461	400	276	12872	448	264	10483	408
6	80	120	11	h	s	220	9950	369	250	11955	390	250	9950	390
6	80	120	12	h	s	244	10216	379	265	12058	501	252	10216	379
6	80	120	13	h	s	234	9001	366	253	10092	423	240	9001	390
6	80	120	14	h	s	236	9905	361	270	11778	450	257	9905	404
6	80	120	15	h	s	249	10357	400	266	12385	474	262	10357	410
6	80	120	16	h	s	245	10232	433	254	11550	478	242	10232	411
6	80	120	17	h	s	237	9987	382	251	11094	431	236	9987	382
6	80	120	18	h	s	245	10039	375	258	12457	446	245	10039	401
6	80	120	19	h	s	226	9909	400	255	11651	461	247	9909	400
6	80	120	20	h	s	219	10531	381	235	12223	503	226	10531	384
6	80	120	1	h	d	1598	75384	2183	1469	75977	2183	1573	75807	2183
6	80	120	2	h	d	1616	73822	2057	1457	75525	2128	1566	73822	2057
6	80	120	3	h	d	1578	74843	2058	1459	75759	2159	1531	75028	2058
6	80	120	4	h	d	1588	74858	2040	1473	78712	2040	1594	74858	2040
6	80	120	5	h	d	1669	80146	2329	1482	81436	2348	1635	80146	2329
6	80	120	6	h	d	1557	77441	2334	1407	81198	2334	1573	77441	2334
6	80	120	7	h	d	1658	80472	2703	1505	82090	2859	1613	80472	2665
6	80	120	8	h	d	1654	77942	2639	1486	79081	2639	1636	77942	2639
6	80	120	9	h	d	1551	73537	1996	1441	72395	2039	1545	73537	1996
6	80	120	10	h	d	1569	74688	2232	1441	76918	2232	1553	74688	2232
6	80	120	11	h	d	1613	77724	2219	1451	78576	2304	1599	77724	2297
6	80	120	12	h	d	1647	81897	2645	1509	83966	2645	1622	81897	2645
6	80	120	13	h	d	1670	80248	2734	1490	81878	2811	1622	80248	2734
6	80	120	14	h	d	1534	71060	1957	1395	74264	2069	1520	72184	1957
6	80	120	15	h	d	1675	79768	2861	1527	81139	2867	1620	79768	2861
6	80	120	16	h	d	1548	69114	1837	1457	69273	1846	1531	68238	1837
6	80	120	17	h	d	1537	68971	1945	1403	73183	1947	1527	70239	1947
6	80	120	18	h	d	1604	78217	2079	1435	79021	2140	1591	78002	2114
6	80	120	19	h	d	1527	67816	1786	1442	71913	1886	1500	67511	1786
6	80	120	20	h	d	1570	75075	2098	1408	74605	2377	1575	73417	2098
6	120	120	1	l	s	372	15378	384	411	16922	428	372	15378	385
6	120	120	2	l	s	371	15354	351	425	16294	394	371	15354	351
6	120	120	3	l	s	379	17143	433	434	19292	489	380	17143	433
6	120	120	4	l	s	394	16584	376	430	19009	501	393	17047	410
6	120	120	5	l	s	372	15627	374	410	16157	458	367	15627	374
6	120	120	6	l	s	362	15852	383	401	15986	472	362	15852	383
6	120	120	7	l	s	376	16170	408	420	17454	454	383	16386	397
6	120	120	8	l	s	401	16729	419	450	18801	503	401	16729	419
6	120	120	9	l	s	372	16730	389	423	18366	493	372	16730	389
6	120	120	10	l	s	413	16099	358	433	19791	444	410	16099	366
6	120	120	11	l	s	402	17645	406	423	19154	484	402	17586	428
6	120	120	12	l	s	367	17232	402	418	20732	515	373	17232	402
6	120	120	13	l	s	378	15845	386	436	17632	458	378	15845	414
6	120	120	14	l	s	392	17065	383	408	19059	515	392	17065	383
6	120	120	15	l	s	396	17571	396	438	20907	562	405	17571	396
6	120	120	16	l	s	380	16934	407	437	18535	489	379	16934	423
6	120	120	17	l	s	393	16668	444	445	20736	509	400	16636	450
6	120	120	18	l	s	354	15647	377	395	16932	445	360	15647	406
6	120	120	19	l	s	382	16919	406	440	18515	469	403	16919	406
6	120	120	20	l	s	382	17011	397	426	19251	456	378	17011	418

Table B.13. (Continued).

M	J	T	V	sw	D	P.1			P.2			P.3		
						ts	tft	fmax	ts	tft	fmax	ts	tft	fmax
6	120	120	1	l	d	2406	96890	2139	2303	101920	2247	2406	96890	2139
6	120	120	2	l	d	2349	92212	1685	2276	90790	1685	2349	92212	1685
6	120	120	3	l	d	2404	95857	1722	2241	99222	1841	2404	95857	1722
6	120	120	4	l	d	2449	100739	1826	2260	100069	1833	2449	100739	1826
6	120	120	5	l	d	2437	94302	1678	2312	95869	1702	2429	93446	1678
6	120	120	6	l	d	2554	108735	2388	2344	111483	2388	2559	108735	2388
6	120	120	7	l	d	2505	107586	2222	2289	109717	2266	2505	107586	2222
6	120	120	8	l	d	2460	95965	1668	2299	93482	1668	2460	95965	1668
6	120	120	9	l	d	2404	92584	1678	2271	91994	1678	2411	92584	1678
6	120	120	10	l	d	2417	97271	1719	2234	97680	1785	2417	97271	1785
6	120	120	11	l	d	2419	92981	2118	2209	94587	2118	2416	92981	2118
6	120	120	12	l	d	2453	89499	2425	2306	93314	2425	2453	89499	2425
6	120	120	13	l	d	2571	93459	1900	2333	94402	1900	2523	93459	1900
6	120	120	14	l	d	2489	94612	1687	2301	97006	1687	2489	94612	1687
6	120	120	15	l	d	2627	111726	2175	2382	112385	2206	2627	111726	2206
6	120	120	16	l	d	2397	92583	1659	2263	97139	1675	2397	92583	1659
6	120	120	17	l	d	2528	102875	2039	2315	105171	2067	2528	102875	2039
6	120	120	18	l	d	2460	94143	1918	2322	97742	1918	2460	94143	1918
6	120	120	19	l	d	2525	102627	2212	2277	105654	2216	2493	102627	2212
6	120	120	20	l	d	2519	88648	2030	2314	91038	2123	2519	88436	2030
6	120	120	1	h	s	387	30016	651	441	31202	931	394	30016	700
6	120	120	2	h	s	392	28593	625	445	35649	863	397	28894	686
6	120	120	3	h	s	396	29944	676	459	29775	874	394	29874	676
6	120	120	4	h	s	382	27509	656	440	30147	854	393	27509	684
6	120	120	5	h	s	385	28512	739	418	29678	912	385	28512	798
6	120	120	6	h	s	373	26901	617	450	29654	831	399	26901	669
6	120	120	7	h	s	395	28679	668	430	31134	799	395	28679	668
6	120	120	8	h	s	389	29076	683	439	30018	781	384	29076	683
6	120	120	9	h	s	347	26546	577	389	28982	737	347	26546	614
6	120	120	10	h	s	411	28127	701	452	30498	945	404	28127	701
6	120	120	11	h	s	396	26093	642	451	31184	826	396	26093	642
6	120	120	12	h	s	365	28871	629	423	30043	846	365	28871	772
6	120	120	13	h	s	384	29197	686	435	29916	843	384	28784	741
6	120	120	14	h	s	391	27860	643	445	31820	837	403	27860	643
6	120	120	15	h	s	405	29202	727	465	33364	841	405	29202	727
6	120	120	16	h	s	383	25894	663	436	28898	781	387	25894	618
6	120	120	17	h	s	388	26554	694	439	30114	827	400	26554	694
6	120	120	18	h	s	401	28066	703	447	31796	836	401	28983	703
6	120	120	19	h	s	389	25658	587	441	29871	844	391	25658	701
6	120	120	20	h	s	376	31374	725	425	35759	878	394	31374	778
6	120	120	1	h	d	2317	167410	2998	2144	171092	3112	2317	167410	2998
6	120	120	2	h	d	2348	163993	2837	2263	164430	2956	2348	163993	2837
6	120	120	3	h	d	2455	171396	3276	2253	177577	3557	2346	171396	3358
6	120	120	4	h	d	2354	162518	2966	2210	164160	3095	2354	162518	2966
6	120	120	5	h	d	2421	170901	3164	2285	173006	3248	2421	170901	3164
6	120	120	6	h	d	2494	180848	3489	2299	187874	3718	2492	180848	3537
6	120	120	7	h	d	2360	165408	3024	2251	166044	3052	2360	165408	3024
6	120	120	8	h	d	2328	167601	2981	2225	171601	3040	2332	167643	2981
6	120	120	9	h	d	2431	165843	2953	2241	168692	3002	2439	165843	2953
6	120	120	10	h	d	2310	163956	3005	2288	164860	3025	2312	163956	3005
6	120	120	11	h	d	2440	173166	3184	2252	181635	3269	2440	173166	3184
6	120	120	12	h	d	2492	180257	3165	2335	186027	3186	2492	180302	3165
6	120	120	13	h	d	2504	178413	3171	2317	181493	3187	2504	178413	3171
6	120	120	14	h	d	2373	165839	2954	2208	171146	2964	2373	167696	2954
6	120	120	15	h	d	2426	172581	3200	2347	178065	3413	2426	172581	3200
6	120	120	16	h	d	2608	178124	4058	2371	182656	4058	2561	178124	4058
6	120	120	17	h	d	2476	175414	3138	2296	182745	3180	2476	175414	3138
6	120	120	18	h	d	2416	179049	3372	2298	179033	3569	2407	178629	3372
6	120	120	19	h	d	2495	183090	3223	2306	187882	3239	2495	183090	3223
6	120	120	20	h	d	2452	175414	3189	2311	175093	3234	2452	175414	3189

**Table B.14. Results obtained by the Wilcoxon Signed-Rank Test comparing the objective values of the different ILS methods of data set SSP-NPM-I.**

Measured Objective	Methods compared	Sample Size	Z-value	Significantly different at *p = 0.05?
ts	(MIP, P.1b)	148	-10.55	yes
ts	(MIP, P.2)	129	-9.86	yes
ts	(MIP, P.3)	96	-8.51	yes
ts	(P.1b, P.2)	133	-1.16	no
ts	(P.1b, P.3)	121	-9.08	yes
ts	(P.2, P.3)	113	-8.50	yes
tft	(MIP, P.1a)	143	-6.25	yes
tft	(MIP, P.2)	137	-9.14	yes
tft	(MIP, P.3)	117	-2.10	yes
tft	(P.1a, P.2)	139	-4.56	yes
tft	(P.1a, P.3)	136	-9.53	yes
tft	(P.2, P.3)	131	-9.75	yes
fmax	(MIP, P.1a)	131	-5.97	yes
fmax	(MIP, P.2)	125	-9.58	yes
fmax	(MIP, P.3)	94	-7.12	yes
fmax	(P.1a, P.2)	138	-4.23	yes
fmax	(P.1a, P.3)	129	-9.80	yes
fmax	(P.2, P.3)	127	-9.78	yes

**Table B.15. Results obtained by the Wilcoxon Signed-Rank Test comparing the objective values of the different ILS methods of data set SSP-NPM-II at various problem types (M|J|T) and densities.**

Problem Type	Density	Measured Objective	Methods compared	Sample Size	Z-value	Significantly different at *p = 0.05?
4 40 60	dense	ts	(P.1b, P.2)	39	-5.36	yes
4 40 60	dense	ts	(P.1b, P.3)	38	-0.88	no
4 40 60	dense	ts	(P.2, P.3)	40	-5.43	yes
4 60 60	dense	ts	(P.1b, P.2)	40	-5.51	yes
4 60 60	dense	ts	(P.1b, P.3)	37	-5.29	yes
4 60 60	dense	ts	(P.2, P.3)	40	-5.51	yes
4 40 120	dense	ts	(P.1b, P.2)	40	-5.51	yes
4 40 120	dense	ts	(P.1b, P.3)	39	-5.44	yes
4 40 120	dense	ts	(P.2, P.3)	40	-5.51	yes
4 60 120	dense	ts	(P.1b, P.2)	40	-5.51	yes
4 60 120	dense	ts	(P.1b, P.3)	34	-4.98	yes
4 60 120	dense	ts	(P.2, P.3)	40	-5.50	yes
6 80 120	dense	ts	(P.1b, P.2)	40	-5.51	yes
6 80 120	dense	ts	(P.1b, P.3)	36	-4.85	yes
6 80 120	dense	ts	(P.2, P.3)	40	-5.51	yes
6 120 120	dense	ts	(P.1b, P.2)	40	-5.51	yes
6 120 120	dense	ts	(P.1b, P.3)	13	-1.50	no
6 120 120	dense	ts	(P.2, P.3)	40	-5.51	yes
4 40 60	dense	tft	(P.1a, P.2)	40	-5.51	yes
4 40 60	dense	tft	(P.1a, P.3)	30	-1.84	yes
4 40 60	dense	tft	(P.2, P.3)	40	-5.51	yes
4 60 60	dense	tft	(P.1a, P.2)	40	-5.35	yes
4 60 60	dense	tft	(P.1a, P.3)	26	-1.03	no
4 60 60	dense	tft	(P.2, P.3)	40	-5.32	yes
4 40 120	dense	tft	(P.1a, P.2)	36	-5.23	yes
4 40 120	dense	tft	(P.1a, P.3)	14	-1.60	no
4 40 120	dense	tft	(P.2, P.3)	36	-5.15	yes
4 60 120	dense	tft	(P.1a, P.2)	38	-5.36	yes
4 60 120	dense	tft	(P.1a, P.3)	18	-3.22	yes
4 60 120	dense	tft	(P.2, P.3)	38	-5.26	yes
6 80 120	dense	tft	(P.1a, P.2)	40	-5.07	yes
6 80 120	dense	tft	(P.1a, P.3)	15	-0.62	no
6 80 120	dense	tft	(P.2, P.3)	40	-5.15	yes
6 120 120	dense	tft	(P.1a, P.2)	40	-4.88	yes
6 120 120	dense	tft	(P.1a, P.3)	6	-0.31	no
6 120 120	dense	tft	(P.2, P.3)	40	-4.92	yes
4 40 60	dense	fmax	(P.1a, P.2)	40	-5.51	yes
4 40 60	dense	fmax	(P.1a, P.3)	34	-0.78	no
4 40 60	dense	fmax	(P.2, P.3)	40	-5.51	yes
4 60 60	dense	fmax	(P.1a, P.2)	35	-5.16	yes
4 60 60	dense	fmax	(P.1a, P.3)	19	-3.82	yes
4 60 60	dense	fmax	(P.2, P.3)	32	-4.94	yes
4 40 120	dense	fmax	(P.1a, P.2)	34	-5.07	yes
4 40 120	dense	fmax	(P.1a, P.3)	19	-0.22	no
4 40 120	dense	fmax	(P.2, P.3)	33	-5.01	yes
4 60 120	dense	fmax	(P.1a, P.2)	30	-4.78	yes
4 60 120	dense	fmax	(P.1a, P.3)	14	-1.66	no
4 60 120	dense	fmax	(P.2, P.3)	29	-4.70	yes
6 80 120	dense	fmax	(P.1a, P.2)	29	-4.70	yes
6 80 120	dense	fmax	(P.1a, P.3)	6	-1.15	no
6 80 120	dense	fmax	(P.2, P.3)	26	-4.46	yes
6 120 120	dense	fmax	(P.1a, P.2)	30	-4.78	yes
6 120 120	dense	fmax	(P.1a, P.3)	4	NA	no
6 120 120	dense	fmax	(P.2, P.3)	28	-4.62	yes



Table B.15. (Continued).

Problem Type	Density	Measured Objective	Methods compared	Sample Size	Z-value	Significantly different at *p = 0.05?
4 40 60	sparse	ts	(P.1b, P.2)	39	-5.36	yes
4 40 60	sparse	ts	(P.1b, P.3)	38	-0.88	no
4 40 60	sparse	ts	(P.2, P.3)	40	-5.43	yes
4 60 60	sparse	ts	(P.1b, P.2)	40	-5.51	yes
4 60 60	sparse	ts	(P.1b, P.3)	37	-5.07	yes
4 60 60	sparse	ts	(P.2, P.3)	29	-5.28	yes
4 40 120	sparse	ts	(P.1b, P.2)	35	-4.09	yes
4 40 120	sparse	ts	(P.1b, P.3)	35	-1.20	no
4 40 120	sparse	ts	(P.2, P.3)	36	-4.68	yes
4 60 120	sparse	ts	(P.1b, P.2)	38	-5.37	yes
4 60 120	sparse	ts	(P.1b, P.3)	36	-4.32	yes
4 60 120	sparse	ts	(P.2, P.3)	32	-4.42	yes
6 80 120	sparse	ts	(P.1b, P.2)	40	-5.51	yes
6 80 120	sparse	ts	(P.1b, P.3)	37	-4.73	yes
6 80 120	sparse	ts	(P.2, P.3)	36	-5.14	yes
6 120 120	sparse	ts	(P.1b, P.2)	40	-5.51	yes
6 120 120	sparse	ts	(P.1b, P.3)	24	-2.64	yes
6 120 120	sparse	ts	(P.2, P.3)	40	-5.51	yes
4 40 60	sparse	tft	(P.1a, P.2)	40	-5.51	yes
4 40 60	sparse	tft	(P.1a, P.3)	30	-1.84	no
4 40 60	sparse	tft	(P.2, P.3)	40	-5.51	yes
4 60 60	sparse	tft	(P.1a, P.2)	40	-5.51	yes
4 60 60	sparse	tft	(P.1a, P.3)	23	-3.25	yes
4 60 60	sparse	tft	(P.2, P.3)	40	-5.51	yes
4 40 120	sparse	tft	(P.1a, P.2)	40	-5.51	yes
4 40 120	sparse	tft	(P.1a, P.3)	34	-2.14	yes
4 40 120	sparse	tft	(P.2, P.3)	40	-5.51	yes
4 60 120	sparse	tft	(P.1a, P.2)	40	-5.51	yes
4 60 120	sparse	tft	(P.1a, P.3)	20	-0.76	no
4 60 120	sparse	tft	(P.2, P.3)	40	-5.51	yes
6 80 120	sparse	tft	(P.1a, P.2)	40	-5.51	yes
6 80 120	sparse	tft	(P.1a, P.3)	10	-2.09	yes
6 80 120	sparse	tft	(P.2, P.3)	40	-5.51	yes
6 120 120	sparse	tft	(P.1a, P.2)	40	-5.48	yes
6 120 120	sparse	tft	(P.1a, P.3)	8	-0.84	no
6 120 120	sparse	tft	(P.2, P.3)	40	-5.50	yes
4 40 60	sparse	fmax	(P.1a, P.2)	40	-5.51	yes
4 40 60	sparse	fmax	(P.1a, P.3)	34	-0.78	no
4 40 60	sparse	fmax	(P.2, P.3)	40	-5.51	yes
4 60 60	sparse	fmax	(P.1a, P.2)	39	-5.43	yes
4 60 60	sparse	fmax	(P.1a, P.3)	30	-3.67	yes
4 60 60	sparse	fmax	(P.2, P.3)	40	-5.42	yes
4 40 120	sparse	fmax	(P.1a, P.2)	39	-5.38	yes
4 40 120	sparse	fmax	(P.1a, P.3)	34	-0.71	no
4 40 120	sparse	fmax	(P.2, P.3)	40	-5.51	yes
4 60 120	sparse	fmax	(P.1a, P.2)	39	-5.44	yes
4 60 120	sparse	fmax	(P.1a, P.3)	30	-3.50	yes
4 60 120	sparse	fmax	(P.2, P.3)	37	-5.30	yes
6 80 120	sparse	fmax	(P.1a, P.2)	40	-5.51	yes
6 80 120	sparse	fmax	(P.1a, P.3)	30	-2.69	yes
6 80 120	sparse	fmax	(P.2, P.3)	38	-5.26	yes
6 120 120	sparse	fmax	(P.1a, P.2)	40	-5.51	yes
6 120 120	sparse	fmax	(P.1a, P.3)	21	-3.42	yes
6 120 120	sparse	fmax	(P.2, P.3)	40	-5.51	yes