SCHEDULING IN MANUFACTURING WITH TRANSPORTATION: CLASSIFICATION AND SOLUTION TECHNIQUES

WORKING PAPER SERIES OF THE CHAIR OF MANAGEMENT SCIENCE / OPERATIONS AND SUPPLY CHAIN MANAGEMENT UNIVERSITY OF PASSAU

Amir Hosseini
Chair of Management Science / Operations
and Supply Chain Management,
University of Passau,
Dr.-Hans-Kapfinger-Straße 12, 94032 Passau,
amir.hosseini@uni-passau.de

Alena Otto
Chair of Management Science / Operations
and Supply Chain Management,
University of Passau,
Dr.-Hans-Kapfinger-Straße 12, 94032 Passau,
alena.otto@uni-passau.de

Erwin Pesch
Chair of Management Information Science, Faculty III,
University of Siegen,
Kohlbettstr. 15, D-57068 Siegen
Erwin.Pesch@uni-siegen.de

June 29, 2023

ABSTRACT

Many modern manufacturing settings feature especially close relationship of the transportation of workpieces between production steps with the scheduling of manufacturing operations. Consider flexible manufacturing systems, reconfigurable manufacturing systems or flexible assembly lines, to name a few. In this paper, we review over 100 papers on scheduling problems in manufacturing with transportation (SchedPT). We classify the reviewed papers according to an extension of the three-field notation of Graham et al. (1979) and outline relevant problem settings, such as characteristics of transporters, material flow or of the buffer system. Afterward, we discuss selected main solution approaches to solve SchedPT. We also collected more than 50 results on polynomially solvable problem variants and performance guarantees. Based on our analysis, we formulate promising directions for future research.

Keywords Scheduling, Manufacturing, Routing, Combinatorial Optimization, Classification

1 Introduction

Internal logistics has for long been known as a reluctant-to-change unit, accounting for 30-80% of the total manufacturing cost (Kulak, 2005; Tompkin and White, 1984) and binding up to 90% of the production time (Gamberi et al., 2009). The ongoing customization of products pushes material handling costs further up, emphasizing the necessity of optimization. However, material handling tasks traditionally form one of the last stages in the hierarchical operational planning and are dictated by finalized schedules of manufacturing processes that resulted from upper-level decisions. Traditional material handling setups are also hard to optimize due to reliance on manual processes as, for instance, pickers or conventional forklifts. But the momentum of change may have come now, for creating conditions to integrate internal logistics decisions into the upstream operational planning. First, companies are investing in digital factories (Geissbauer et al., 2017; Olsen and Tomlin, 2020) interconnecting machines, robots, and products across a common data-sharing infrastructure, which lays opportunities for integrated planning. Second, new affordable and flexible autonomous transportation technologies appeared, such as autonomous mobile robots. Recent studies reveal that integrated planning for manufacturing and internal logistics may significantly cut production costs and improve further key performance indicators (Fragapane et al., 2022b; Sule, 1994).

Anticipating the outlined developments in factories, we survey the literature on optimization approaches for the integrated planning of manufacturing and internal logistics. We denote the problem settings that are in focus of our study as *the scheduling problems in manufacturing with transportation (SchedPT)*.

In the following, we outline the methodology of search, including the definition of SchedPT (Section 1.1), and describe common industrial settings which SchedPT refer to (Section1.2). Related literature is discussed in Section 1.3. Section 1.4 summarizes the contribution of the article and outlines the structure of the paper.

1.1 Problem definition and the methodology of search

SchedPT combine classical scheduling with transportation decisions between manufacturing steps inside one factory (internal logistics) and can be broadly outlined as follows (see Figure 1).

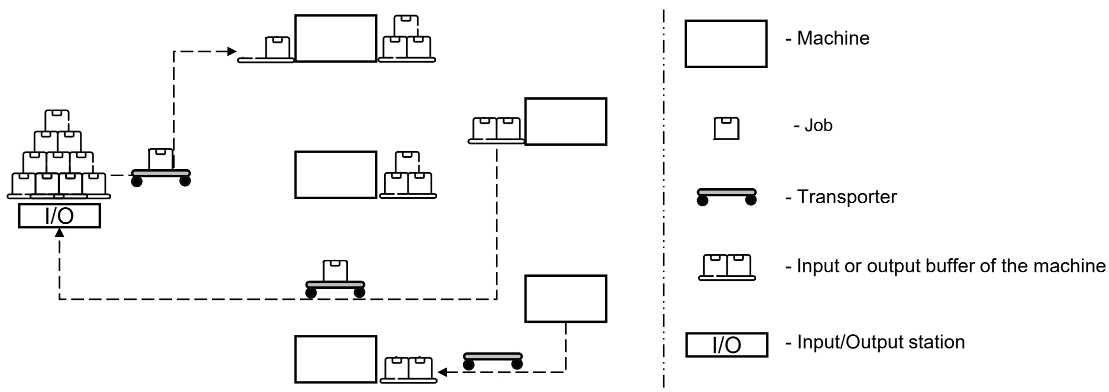


Figure 1: Schematic illustration of the setting in focus of this review

A factory consists of a set of *machines* M. We use the term ‘machine’, common in the scheduling literature, and a machine may refer to a CNC machine, a station operated by one or several employees, intermediate storage area, or even to a larger production unit, such as a manufacturing cell. Workpieces (*jobs*) $j \in J$ have to be processed on all or on selected machines, possibly under some further constraints. The material flow on the machines can be arranged in any order, e.g., on parallel machines, in (hybrid) flow shops, (flexible) job shops or open shops. *Transporters* convey jobs between machines. Moving a job between two machines requires some *transportation time* and may be subject to a number of constraints, such as the availability of the transporter or conditions for the collision-free routing. Machines may have input and output *buffers*. These buffers have different capacities and decouple the start (end) of the job processing by a machine from the moment when this job is delivered to this machine (picked-up from this machine) by a transporter. Moreover, there may be a single *input/output station (I/O)* or separate *input* (I) and *output* (O) stations. Input and output stations serve to model the entry and exit points of the jobs in certain manufacturing systems: Each job enters the system in I (or I/O), from which it has to be picked up by a transporter and moved to its first machine. Similarly, each job exits the system in O (or I/O), to which it has to be moved by a transporter after the job has been processed on all the required machines.

The problem is to schedule the processing of the jobs in J on machines M and their transportation between these machines to optimize some given objective(s). We limit our interest to optimization problems where

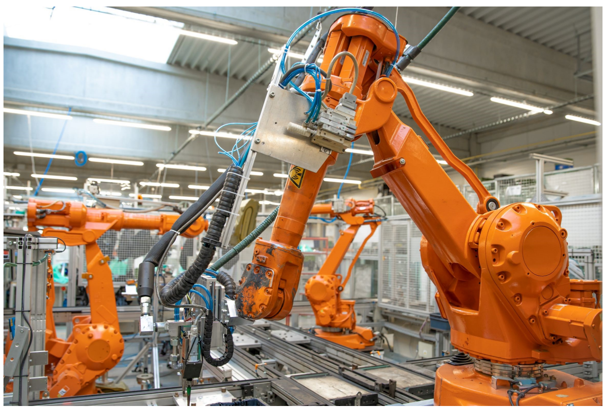
- at least one of the machine scheduling decisions is to be made – either sequencing of jobs on machines or, in case several alternative machines are available, the assignment of jobs to machines, and

- transportation is considered, such as transportation time or transportation-related decisions, e.g., assignment of jobs to transporters, routing of transporters or sequencing of jobs moved by transporters.

We reviewed papers on optimization approaches to SchedPT published since 1980 in English in 38 major journals in optimization, operations management, and industrial engineering (see Appendix B for the list of the journals). This resulted in 103 articles chosen for this review.

1.2 Common industrial settings described by SchedPT

SchedPT provide a simple, yet powerful framework that describes various modern manufacturing settings, which feature especially close relationship of the transportation of jobs between production steps with the scheduling of manufacturing operations. In the following, we introduce some of these settings.



©[Nataliya Hora] / Adobe Stock

Figure 2: Example of a flexible manufacturing system (FMS). Workpieces are transported between robotic arms ('machines') with a flexible jig.

©AUDI AG

Figure 3: Example of a flexible assembly line (FAL). Mobile robots move car bodies ('jobs') on their individual route through the processing stations.

Flexible manufacturing systems (FMS) describe systems of numerically controlled, flexible machines, in which jobs are moved between machines by automated material handling equipment, such as robotic arms or special belts moving standardized pallets (Błażewicz et al., 2002; Buzacott and Yao, 1986). The number of jobs that can be simultaneously transported in an FMS is usually limited, which may lead to significant waiting times in the production process. Hence, the importance of the integrated planning and SchedPT.

A special kind of small and relatively simple FMS represent *robotic cells (RCs)*. Whereas job routes within the FMS may be (almost) arbitrary, RCs are often composed of a few machines combined via unidirectional material flow (flow shop); the transporters in RCs are usually robotic arms. RCs is among currently most intensively investigated SchedPT variants in the literature.

Cellular manufacturing (CM) generalizes the concept of manufacturing in cells for each family of products (Morris and Tersine, 1990). Ideally, all the required manufacturing steps for one product have to be limited to one manufacturing cell, because transportation cost and time *inside* one cell are kept negligible. However, switches of jobs *between* different manufacturing cells often cannot be avoided. Such intercellular transportation consumes significant time and cost, which have to be considered in operational planning (cf. Feng et al., 2018).

Flexible assembly lines (FALs) have been recently introduced in a number of industries (Fragapane et al., 2022a; Hottenrott and Grunow, 2019). In traditional assembly lines, conveyor systems that transport workpieces along sequentially arranged stations are rigid: Each workpiece spends the same time at each station and visits the stations in the same order. In contrast, in FALs, autonomous mobile robots or automated guided vehicles (AGVs) transport jobs on individual routes between assembly stations, so that a job may spend more time at specific stations and skip others.

©[chesky] / Adobe Stock

Figure 4: Example of a manufacturing system consisting of several robotic cells and mobile robots that move jobs between the cells.

©[HAIYAN] / Adobe Stock

Figure 5: Example of a simple routing-scheduling system. Operators ('machines') serve several CNC machines ('immobile jobs') in a solar panel manufacturing workshop.

FALs are deployed in those parts of the assembly, in which the process variability – the variance in processing times for different jobs at different stations – is particularly high. To exploit the benefits of FALs, machine scheduling at stations and job routing between the stations have to be performed simultaneously, and an SchedPT setting emerges.

Reconfigurable manufacturing systems (RMS) consist of affordable machines of limited functionality and low setup costs and times (ElMaraghy, 2005; Koren et al., 2017; Mehrabi et al., 2000). In contrast to FMS, RMS emphasize fast and low-cost reconfigurability – the number and the arrangement of the machines can be easily changed. Such reconfigurability can only be achieved with a flexible transportation system.

In the *routing-scheduling (RS)* settings, machines travel to visit immobile jobs, which are located at different points in space. RS refers to the manufacturing of heavy parts that are too big or too heavy to be transported between machines (e.g., engine casings of ships) as well as to maintenance operations at immovable machines by a mobile robot (cf. Averbakh and Berman, 1996; Averbakh et al., 2006).

1.3 Related literature

To the best of our knowledge, there is no comprehensive literature review on scheduling in manufacturing with transportation. The available literature reviews either separate aspects of SchedPT or examine it on the side as part of a broader topic. Nouri et al. (2016a) review 25 articles on a subproblem of SchedPT, in which the machines form a job shop. Seminal studies of Brucker et al. (2004); Hurink and Knust (2001) and Lee and Chen (2001) summarize the results on the complexity of certain scheduling problems with transportation. Seminal papers of Allahverdi et al. (1999, 2008) and Allahverdi (2015), which investigate scheduling problems with setup times and setup cost, also include papers with job-dependent transportation times. Several articles examine planning and optimization approaches for FMS (Błażewicz et al., 2019b; Buzacott and Yao, 1986; Chan, 2004; Gunasekaran et al., 1993), which is a specific setup of SchedPT. Scheduling and routing of AGVs is surveyed by Fazlollahtabar and Saidi-Mehrabad (2015); Qiu et al. (2002) and Vis (2006). This is a subproblem of SchedPT, in which the schedules of jobs on machines are given and these schedules dictate the time windows, when AGVs have to visit the machines.

Further, a number of surveys examine integrated scheduling and routing in the areas, distinct from SchedPT. For instance, in *the integrated production and outbound distribution scheduling (IPODS)*, final products with a limited shelf life have to be delivered to the customers shortly after they have been manufactured (Chen, 2010; Chen and Lee, 2008; Fahimnia et al., 2013). So that the machine scheduling and the delivery schedules of final products to the customers, have to be considered simultaneously. IPODS focuses on the bundling of final products to shipments that fit the capacity of the outbound vehicles and on the routing of the vehicles, whereas production shop configurations are usually kept fairly simple. In *the workforce scheduling and routing problem (WSRP)*, several workers have to perform a set of tasks, each placed at a specific geographic location (Castillo-Salazar et al., 2016; Paraskevopoulos et al., 2017). The problem is motivated by services, such as nurses visiting patients, technicians carrying out maintenance and repair, or security guards surveying facilities. We exclude from our survey *cyclic scheduling problems (CSPs)*, such as scheduling of robotic cells or hoist scheduling. CSPs refer to a specific variant of SchedPT that has been examined in-depth in many surveys (Brauner, 2008; Crama et al., 2000; Dawande et al., 2005; Hall et al., 1998). It looks for a cyclic sequence of transporter moves (a robot or a hoist) in order to maximize the throughput. CSPs usually study flow-shop configurations with blocking and an infinite number of single-type jobs. SchedPT are also distinct from the *machine scheduling with a single server* (Brucker et al., 2005; Dosa and Tuza, 2018; Edis et al., 2013; Glass et al., 2000; Hall et al., 2000). In this class of problems, the single server performs the *setup*. Before processing, each job has to be setup (e.g., loaded) on the respective machine by the server. *Both* the server and the respective processing machine are busy during this setup operation, – this is the main distinction of the setup from the transportation, which is in focus of SchedPT. Consider an example of a network server (= server) that sets up the workstations (= machines) by loading the required software. We also do not include papers that have its main focus on logistics, as there are, for instance, plenty of papers on *crane scheduling for container transport*, see, e.g., the classification scheme by Boysen et al. (2017) or recent papers on crane scheduling in container blocks at sea ports (Kizilay et al., 2020; Kovalyov et al., 2018; Nossack et al., 2018; Sun et al., 2021b) or rail transshipment terminals, cf. (Archetti et al., 2021; Li et al., 2017, 2019b; Schulz et al., 2021). And finally, as we target studies in optimization, simulation-based approaches are out of the scope of our survey.

1.4 Contribution

Our contribution is as follows. To the best of our knowledge, this article provides the first extended review on scheduling in manufacturing with transportation (SchedPT). We adapt the famous three-field notation of Graham et al. (1979) to include transportation aspects and review and classify 103 papers on SchedPT. We summarize the existing results on polynomially solvable SchedPT cases as well as on SchedPT variants with worst-case and competitive ratios. Further, we highlight algorithmic ideas on how to approach SchedPT and explain them in a unified manner. Based on this analysis, we advise on future research directions.

We proceed with an outline of the notation in Section 2 and overview the articles in Section 3. Section 4 examines solution approaches to SchedPT and Section 5 concludes with future research directions.

2 Classification of the literature

To organize the reviewed literature, we extend the seminal three-field notation of $\alpha|\beta|\gamma$, which was proposed by Graham et al. (1979) and refined in a number of subsequent studies. Its current standards have been largely set by the influential books of Błażewicz et al. (2019a) and Pinedo (2012). Here, the first field (α) describes the machine environment. The second field (β) is reserved for processing characteristics and constraints. And the third field (γ) defines the objective function(s). We adapt this notation as follows:

- Following Hurink and Knust (2001) and Knust (2010), we extend field α to include the description of transporters. This decision seems straightforward, since in many SchedPT variants, a transporter can be formally interpreted as a machine. Observe, that some articles (cf. Lee and Chen, 2001) insert transporters in field β, which is different from this work.
- We introduce additional machine environments to field α that describe manufacturing systems with input and output stations common in FMS (cf. Błażewicz et al., 2002; Stecke, 2013). We add further transportation-related features to field β and introduce several new entries to field γ to cover widespread transportation-related objectives.

- The default values in each field are selected such that whenever no transportation is considered, our notation converges to that of Błażewicz et al. (2019a) and Pinedo (2012).

Machine environment and transporters					Processing characteristics and constraints							Objective(s)
$\alpha 1$[1]	$\alpha 2$[1]	$\alpha 3$	$\alpha 4$	$\alpha 5$	$\beta 1$	$\beta 2$	$\beta 3$	$\beta 4$	$\beta 5$	$\beta 6$	$\beta 7$	γ
Machine layout	Number of machines/stages[2]	Transporters	Number of transporters	Capacity of transporters	Processing time	Time-window parameters	Setup times	Transportation time	Empty travel time	Buffer system	Other constraints	

[1] Expanded notation for sub-fields $\alpha 1$ and $\alpha 2$ allows to describe manufacturing systems with input and output stations.
[2] The number of stages is relevant for hybrid flow shops, additional entries may specify the number of machines at each stage.

Table 1: Overview of the notation system.

Table 1 provides an overview of the proposed notation, the complete description of which is given in Appendix A. In the following, we outline the extensions to the conventional notation that cover the aspects of transportation.

2.1 Field α: Machine environment and transporters

This field describes the characteristics of the machines and transporters. The notation for transporters mimics that for the machines: Similar to sub-fields $\alpha 1$ and $\alpha 2$ for machines, sub-fields $\alpha 3$ and $\alpha 4$ refer to the type and number of transporters, respectively.

Expanded notation for the machine environment ($\alpha 1, \alpha 2$): We add a possibility to describe manufacturing systems with input and output stations ($I/O, I$ and O). Though formally these stations can be modeled as special kinds of machines with zero processing times for jobs and infinite input and output buffers, they are accounted for separately in the current convention (cf. Kise et al., 1991). For example, an RC with two sequentially arranged machines and one I/O is usually described as a specific *two-machine* flow shop; we denote it as I/O+$F2$ in our notation.

Remark: Because the processing time at input and output stations is always zero and their input and output buffers have always infinite capacity, we skip this information from the respective sub-fields $\beta 1$ (processing time) and $\beta 6$ (buffer system) to simplify the notation, e.g., entry $b_i^{in} = 0$ refers to the input buffer capacity of all the machines, except for the input and output stations.

Remark: We use nI to mark n input stations. Notion nI is used, for instance, to model initial geographic locations of the jobs (cf. Levner et al., 1995b; Li et al., 2022)

Transporters ($\alpha 3 \in \{\circ, T, TH, TD, TJ\}$):

$\alpha 3 = \circ$: There is either *no* (as in classical machine scheduling) or an *infinite number* of transporters. In the latter case, any job can be transported immediately, since there is always an available transporter.

$\alpha 3 = T$: There is a finite number of *identical* transporters in the system.

$\alpha 3 = TH$: There is a fleet of *heterogeneous* transporters in the system.

$\alpha 3 = TD$: Each of multiple transporters is *dedicated* to some zone of operation.

$\alpha 3 = TJ$: The transporter *escorts* a job to all required machines and remains at the machine while the job is processed. Consider mobile pods transporting car bodies in FALs of automobile plants as an example. Entry $\alpha 3 = TJ$ signifies that the number of escorting transporters may become a bottleneck, otherwise the classification reduces to the case of the infinite number of transporters ($\alpha 3 = \circ$).

Remark: If $\alpha 3 = \circ$, then sub-fields $\alpha 4$ and $\alpha 5$ are void.

Remark: In case of *routing-scheduling problems (RS)*, machines and transporters are merged into one entity, since machines travel between immobile jobs themselves. We follow the convention in the literature (e.g. Averbakh and Berman, 1996) and view an RS-problem as a (mathematically equivalent) case of a conventional machine scheduling problem with job-dependent setup times $s_{ijj'}$ (= travel times of mobile machine i between the respective jobs j and j'). The subfield $\alpha 3$ is left empty.

Number of transporters ($\alpha 4 \in \{cons, r\}$) :

$\alpha 4 = cons$: The number of transporters equals exactly some constant number $cons \in \mathbb{N}$.

$\alpha 4 = r$: The number of transporters is any number $r \in \mathbb{N}$.

Capacity of transporters ($\alpha 5 \in \{\circ, c_t\}$): The capacity is measured in the number of jobs that each transporter can carry. A non-empty entry of this sub-field is placed *in brackets* for a better readability.

$\alpha 5 = \circ$: The capacity of all the transporters is *one*. This is the case in most reviewed studies.

$\alpha 5 = c_t$: Each transporter t can carry at most $c_t \in \mathbb{N}$ jobs at a time (except for the case described by the default value $\circ$). Following the convention, the same capacity for each transporter is $c_t = c$ if it can be arbitrary and $c_t = cons, cons \in \mathbb{N}$, if it is fixed. We skip index t if there is only one transporter.

To sum up, 'I+$F2$+$O, T1$' refers, for example, to a two-machine flow shop with an input and an output station and a single transporter of capacity 1. '$Om, T2(c_t = n)$' denotes an open shop with two identical transporters, each of which can transport all jobs at a time.

2.2 Field β: Processing characteristics and constraints

This field specifies all the remaining relevant characteristics of the problem. Subfields $\beta 2, \beta 3$ and $\beta 7$ may contain multiple entries. For the parameters in this field, we follow a useful convention and mark the set of relevant features, on which the respective parameter may depend in the problem formulation, with *indices*. Consider, for example, parameter t that denotes transportation time. Notation $t_{ii'p}$ indicates that the transportation time may depend on the distance between the origin (machine i) and destination (machine i') and the selected route (path p) between these two machines. It goes without saying that other factors are irrelevant, for instance, the transportation time is the same for all the jobs and all the transporters. In the following, we use $_*$ (e.g., t_*) to indicate that the respective parameter should be used with a combination of the indices from Table 2 as required by the problem formulation.

Index	Description	Index	Description
j	index for jobs	t	index for transporters
i	index for machines	p	index for connecting paths (between machines)
s	index for stages	m	index for the mode of operation
f	index for the families of jobs or job types		

Table 2: Applied convention for the indices of the parameters.

Setup times ($\beta 3 \in \{\circ, s_*, v_*, l_*, u_*\}$): In this category, we describe different kinds of the setup times. In contrast to the conventional *setup time* s_*, the *removal time* v_* refers to the time needed to remove the tools, jigs and fixtures after the job has been processed by the machine. The *loading* (l_*) and *unloading* (u_*) times denote the duration of the handover operation of a job between a machine and a transporter. During this time, the respective transporter, machine and job are blocked and cannot be involved in other operations. The default value ($\beta 2 = \circ$) refers to the systems, in which setup times are irrelevant.

Transportation time ($\beta 4 \in \{\circ, t_*\}$): With only few exceptions, SchedPT formulations contain transportation time. The default value ($\beta 4 = \circ$) means that this parameter is irrelevant.

Empty travel time ($\beta 5 \in \{\circ, et_*\}$): Empty travel time et_* refers to an empty trip of a transporter, e.g., traveling to the location of the next job after the previous one has been delivered. The default value ($\beta 5 = \circ$) indicates that this parameter is irrelevant, which is the case, for instance, if the number of transporters is sufficiently large and there is no need to wait for the arrival of an empty transporter.

Buffer system ($\beta 6 \in \{\circ, b_i^{in}, b_i^{out}\}$):

$\beta 6 = \circ$: The capacity of the input and output buffers of the machines is sufficient and, thus, irrelevant.

$\beta 6 = b_i^{in}$, $\beta 6 = b_i^{out}$: The capacity of the input (b_i^{in}) or output (b_i^{out}) buffers of the machines is limited. The capacity is measured in the number of jobs (workpieces) that the respective buffer can accommodate. Limited buffer capacity may lead to *blocking*, when a transporter is blocked because it cannot handover the transported job to the machine with a full input buffer or when a machine is blocked because it cannot release the processed job neither to its full output buffer nor to a transporter.

Other constraints ($\beta 7 \in \{\circ, \ldots, coll\}$): And finally, this last sub-field is devoted to any other remaining characteristics and constraints.

$\beta 7 = coll$: Collisions between the transporters are possible in the transportation network.

2.3 Field γ: Objective function

Objective function ($\gamma \in \{\ldots, TTT, TWT, TIT, BMW, R_{max}, \gamma^*\}$: This field describes objectives and has no default value. In the multi-objective problems, the objectives are separated by commas, e.g., $\alpha|\beta|\gamma_1, \gamma_2$, where γ_i is the ith objective. If these objectives are arranged lexicographically, we show their lexicographical order as a superscript, e.g., $\alpha|\beta|\gamma_1^1, \gamma_2^2$. A weighted sum of objectives is joined by sign '+': $\alpha|\beta|\gamma_1$+γ_2. And finally, we connect two objectives with $\vee$ to denote that a family of optimization problems, each having either the first or the second objective, is considered, e.g. $\alpha|\beta|\gamma_1 \vee \gamma_2$.

We introduce the following notation for the transportation-related objective functions:

$\gamma = TTT$: Minimize total transportation time of the transporters.

$\gamma = TWT$: Minimize total waiting time of the jobs in input and output buffers of the machines. This objective is often used as a proxy for the required buffer space (cf. Zhang et al., 2012).

$\gamma = TIT$: Minimize total idle time of the machines.

$\gamma = BMW$: Balance machine workload, which may refer, for instance, to the minimization of the maximum workload of the machines or to the minimization of the total processing time on the machines.

$\gamma = R_{max}$: Minimize the makespan in RS, which refers to the timespan from the moment, when mobile machines leave the start depots, until the last machine reaches its end depot (cf. Chernykh et al., 2013).

$\gamma = \gamma^*$: A specialized objective, included neither in the notation of Błażewicz et al. (2019a) and Pinedo (2012) nor in our extension introduced above. These objectives are mostly specific to a single publication.

3 Overview

Table 4 provides an overview of the papers in this review. For each paper, it outlines the studied SchedPT variant and briefly summarizes the paper's contribution using the notation of Table 3.

Symbol	Description
B	Upper or lower bounds
E	Customized exact solution procedure
EX	Computational experiments
MH	Customized meta- or mat-heuristic algorithm
H	Further customized heuristic algorithms
M	Mixed-integer programming or constraint programming model
P	Formal analysis, such as complexity analysis, proofs of the exactness of the designed algorithms, worst-case ratios

Table 3: Glossary of abbreviations to describe the contributions.

The reviewed articles investigate different types of transportation systems (see Figure 6). The majority of the papers examine the basic variant of SchedPT with no or infinite number of transporters. Here, transportation-related aspects often narrow down to only one group of parameters – *transportation time*. SchedPT with a *single transporter* are in focus in 21% of the papers. Mostly, these papers investigate FMS or RCs. A differing setting is introduced by Lee and Strusevich (2005), in which a single *transporter of sufficient capacity* ($c \geq n$) commutes between two machines to transport jobs in an open shop. Only about a quarter of the papers consider *several transporters*. In 8% of the papers, transporters act in their *dedicated* areas of operation. Consider, for instance, dedicated transporters in hybrid flow shops, where machines are

Reference	α	$\beta1, \beta2$	$\beta3$	$\beta4, \beta5$	$\beta6$	$\beta7$	γ	Contribution
Single-machine SchedPT variants								
Karuno et al. (2002)	1	$[r_j]$	$s_{jj'}$				$R_{max} \vee L_{max}$	H-P
Parallel-machine SchedPT variants								
Boudhar and Haned (2009)	Pm			$t_{ii'}$		$prmp$	C_{max}	B-E[1]-EX-M-H-P
Haned et al. (2012)	Pm	$[p_{ij} = p]$		$t_{ii'}$		$prmp$	C_{max}	E[1]-EX-H-P
Lee et al. (2006)	$P2, T1(c \geq n)$			$t_{ii'} = t$		$prmp, brkdwn$[2]	γ^*	E-H-P
Li et al. (2022)	nI+Pm[3]	r_j		$t_{ii'}$			C_{max}	B-EX-H-M-P
Shams and Salmasi (2014)	Pm			$t_{ii'} = t$		$prmp$	C_{max}	EX-H-M-P
Open-shop SchedPT variants								
Averbakh et al. (2005)	$O2$		$s_{ff'}$				R_{max}	H-P
Averbakh et al. (2006)	Om		$s_{jj'}$[4]				R_{max}	H-P
Chernykh et al. (2013)	Om		$s_{jj'}$[4]				R_{max}	H-P
Khramova and Chernykh (2021)	$O2$[5]		$s_{ijj'}$[4]				R_{max}	E-H-P
Lee and Strusevich (2005)	$O2, T1(c \geq n)$			$t_{ii'}, et_{ii'}$			C_{max}	H-P
Lushchakova et al. (2009)	$O2, T1(c \geq n)$			$t_{ii'} = et_{ii'} = t$			γ^*	H-P
Mejía and Yuraszeck (2020)	I/O+Om		$s_{ijj'}$	$t_{ii'}$			C_{max}	EX-M-MH
Rebaine and Strusevich (1999)	$O2$			$t_j(\leq \min_{i,j}\{p_{ij}\})$			C_{max}	E-H-P
Rebaine and Strusevich (1999)	$O2$			$t_{ii'}$			C_{max}	H-P
Strusevich (1999)	$O2$			t_j			C_{max}	H-P
Zhang and van de Velde (2010)	$O2$[6]			t_j			C_{max}	H-P
Zhang and van de Velde (2015)	$O2$			$t_j = t < \min_{i,j}\{p_{i,j}\}$		nwt	γ[7]	E-H-P
Flow-shop SchedPT variants								
Aanen et al. (1993)	$F2$		$s_{ijj'}, l_{ij}$	t_j		$rcrc$	C_{max}	B-EX
Agnetis et al. (1996)	I/O+$F2, T1$		$l_{I/O} = u_{I/O}$	$t_{ii'} = et_{i'i}$	$b_i^{in} = b_i^{out} = 0$	$prmu, prec$	C_{max}	E-P
Aguirre et al. (2014)	I+Fm+$Om, T1$			$t_{ii'}, et_{ii'}$	$b_i^{in} = b_i^{out}$	$prmu, nwt$[8]	C_{max}	EX-H-M
Ahmadi-Javid and Hooshangi-Tabrizi (2015)	Fm			$t_{ii'j}, et_{ii'}$		$prmu$	C_{max}	EX-M-MH
Averbakh and Berman (1996)	$F2$		$s_{jj'}$[4]			$[prmu]$	TTT^1, R_{max}^2	E[1]-H-P
Averbakh and Berman (1996)	$F2$		$s_{jj'}$[4]			$prmu$	R_{max}	B-H-P
Averbakh and Berman (1999)	Fm		$s_{jj'}$[4]			$[prmu]$	R_{max}	B-H-P
Błażewicz et al. (2002)	I+$F3$+O[9]$, T1$		$s_{ijj'}$	$t_{ii'} = et_{i'i}$	$b_{i\neq 2}^{in} = b_i^{out} = 0$	$prec, batch(O)$	C_{max}	EX-H
Cao and Bedworth (1992)	Fm		s_{ij}	$t_{ii'j}$		$prmu$	C_{max}	EX-H
Carlier et al. (2010)	I+Fm+$O, T1$			$t_{ii'} = et_{i'i}$	$b_i^{in} = b_i^{out} = 0$	$prmu$	C_{max}	B-EX-MH
El Amraoui and Elhafsi (2016)	I+Fm+$O, T1$	p_{ij}[10]		$t_{ii'j}, et_{ii'}$		nwt	C_{max}	EX-H-M
Hurink and Knust (2001)	$F2, T1$	$[p_{ij} = p]$		t_j, et		$prmu$	C_{max}	E[1]-H-P
Hurink and Knust (2001)	$Fm, T1$	$p_{ij} = 1$		$t_{ii'}$		$prmu, n \geq m-1$	C_{max}	E-H-P
King et al. (1993)	I+$F2$+$O, T1$			$t_{ii'}, et_{ii'}$		$prmu$	C_{max}	B-EX-H-M
Kise et al. (1991)	I/O+$F2, T1$		$l_{I/O} = u_{I/O}$	$t_{ii'} = et_{i'i}$	$b_i^{in} = b_i^{out} = 0$	$prmu$	C_{max}	E-EX-P
Kise et al. (1991)	I+$F2$+$O, T1$		$l_{I/O} = u_{I/O}$	$t_{ii'} = et_{i'i}$	$b_i^{in} = b_i^{out} = 0$	$prmu$	C_{max}	E-EX-P
Lee and Chen (2001)	$F2, T1$			$t_{1,2}, et$		$prmu$	C_{max}	H-P
Lee and Chen (2001)	$F2, Tr(c)$	$p_{1,j} = p$		$t_{1,2}, et$		$prmu$	C_{max}	E-H-P
Lee and Strusevich (2005)	$F2, T1(c \geq n)$			$t_{1,2}, et$			C_{max}	H-P
Levner et al. (1995a)	I+$F2$+$O, TD3$		l_{ij}, u_{ij}	$t_{1,2} = t, et_{2,1} = et$	$b_1^{in} = b_1^{out} = 0$	$prmu$	C_{max}	E[1]-EX-P
Levner et al. (1995b)	nI+$F2$+$O, T1$		s_{ij}, l_{ij}, u_i	$t_{ii'}, et_{ii'}$	$b_i^{in} = b_i^{out} = 0$	$prmu$	C_{max}	E-EX-P
Liou and Hsieh (2015)	Fm		$s_{ff'}$	$t_{ii'j}$		$prmu, prec$	C_{max}	EX-MH
Jiang and Wang (2019)	I+Fm+O		$s_{ijj'}$	t_m		$prmu$	C_{max}, γ[11]	EX-H-M-MH
Maggu and Das (1980)	$F2$			t_j		$prmu$	C_{max}	E-H-P
Naderi and Azab (2021)	Fm[12]		$s_{ff'}$	$t_{ii'j}$			C_{max}	EX-M-MH
Panwalkar (1991)	$F2, T1$			$t_{1,2}, et$	$b_1^{out} = 0$		C_{max}	E-H-P
Sarin et al. (2008)	Fm	$p_{ij} = p$	$s_{ff'}$	$t_{ii'} = t$			γ[13]	EX-H-P
Shabtay et al. (2014)	Fm, TDr[14]	$p_{ij} = p$		$t_{ii't}, et_{ii't}$		nwt	C_{max}, γ[13],[15]	E[1]-H-P
Soukhal and Martineau (2005)	I+$F2$+$O, T1$		$l_i = u_i = u$	$t_{ii'} = et_{i'i}$	$b_i^{in} = b_i^{out} = 0$	$prmu$	C_{max}	B-EX-M-MH
Steiner and Xue (2005)	I+Fm+$O, T1$		$l_i = u_i = u$	$t_{ii'} = et_{i'i}$	$b_i^{in} = b_i^{out} = 0$	$prmu, rcrc$	C_{max}	E-H-P

Stern and Vitner (1990)	$F2$			t_j, et	$b_1^{out} = b_2^{in} = 0$		C_{max}	B-EX
Stevens and Gemmill (1997)	$F2$			$t_{1,2}, et$	$b_1^{out} = 0$		L_{max}	EX-H
Tang and Liu (2009)	$F2, T1(c = b^{[16]})$			$t_{1,2} = et$		$batch(1)$	C_{max}	EX-H-P
Tang et al. (2010)	$F2, T1$			$t_{1,2}, et$			C_{max}	EX-H-M-P
Yang and Chern (2000)	$F2$		s_{if}, v_{if}	t_j		$prmu, prec$	C_{max}	E-H
Zhang and van de Velde (2015)	$F2$			t_j		nwt	$\gamma^{[7]}$	P
Zhang and van de Velde (2015)	Fm			$t_{ii'j} = t$		nwt	$\gamma^{[7]}$	E-H-P
Zhong and Chen (2015)	$F2, T1(c^{[17]})$			$t_{1,2} \geq et$			C_{max}	H-P
Job-shop SchedPT variants								
Abdelmaguid et al. (2004)	I/O+Jm, Tr			$t_{ii'}, et_{ii'}$			C_{max}	EX-MH
Babu et al. (2010)	I/O+Jm, Tr	r_j		$t_{ii'}, et_{ii'}$			C_{max}	EX-MH
Bilge and Ulusoy (1995)	I/O+Jm, Tr	r_j		$t_{ii'}, et_{ii'}$			C_{max}	EX-H-M
Dang et al. (2019)	I/O+Jm, Tr			$t_{ii'}, et_{ii'}$			C_{max}	EX-M-MH
Hurink and Knust (2002)	$Jm, T1$			$t_{ii'j}, et_{ii'}$			C_{max}	EX-MH-P
Hurink and Knust (2005)	$Jm, T1$			$t_{ii'}, et_{ii'}$			C_{max}	EX-MH
Jeong et al. (1999)	Jm	r_j	s_{ij}	$t_{ii'}$		$prmp$	C_{max}	EX-H
Lacomme et al. (2013)	I/O+Jm, Tr			$t_{ii'}, et_{ii'}$			C_{max}	EX-MH
Liu and Kozan (2017)	I+Jm+$O, T1$			$t_{ii'}, et_{ii'}$	$b_i^{in} = b_i^{out} = 0$		C_{max}	EX-H-MH
Nouri et al. (2016b)	I/O+Jm, THr			$t_{ii't}, et_{ii't}$			C_{max}	EX-M-MH
Paulli (1995)	Jm, TJr						C_{max}	EX-H-MH
Saidi-Mehrabad et al. (2015)	I/O+Jm, TJr			$t_{ii'p}, et_{ii'p}$		$coll$	C_{max}	EX-M-MH
Sun et al. (2021a)	I+Jm+$O, T1$			$t_{ii'}, et_{ii'}$	$b_i^{in} = b_i^{out} = 0$		C_{max}	EX-M
Ulusoy and Bilge (1993)	I/O+Jm, Tr	r_j		$t_{ii'}, et_{ii'}$			C_{max}	EX-H-M
Ulusoy et al. (1997)	I/O+Jm, Tr	r_j		$t_{ii'}, et_{ii'}$			C_{max}	B-EX-MH
Yan et al. (2018)	I+Jm+$O^{[6]}, T1$	p_{ij}[10]		$t_{ii'j}, et_{ii'}$		nwt	C_{max}	EX-M
Zeng et al. (2019)	$Jm, Tr(c)$			$t_{ii'}, et_{ii'}$			C_{max}	EX-M-MH
Zhang and van de Velde (2015)	$J2$			$t_j = t < \min_{i,j}\{p_{i,j}\}$		nwt	$\gamma^{[7]}$	E-H-P
Zheng et al. (2014)	Jm, Tr			$t_{ii'}, et_{ii'}$			C_{max}	B-EX-M-MH
Hybrid flow-shop SchedPT variants								
Baumann and Trautmann (2014)	$HF3^{[18]}$		$s_{ijj'}$	$t_{ss'j}$	$b_i^{in} = b_i^{out} = 0$		C_{max}	EX-H-M
Botta-Genoulaz (2000)	HFm		s_{sj}, v_{sj}	$t_{ss'j}$		$prec$	L_{max}	EX-H
Dessouky et al. (1996)	HFm, TDr			$t_{ss't}$	$b_i^{in} = b_i^{out} = 0$	$M_j, batch(i)$	T_{max}	EX-H-M
Elmi and Topaloglu (2013)	I+$HFm^{[18]}$+O, Tr			$t_{ii'}, et_{ii'}$		M_j	C_{max}	EX-M-MH
He et al. (2020)	$HFm^{[18]}$	r_j	$s_{iff'}$	$t_{ii'}, et_{ii'}$		$M_j, prec$	C_{max}, TTT, γ^*	EX-M-MH
Lati and Gilad (2010)	I/O+$HFm, T1$			$t_{ii'} = et_{i'i}$	$b_i^{in} = b_i^{out} = 0$	$prmu$	TIT	EX-H
Lei et al. (2020)	$HFm^{[18]}, TDr^{[19]}$			$t_{ii'}, et_{ii'}$	$[b_i^{in} = b_i^{out} = 0]$	$[prmu]$	C_{max}	EX-H-M-MH
Lian et al. (2021)	HFm	p_{ij}[10]	$s_{ff'} = s$	$t_{ss'}$		$batch(m)$	$C_{max}, \gamma^{[11]}, \gamma^{[11]}$	EX-M-MH
Naderi et al. (2009)	HFm		$s_{ijj'}$	$t_{ii'j}$			$\sum w_jT_j$	EX-M-MH
Nishi et al. (2011)	HFm, Tr			$t_{ii'p}, et_{ii'p}$		$coll$	$\sum w_jT_j$	EX-H-M
Pan (2016)	$HF4$		$s_{4,j}$	$t_{ss'}$	$b_i^{in} = b_i^{out} = 0$		$C_{max} + TWT$	EX-M-MH
Pan et al. (2022)	HFm		$s_{mff'} = s$	$t_{ss'}$		$batch(m)$	$\sum C_j, TIT, \gamma^{[11]}$	EX-H-M
Tang et al. (2010)	$HF2(3,6)^{[20]}, TD3$			$t_{ii'}, et_{ii'}$	$b_1^{out} = 0$		TIT+C_{max}+TWT	EX-M-MH-P
Wang et al. (2021)	$HFm^{[21]}$		$s_{sjj'}$	$t_{ss'}$			$C_{max}, \gamma^{[11]}$	EX-M-MH
Zhong and Chen (2015)	$HF2(2,1), T1$			$t_{ss'} \geq et_{ss'}$			C_{max}	H-P
Flexible job-shop SchedPT variants								
Agnetis and Arbib (1997)	$FJm^{[12]}$			$t_{ii'j}$			$C_{max} \vee \gamma^*$	E[1]-P
Anwar and Nagi (1998)	$FJm^{[12]}$			$t_{ii'}, et_{ii'}$			C_{max}	EX-H-M
Bożek and Werner (2018)	FJm		$s_{ijj'}$	$t_{ii'}$			C_{max}	EX-M-MH
Ebrahimi et al. (2020)	$FJm^{[22]}$			$t_{ii'}$			$\sum w_jT_j, \gamma^{[11]}$	EX-M-MH
Feng et al. (2015)	I+FJm+$O^{[6]}, T1$	p_{ij}[10]		$t_{ii'j}, et_{ii'}$		nwt	C_{max}	EX-M
Feng et al. (2018)	FJm	$\tilde{d}_j$		$t_{ii'}$			C_{max}, BMW	EX-M-MH
Hottenrott and Grunow (2019)	$FJm^{[12]}$			$tt_{ii'}$			γ^*, TTT	E[1]-EX-M-MH
Hottenrott et al. (2022)	$FJm^{[12]}$			$t_{ii'}$			γ^*	E[1]-EX-M
Ivens and Lambrecht (1996)	FJm	r_j	$s_{ijj'}$	$t_{ii'}$		$prmp$	$C_{max} \vee L_{max}$	EX- H
Li et al. (2019a)	FJm		s_{ij}	$t_{ii'}$			$C_{max}, \gamma_1^{[13]}, \gamma_2^*$	EX-M-MH

Liu and MacCarthy (1997)	FJm	r_j	$s_{ijj'}$	$t_{ii'}, et_{ii'}$	b_i^{in}	$brkdwn$	$C_{max} \vee T_{max} \vee \sum C_j$	EX-H-M
Qin et al. (2019)	FJm	$r_{ij}, \tilde{d}_{ij}$		$t_{ii'}$			$C_{max}, \sum T_j, \gamma^{[13]}$	EX-M-MH
Rahimi et al. (2020)	$FJm^{[23]}$			$t_{ii'j}$			C_{max}	EX-M-MH
Rossi (2014)	FJm	r_j	$s_{ijj'}$	$t_{ii'}$			C_{max}	EX-MH
Rossi and Lanzetta (2020)	FJm		s_{im}	$t_{ii'}$			C_{max}	EX-MH
Sawik (1998)	$FJm^{[12]}$			$t_{ii'}$	b_i^{in}	$prec$	$BMW \vee TTT$	EX-H-M
Sawik (2000)	$FJm^{[12]}$			$t_{ii'}$	b_i^{in}	$prec$	BMW, TTT	EX
Schutten (1998)	FJm	r_j	$s_{ijj'}$	$t_{ii'}$		$mlrs, brkdwn, prmp$	$C_{max} \vee L_{max}$	H
?	FJm		$s_{ijj'}$	$t_{ii'}$			C_{max}, BMW, γ^*	EX-M-MH
Yang et al. (2016)	I/O+FJm, Tr			$t_{ii'}, et_{ii'}$			C_{max}	EX-M-MH
Zhang and Wong (2016)	FJm		$s_{ijj'}, l_{ij}, u_{ij}$	$t_{ii'}, et_{ii'}$			C_{max}	EX-MH
Zhang et al. (2014)	FJm, Tr	$p_{ij}{}^{[10]}$		$t_{ii'}, et_{ii'}$	$b_i^{in} = b_i^{out}$	$nwt^{[8]}$	C_{max}	EX-H
Zhang et al. (2012)	FJm, Tr	$p_{ij}{}^{[10]}$		$t_{ii'}, et_{ii'}$			C_{max}, TWT	EX-M-MH
Zhang et al. (2020)	$FJm^{[12]}$		$s_{iff'}$	$t_{ii'}$		$prec$	$C_{max}, \sum T_j, BMW$	EX-MH

Notes: Square brackets *[xxx]* signify that the paper studied different versions of the problem – with and without characteristic *'xxx'*. Observe that articles may have several entries in the table if they studied several SchedPT variants.

The relevant conventional notation used in this table, e.g. $mlrs$ or $batch(m)$, is summarized in Appendix A for convenience.

[1] A customized exact solution procedure is proposed for a special case of the problem, e.g. for a two-machine case. [2] One machine is not available for a given period of time. [3] Scheduling-location problem.
[4] Metric setup time. [5] Variable depot RS: Machines can start and end in arbitrary locations. [6] Online problem. [7] Interval shop scheduling: Maximize the weighted number of completed jobs. Jobs can be accepted or rejected and each job has a given fixed start and end time at each machine. [8] No-wait constraints are imposed only for selected operations (processing steps). [9] Machine 2 represents intermediate storage. After completion at machine 1, some jobs leave the system as a batch for outsourced processing, after which they are moved directly to machine 3. [10] Processing time can be an arbitrary number from a given interval.
[11] Energy-related objective. [12] Assembly problem: Each job consists of a set of tasks, which are subject to precedence relations; task-specific constraints are possible, such as task-to-station assignment restrictions or setup times between the tasks of the same job. [13] Cost-related objective. [14] Robot (=transporter) selection and scheduling problem. Machine idle time is not allowed.
[15] Different ways of coupling of the objectives are investigated (weighted sum, hierarchical and Pareto frontier). [16] The capacities of the batching machine and of the transporter are equal (b).
[17] The transporter's capacity limits the total weight of the jobs it can carry. [18] Unrelated machines at each stage. [19] There is a single transporter between each pair of consecutive stages of machines.
[20] Waiting time of jobs between consecutive stages is limited. [21] Each job can be processed by more than one machine simultaneously, which reduces the processing time, but increases the consumed energy.
[22] Integrated scheduling and machine layout problem. [23] Integrated cell formation, cellular scheduling, and cellular layout problem.

Table 4: Reviewed articles.

arranged in stages and a dedicated fleet of transporters performs transportation between each pair of consecutive stages of machines (Lei et al., 2020). In another example, transporters represent robotic arms mounted on the single track positioned alongside the machines, each transporter has its dedicated zone of operation that stretches over several consecutive machines (Shabtay et al., 2014). Finally, the dedicated areas of operation may be dictated by the functions of the heterogeneous transporters, as illustrated in Figure 4. Here, robotic arms transport workpieces from the intermediate storage to numerically controlled machines inside robotic cells, whereas mobile robots move workpieces between robotic cells (see also Levner et al., 1995a).

Input and output buffers of machines are predominantly assumed to have an infinite capacity (70% of cases), so that no blocking is possible: Transporters can always drop the delivered jobs into input buffers as well as machines can always pass on the processed job to its output buffers (see Figure 7). The majority of the remaining papers assume the buffer capacity of 0. This assumption is common for RCs as well as for applications from the chemical and metal processing industries. In the latter case, the no-wait constraints are widespread, which prohibit a waiting time between two subsequent processing steps to maintain the required temperature or other characteristics of the job. Observe that we count SchedPT variants with no-wait constraints, such as Shabtay et al. (2014) and Yan et al. (2018), in the ‘No buffer’-category in Figure 7, as no buffers between machines are required.

Apart from input and output buffers alongside machines, several papers consider *intermediate storages*. In contrast to input and output buffers, machines cannot immediately access an intermediate storage, so that jobs have to be moved from the intermediate storage to their next machine by a transporter; moreover, intermediate storages are often not associated with a particular machine. In our notation, intermediate storages represent a special kind of machine with zero processing times (cf. Błażewicz et al., 2002).

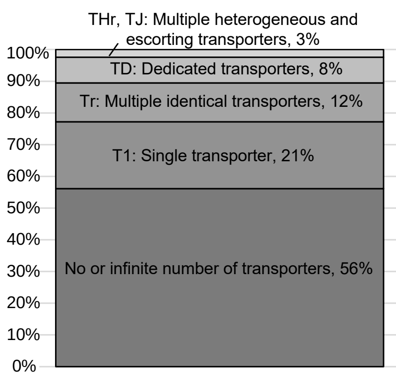


Figure 6: Problems by the examined transportation system.

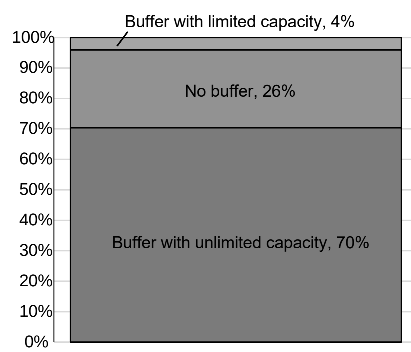


Figure 7: Problems by the examined type of buffers.

Only 2 papers out of 103 examine prone-to-collision transportation networks (Nishi et al., 2011; Saidi-Mehrabad et al., 2015). This is a simplification, which partially reflects the fact that a lot of effort has been devoted by the companies to eliminate the possibility of collision or delays, such as one-way lanes, side lanes or dedicated fleets of transporters between each subsequent pair of machine stages. Figure 8 outlines *manufacturing settings*, in which SchedPT have been studied (see also Appendix C). About a half of the papers (40%) do not emphasize the setting that motivated their research. If we leave these cases aside, flexible manufacturing systems (FMS) and robotic cells (RCs) emerge as most researched concepts (31% of papers). Around 18% of papers discuss flexible assembly lines (FAL), cellular manufacturing (CM) and routing-scheduling problems (RS). In *FALs* and related problems centered around assembly processes, each job, which refers to a product or model, consists of discrete activities, or *tasks*. Tasks have precedence relations and several tasks may be assigned to the same machine, or *station*. Therefore, task allocation to the machines and the resulting routing of the jobs among the machines is a usual part of decision making in these problems. A central trade-off for *RMS* is whether to reconfigure the machines and their arrangement if major changes in the product mix occur. For instance, in Naderi and Azab (2021), the unproductive time (e.g., setup and transportation time) can be significantly reduced by switching to the most favorable configuration for each subfamily of products. However, each reconfiguration is optional and consumes a significant amount of time.

The remaining papers (11%) examine production processes that are specific for given industries. Consider, for instance, *steel industry* where the melted steel has to be processed immediately; which enforces meticulous scheduling and routing of the transportation devices (industrial cranes or mobile robots) (Lian et al., 2021; Pan, 2016; Tang et al., 2010). Another example is the fabrication of *semiconductor wafers*, where each job usually undergoes around 300-900 processing steps conducted at more than one hundred flexible machines (Mönch et al., 2011), so that the transportation between these machines and the buffer management are of vital importance.

If we look at the material flow, more than one third of the articles (34%) describe the *flow-shop* environment, in which each job visits machines in the same order (see Figure 9). About one sixth of the articles focuses on the *job shop*, where the sequence of machine visits is given, but may be different for each job. In the remaining cases, the route of the jobs through the machine environment is not known *a priori* and is part of the decision process. Among such papers, it is surprising to meet *parallel machines* and a *single machine* (7% of papers), since here each job has to be processed by one machine only. These articles mostly refer either to RS, or to the case of the *machine disruption* (cf. Lee et al., 2006), in which jobs have to be reassigned to intact machines whereas the reassignment to another machine causes additional time for transportation, or to *the scheduling-location problem (ScheLoc)* (cf. Li et al., 2022). In ScheLoc, jobs enter the production system at specific geographic locations and we have to *a)* position a given set of identical machines as well as to *b)* assign jobs to these machines, taking into account the required transportation from the job's initial location to the position of the machine. ScheLoc is motivated, e.g., by the mining industry, where minerals (jobs) have to be crushed by movable crushing machines. In the *open shop*, each job has to be processed at each machine exactly once, but there are no restrictions on the sequence of machine visits.

Figure 8: Problems by the examined manufacturing setting.

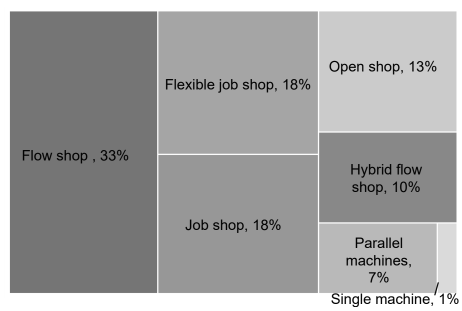


Figure 9: Problems by the examined material flow.

The remaining settings feature most complex manufacturing environments. In the *hybrid flow shops*, machines are arranged in stages, each stage usually consists of identical machines, so that at each processing step a job has to be assigned to one of the machines of the respective stage. Finally, the most flexible environment represents the *flexible job shop*, in which machines are flexible and the subset of eligible machines can be defined for each operation of each job arbitrarily.

4 Solution approaches

The solution of SchedPT variants often requires a nontrivial combination of techniques and know-how from the machine scheduling and from the routing literature. In this section, we highlight some existing ideas on how to approach SchedPT and explain them in a unified manner. We start with some basic notions and an example in Section 4.1 that we use throughout this section. We proceed with Sections 4.2 and 4.3 that guide through known polynomially solvable variants of SchedPT as well as the problem variants with known approximation guarantees, respectively. Section 4.4 briefly introduces the notion of the disjunctive graph and the related techniques. Selected transformations to the routing problems are discussed in Section 4.5. We conclude with final remarks on the modeling and hybrid solution approaches (Section 4.6).

4.1 Illustrative example and some basic notions

Consider a simple flow-shop production system with two machines and a robotic arm (transporter) that moves the jobs between the machines. Transportation times between the machines are job-specific because of non-standard size or extra large weight of the respective jobs. The empty travel time between the machines is not negligible. A job can only be transported if the transporter is available and waiting times may emerge. Assume that there are infinitely large input and output buffers of the machines. Our objective is to minimize the makespan. Table 5 illustrates possible parameters with two jobs $J = \{1, 2\}$. According to our notation, the problem is $F2, T1|t_j, et|C_{max}$.

We use the term *operation* o_{ij} to describe a processing step of job j performed on machine i. We denote the set of operations required to complete job j as O_j. In our example with two machines, each job consists of exactly two operations and the duration of operation $o_{ij} \in O_j$, which is processed on machine i, is p_{ij}.

Job	Processing times		Transportation	Empty travel
j	p_{1j}	p_{2j}	time, t_j	time, et
1	1	2	4	1
2	3	4	1	1

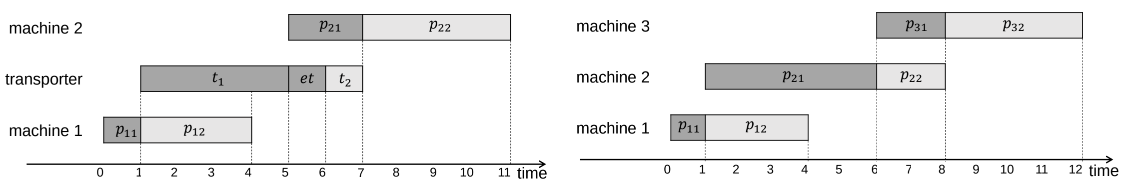
Table 5: An illustrative instance for $F2, T1|t_j, et|C_{max}$.

We can limit our attention to *active* schedules, that are schedules in which no job can start its processing earlier without delaying another one. For this problem the set of active schedules contains optimal ones. Therefore, to find an optimal schedule, it is sufficient to decide in which *sequence* the jobs have to be processed on each of the machines and transported by the transporter. In our example, there are two possible processing sequences of jobs on a machine (transporter), $1 \to 2$ and $2 \to 1$, which results in $2^3 = 8$ active schedules. An optimal schedule is to always process job 1 before job 2, which results in the optimal makespan of 11 (see the *Gantt chart* in Figure 10a).

As mentioned in Section 2, the transporter can be interpreted as an additional machine in some SchedPT variants. Indeed, in our example, the transporter resembles an additional machine with processing times $p_{tr,j} := t_j$ and setup times $s_{tr,jj'} = et$. Moreover, as discussed in Hurink and Knust (2001), with $p_{tr,j} := t_j + et$ problem $F2, T1|t_j, et|C_{max}$ is equivalent to $F3||C_{max}$. Figure 10b illustrates an optimal solution of the resulting $F3||C_{max}$ with objective 12. By shifting the starting times of the jobs on machine 3 to the left by $et = 1$, we receive an optimal schedule for the original problem.

4.2 Polynomially solvable SchedPT variants

Almost all scheduling problems with several machines are known to be notoriously hard to solve (Chen et al., 1998). The same applies to most SchedPT variants, since they additionally include transportation aspects. Not surprisingly, known polynomially solvable SchedPT cases (see Table 6) are usually derived from basic machine scheduling problems known to be in P: two-machine flow-shop problems with no-wait constraints



(a) The original problem.

(b) The transformed problem to $F3||C_{max}$.

Figure 10: Gantt charts for an optimal solution for the instance from Table 5.

($F2|nwt|\gamma$), two-machine flow shop ($F2||C_{\max}$), two-machine open shop ($O2||C_{\max}$), and variants of the parallel machine problem with preemption ($Pm|*, prmp|C_{max}$). This section extends the reviews on the complexity of SchedPT by Hurink and Knust (2001), Brucker and Knust (2009), and Lee and Chen (2001).

A group of efficiently solvable *flow-shop SchedPT* cases include no-wait or blocking constraints. Exact solution methods for two-machine flow shops $F2|nwt|C_{max}$ and $F2|b_i^{in} = b_i^{out} = 0|C_{max}$ were originally proposed in the seminal work by Gilmore and Gomory (1964) motivated by the steel manufacturing (see also Section 4.5). Several subsequent studies extend these algorithms by introducing transportation aspects. They consider, for instance, cases of input and output stations, loading/unloading times (Kise et al., 1991), job-dependent setup times (Levner et al., 1995b), transporters with swapping devices (Agnetis et al., 1996), and reentrant robotic systems (Steiner and Xue, 2005). Further polynomial algorithms have been suggested by Levner et al. (1995a), Panwalkar (1991), and Shabtay et al. (2014).

The remaining polynomially solvable flow-shop SchedPT variants are mostly limited to two-machine problems with one or an infinite number of transporters. Consider the famous result of Maggu and Das (1980) and Maggu et al. (1982) in more detail, which say that $F2|t_j, prmu|C_{max}$ is polynomially solvable. Observe that this problem has an infinite number of transporters in contrast to $F2, T1|t_j, et|C_{max}$ from Section 4.1. Indeed, in the former, we do not have to wait until the transportation of the previous job is finished, but several transporters may move jobs simultaneously. We can transform $F2|t_j, prmu|C_{max}$ into the basic flow-shop problem $F2||C_{max}$ by setting $p'_{ij} := p_{ij} + t_j$ and solve it with the algorithm of Johnson (1954), but will have to correct the makespan of the resulting solution by subtracting $\sum_{j\in J} t_j$. To recover an optimal schedule for the original problem, we shift the start times of the jobs on the second machine to their earliest possible starting time. For illustration, ignore the empty travel times in the example from Section 4.1 and assume that the number of transporters is infinite. The processing times in the obtained instance of $F2||C_{max}$ are 5 and 6 for job 1 as well as 4 and 5 for job 2 on machines 1 and 2, respectively, and this results in an optimal solution to process job 2 before job 1 on each machine with a makespan of 15. Hence, the optimal makespan of the original $F2|t_j, prmu|C_{max}$-instance equals $15 - (4 + 1) = 10$. Observe that the related problem without permutation, $F2|t_j|C_{max}$, is NP-hard in the strong sense (Yu et al., 2004).

Yang and Chern (2000) extend the results of Maggu and Das (1980) for the case of family-dependent setup and removal times. The case of a single transporter is studied by Hurink and Knust (2001). Some flow-shop SchedPT variants with several transporters remain polynomially solvable as well (Lee and Chen, 2001).

Further polynomially solvable SchedPT variants include two-machine open-shop (Khramova and Chernykh, 2021; Rebaine and Strusevich, 1999) and parallel machine problems with preemption (Boudhar and Haned, 2009; Haned et al., 2012). In the latter, each job preemption and transfer of the job part to another machine causes transportation time. Rescheduling in the aftermath of a disruption on one of the machines is discussed by Lee et al. (2006). Zhang and van de Velde (2015) study the *interval shop scheduling problem*, which is to maximize the weighted number of completed jobs. Jobs can be accepted or rejected and each job has a given fixed start and end time at each machine.

Several variants of the routing-scheduling problem (RS) are also polynomially solvable (Averbakh and Berman, 1996; Khramova and Chernykh, 2021). Observe that the *single-machine RS* represents a *traveling salesman problem (TSP)* and we refer to, e.g., Gutin and Punnen (2006) and Lawler et al. (1991) for its polynomially solvable variants. However, in case of several machines, RS are quite distinct from conventional routing problems because of the characteristic *waiting times*. Indeed, the arrived machine may have

Polynomially solvable problem	Reference
Flow-shop SchedPT variants with no-wait or blocking constraints	
I/O+$F2, T1^{[1]}\|l_{I/O} = u_{I/O}, t_{ii'} = et_{i'i}, b_i^{in} = b_i^{out} = 0, prmu, prec^{[2]}\|C_{max}$	Agnetis et al. (1996)
I/O+$F2, T1\|l_{I/O} = u_{I/O}, t_{ii'} = et_{i'i}, b_i^{in} = b_i^{out} = 0, prmu\|C_{max}$	Kise et al. (1991)
I+$F2$+$O, T1\|l_{I/O} = u_{I/O}, t_{ii'} = et_{i'i}, b_i^{in} = b_i^{out} = 0, prmu\|C_{max}$	-//-
I+$F2$+$O, TD3\|l_{ij}, u_{ij}^{[3]}, t_{1,2} = t, et_{2,1} = et, b_1^{in} = b_1^{out} = 0, prmu\|C_{max}$	Levner et al. (1995a)
nI+$F2$+$O, T1\|s_{ij}, l_{ij}, u_i, t_{ii'}, et_{ii'}, b_i^{in} = b_i^{out} = 0, prmu\|C_{max}$	Levner et al. (1995b)
$F2, T1\|t_{1,2}, et, b_1^{out} = 0\|C_{max}$	Panwalkar (1991)
$Fm, TDr^{[4]}\|p_{ij} = p, t_{ii't}, et_{ii't}, nwt\|C_{max} + \gamma^{*[5]}$	Shabtay et al. (2014)
$Fm, TDr^{[4]}\|p_{ij} = p, t_{ii'}, et_{ii't}, nwt\|C_{max}, \gamma^{*[5]}$	-//-
$Fm, TDr^{[4,6]}\|p_{ij} = p, t_{ii't}, et_{ii't}, nwt\|C_{max}, \gamma^{*[5]}$	-//-
I+$F2$+$O, T1\|l_i = u_i = u, t_{ii'} = et_{i'i}^{[7]}, b_i^{in} = b_i^{out} = 0, prmu, rcrc\|C_{max}$	Steiner and Xue (2005)
Further flow-shop SchedPT variants	
$F2, T1\|p_{ij} = p, t_j \in \{t_1, t_2\}, et, [prmu]\|C_{max}$	Hurink and Knust (2001)
$F2, T1\|p_{ij} = 1, t_j, et, [prmu]\|C_{max}$	-//-
$Fm, T1\|p_{ij} = 1, t_{ii'}, prmu, n \geq m-1\|C_{max}$	-//-
$F2, Tr(c)\|p_{1,j} = p, t_{1,2}, et, [prmu]\|C_{max}$	Lee and Chen (2001)
$F2\|t_j, prmu\|C_{max}$	Maggu and Das (1980)
$F2\|s_{if}, v_{if}, t_j, prmu, prec\|C_{max}$	Yang and Chern (2000)
Two-machine open-shop SchedPT variants	
$O2^{[8]}\|s_{ijj'}{}^{[9]}\|R_{max}$	Khramova and Chernykh (2021)
$O2\|t_j \leq \min_{i,j}\{p_{ij}\}\|C_{max}$	Rebaine and Strusevich (1999)
Parallel machine SchedPT variants with preemption	
$Pm\|t_{ii'} = 1, prmp\|C_{max}$	Boudhar and Haned (2009)
$P2\|p_{ij} = p, t_{ii'}, prmp\|C_{max}$	Haned et al. (2012)
$P3\|p_{ij} = p, t_{ii'}, prmp\|C_{max}$	-//-
$Pm\|p_{ij} = p, t_{ii'} = t, prmp\|C_{max}$	-//-
$P2, T1(c \geq n)\|t_{ii'} = t, prmp, brkdwn^{[10]}\|\gamma^*$	Lee et al. (2006)
Further SchedPT variants	
$F2^{[11]}\|s_{jj'}{}^{[9]}\|TTT^1, R_{max}^2$	Averbakh and Berman (1996)
$F2^{[12]}\|s_{jj'}{}^{[9]}, [prmu]\|TTT^1, R_{max}^2$	-//-
$J2\|t_j = t < \min_{i,j}\{p_{ij}\}, nwt\|\gamma^{*[13]}$	Zhang and van de Velde (2015)
$Fm\|t_{ii'j} = t, nwt\|\gamma^{*[13]}$	-//-
$O2\|t_j = t < \min_{i,j}\{p_{ij}\}, nwt\|\gamma^{*[13]}$	-//-

Note: $[prmu]$ denotes that the exact algorithm was developed both for problem variants with and without permutation.

[1] Transporter with a swapping device allowing to exchange the part currently on the AGV for the one currently on the machine.

[2] Jobs are arranged in lots of similar jobs, jobs inside of one lot have to be processed consequently.

[3] Besides (un)loading times, there is a delay ('placement time') before a job, which has been loaded into the buffer of machine 2, is available for processing.

[4] Robot (=transporter) selection and scheduling problem. Machine idle time is prohibited. Robots share the same track and cannot pass each other.

[5] Cost-related objective. [6] Transporters have the same cost but different velocities.

[7] Constant travel times between consecutive locations (I and machine 1, machine 1 and machine 2 etc.)

[8] Variable depot RS. Either the routing subproblem is polynomial and machines are uniform (e.g., differ by speed) or the transportation network is a cactus.

[9] Metric setup time. [10] Job rescheduling: One machine is temporarily unavailable, its jobs may wait until it is repaired or may be transported (reassigned) to another machine. [11] Transportation network is a tree. [12] Transportation network is a cactus.

[13] Interval shop scheduling: Maximize the weighted number of completed jobs. Jobs can be accepted or rejected and each job has a given fixed start and end time at each machine.

Table 6: Polynomially solvable SchedPT variants.

to wait until the respective job has been processed by the previous machine. Borrowing the terminology from routing problems, the *transportation network* describes a graph with nodes being jobs and labeled arcs referring to the travel times between the respective jobs. The *routing subproblem* denotes the respective RS with zero processing times ($p_{ij} = 0$). Obviously, polynomially solvable RS imply that their routing subproblem is polynomially solvable as well.

4.3 SchedPT variants with polynomial algorithms that have performance guarantees

Since most SchedPT variants are NP-hard, they are often solved heuristically in practice. Therefore, it is of interest, whether some fast (polynomial) heuristic algorithms are *guaranteed* to return solutions close to optimality. Before we move further, let us recall some terminology (cf. Pinedo, 2012), which we define *for the problems with a minimization objective*.

Definition ($(1+\epsilon)$-approximation algorithm)**.** *Let $\epsilon > 0$ be a small number. An algorithm ALG is called an $(1+\epsilon)$-approximation algorithm for some optimization problem, if for any instance I of that problem the algorithm ALG returns a feasible solution with objective value $ALG(I)$ such that*

$$ALG(I) \leq (1+\epsilon) \cdot OPT(I), \tag{1}$$

where $OPT(I)$ is the optimal objective value of instance I.

The value of $1+\epsilon$ is the *performance guarantee* or the *worst-case ratio*. (In case of a maximization problem, the worst-case ratio is $1-\epsilon$). The worst-case ratio is called *tight* if for some instance I' equality holds in (1). In *online* optimization problems, the concept of performance guarantee has to be adapted to deal with dynamically arriving information, so that the notion of *competitive ratio* was developed.

Definition ($(1+\epsilon)$-competitive algorithm)**.** *An online algorithm is $(1+\epsilon)$-competitive if the objective value of the schedule generated by the algorithm is at most $(1+\epsilon)$ times larger than the optimal objective value for the schedule that has been created in an offline manner with all data known beforehand.*

The value of $(1+\epsilon)$ is called the *competitive ratio*.

Performance guarantees for any fixed $\epsilon > 0$ (so-called polynomial approximation schemes) are known for a number of classical machine scheduling problems provided the number of machines is fixed – such as $Om||C_{max}, Fm||C_{max}$, $Jm||C_{max}$, and for several variants of the parallel machine problem (see Sevastianov and Woeginger, 1998; Stevens and Gemmill, 1997; Woeginger, 1997). Not surprisingly, much research effort has been invested in extending these results to include transportation aspects (see Table 7).

A number of interesting findings has been received for *RS*. The designed approximation schemes utilize a hierarchical approach and rely on the routing subproblems that are either polynomially solvable or have worst-case ratios (cf. Averbakh and Berman, 1999; Averbakh et al., 2005, 2006; Chernykh et al., 2013; Karuno et al., 2002; Khramova and Chernykh, 2021).

Problem	Performance guarantee Competitive ratio	Reference
Routing-scheduling SchedPT variants		
$Fm\|s_{jj'}{}^{[1]}, [prmu]\|R_{max}$	$\frac{m+1}{2}$	Averbakh and Berman (1999)
$O2\|s^{[2]}_{ff'}\|R_{max}$	$\frac{6}{5}$	Averbakh et al. (2005)
$O2^{[3]}\|s_{jj'}{}^{[1]}\|R_{max}$	$\frac{3}{2}^{\dagger}$	Averbakh et al. (2006)
$O2\|s_{jj'}{}^{[1]}\|R_{max}$	$\frac{7}{4}^{\dagger}$	-//-
$Om^{[3]}\|s_{jj'}{}^{[1]}\|R_{max}$	$\frac{m+3}{2}$	-//-
$Om\|s_{jj'}{}^{[1]}\|R_{max}$	$\frac{m+4}{2}$	-//-
$O2^{[3]}\|s_{jj'}{}^{[1]}\|R_{max}$	$\frac{4}{3}$	Chernykh et al. (2013)
$O2\|s_{jj'}{}^{[1]}\|R_{max}$	$\frac{13}{8}$	-//-
$1^{[4]}\|r_j, s_{jj'}\|R_{max}$	$\frac{3}{2}^{\dagger}$	Karuno et al. (2002)
$1^{[4]}\|s_{jj'}\|L_{max}$	$\frac{3}{2}^{\dagger}$	-//-
$O2^{[5]}\|s_{ijj'}{}^{[1]}\|R_{max}$	$\frac{3}{2}$	Khramova and Chernykh (2021)
Online open-shop SchedPT variants		
$O2^{[6]}\|t_j\|C_{max}$	$2^{\dagger}$	Zhang and van de Velde (2010)
$O2^{[6]}\|t_j \leq \min_{i,j}\{p_{ij}\}\|C_{max}$	$\frac{5}{3}^{\dagger}$	-//-
Further open-shop SchedPT variants		
$O2, T1(c \geq n)\|t_{ii'} = et_{ii'} = t\|C_{max}$	$\frac{5}{3}$	Lee and Strusevich (2005)
$O2, T1(c \geq n)\|t_{ii'} = et_{ii'}\|C_{max}$	2	-//-
$O2, T1(c \geq n)^{[7]}\|t_{ii'} = et_{ii'} = t\|\gamma^*$	$\frac{7}{5}^{\dagger}$	Lushchakova et al. (2009)
$O2\|t_{ii'} = t\|C_{max}$	$\frac{3}{2}^{\dagger}$	Rebaine and Strusevich (1999)
$O2\|t_{ii'}\|C_{max}$	$\frac{8}{5}^{\dagger}$	-//-
$O2\|t_j\|C_{max}$	$\frac{3}{2}^{\dagger}$	Strusevich (1999)
Further flow-shop SchedPT variants		
$F2, T1(c \geq n)\|t_{1,2}, et\|C_{max}$	$\frac{3}{2}$	Lee and Strusevich (2005)
$F2, T1(c = b^{[8]})\|t_{1,2} = et, batch(1)\|C_{max}$	2	Tang and Liu (2009)
$F2, T1\|t_{1,2}, et\|C_{max}$	2	Tang et al. (2010)
$HF2(3,6)^{[9]}, TD3\|t_{ii'}, et_{ii'}, b_1^{out} = 0\|TIT + C_{max} + TWT$	$\frac{15}{2}$	-//-
$F2, T1(c^{[10]})\|t_{1,2} \geq et\|C_{max}$	$2^{\dagger}$	Zhong and Chen (2015)
$HF2(2,1), T1\|t_{ss'} \geq et_{ss'}\|C_{max}$	$2^{\dagger}$	-//-

Note: Ratios with dagger symbol (†) are tight.
[1] Metric setup time.
[2] There are only two families of jobs. [3] The routing subproblem is polynomially solvable.
[4] RS with line-shaped transportation networks. [5] Variable depot RS with uniform machines. [6] Online problem.
[7] At the beginning, all jobs and the transporter are located at the same machine.
[8] The capacity of the transporter is equal to the capacity of the batching machine (b).
[9] Maximal waiting time of jobs between consecutive stages is limited. The weights of TIT and TWT can not be bigger than the weight of C_{max}.
[10] The transporter's capacity limits the total weight of jobs it can carry.

Table 7: SchedPT variants with known approximation guarantees or competitive ratios.

Zhang and van de Velde (2010) formulate competitive ratios for online two-machine open-shop SchedPT, in which jobs arrive dynamically at *a priori* unknown points of time. The authors study the so-called *non-clairvoyant* case, when both processing times p_{ij} and transportation times t_j are *unknown* until the respective processing step has been finished. The heuristic of Zhang and van de Velde (2010) works also in the clairvoyant case, when the job-specific information is revealed upon the arrival of the job; the performance guarantee remains as cited in Table 7, though it may not be tight anymore.

Worst-case ratios have been found for the two-machine *open shop* with job-dependent (Strusevich, 1999) and machine-dependent (Rebaine and Strusevich, 1999) transportation times as well as in case of one uncapacitated transporter (Lee and Strusevich, 2005; Lushchakova et al., 2009). Observe that in a two-machine open shop, the transporter's trips from machine 2 to machine 1 need not necessarily be empty, therefore we differentiate between machine-dependent ($t_{ii'}$) and constant ($t_{ii'} = t$) travel times.

The known performance guarantee results for the *flow-shop* SchedPT refer to a fixed number of transporters (single or multiple) as well as to constant or machine-dependent transportation times (Lee and Strusevich, 2005; Tang and Liu, 2009; Tang et al., 2010; Zhong and Chen, 2015).

To conclude, we would like to highlight the *SYMM* heuristic for $Fm||C_{max}$ developed by Averbakh and Berman (1999), which was used to construct performance guarantees for routing-scheduling SchedPT variants. The performance guarantee of SYMM is $\frac{m+1}{2}$. SYMM generates permutation schedules, i.e. solutions with the same processing sequence of jobs on each machine. Let S be this processing sequence, then SYMM examines the objective values $F(S)$ of S and $F(S^{-1})$ of the reverse sequence S^{-1} and returns, whichever is the best. For illustration, we modify the example from Section 4.1 to $F3||C_{max}$ by ignoring empty travel times and by interpreting the transporter as a machine, as described above. Let S here be a schedule where job 1 is processed before job 2 on each machine. Then, S^{-1} is to process job 2 before job 1 on each machine, $F(S)$ equals 11 and $F(S^{-1})$ equals 10. So, SYMM advises to sequence job 2 always before job 1. Since the performance guarantee is $\frac{m+1}{2} = \frac{3+1}{2} = 2$, the optimal objective value of the constructed $F3||C_{max}$-instance cannot be lower than $\frac{10}{2} = 5$. Observe that SYMM can be effective in constructing lower bounds for $Fm||C_{max}$, because the worst of the generated schedules (set $\mathcal{S}$) determines a lower bound, i.e., $OPT \geq \frac{2}{m+1} \max_{S \in \mathcal{S}}\{\min\{F(S), F(S^{-1})\}\}$.

4.4 Solution approaches based on the properties of the disjunctive graph

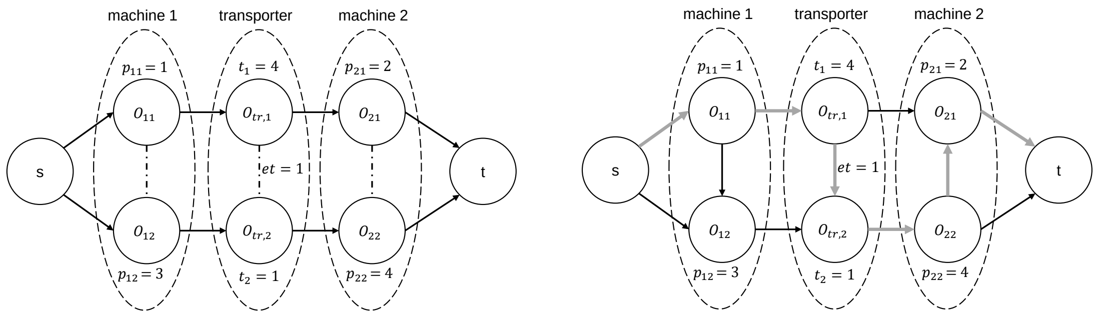
A widespread technique to solve SchedPT variants with the makespan objective is the *disjunctive graph (DG)*. The DG was introduced in machine scheduling by Roy and Sussmann (1964) and Balas (1969) as an elegant tool to visualize the existing precedence relations and interdependencies in the shop. It has been actively used to exclude dominated (less attractive) solutions as well as to derive lower and upper bounds, which are part of customized heuristic and exact solution algorithms.

Definition. *Disjunctive graph $DG = \{V, C \cup D\}$ is a graph with a set of nodes V representing operations, two additional special nodes – source s and target node t –, and two types of edges:*

- *conjunctive or directed edges C, which reflect the required precedence relations between operations,*
- *disjunctive or undirected edges D, which indicate that an overlapping processing of the edge defining operations is infeasible.*

Node labels in the DG represent the processing times of the operations. Edge labels indicate the time required to move between the two nodes along this edge, e.g. as empty travel times.

Figure 11a illustrates a DG for our motivational example from Section 4.1. As discussed earlier, we can interpret the transporter as an additional machine and its movement as the operations of this machine. The resulting DG has eight nodes: six nodes depicting operations, a source, and a target. The disjunctive edge between the transport operations reflects the empty travel time and has the weight of 1.



(a) Disjunctive graph. (b) Directed acyclic graph for a feasible solution.

Figure 11: The disjunctive graph of the example from Section 4.1.

In a solution of a scheduling problem modeled as a DG, each disjunctive edge is to be directed such that the resulting directed graph is *acyclic*. In Figure 11a, there are three disjunctive edges and 8 possible ways of their orientation. Figure 11b illustrates the resulting directed acyclic graph for solution $S' = ((o_{11}, o_{12}), (o_{tr,1}, o_{tr,2}), (o_{22}, o_{21}))$, in which job 1 is processed before job 2 on machine 1 and on the transporter, but machine 2 performs job 2 first. The makespan of S' equals to the length of the longest, or *critical*, path in this graph, which is $(s, o_{11}, o_{tr,1}, o_{tr,2}, o_{22}, o_{21}, t)$ with the length of 13. Observe that the path length equals to the sum of the labels of the visited arcs *and nodes* (except for the start and end nodes).

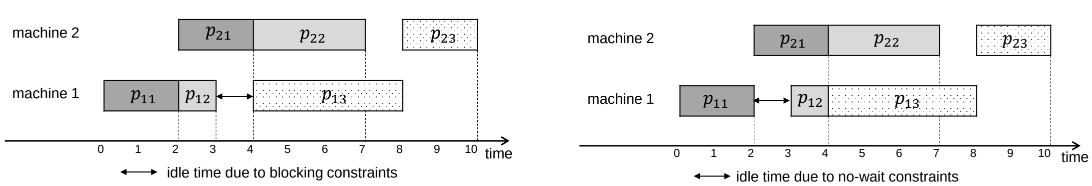
The DG is often used to design *fix & optimize heuristics*, such as *the shifting bottleneck heuristic (SBH)* (Adams et al., 1988). Here, we start with an empty partial solution and stepwise extend it by fixing a complete sequence of operations for one machine at a time, until we receive a feasible solution. Observe that in a *partial solution* S', the directions of selected disjunctive edges are fixed. Below, we describe the idea of the SBH in a small example and refer to Adams et al. (1988) for details. Consider the DG in Figure 11a and let the current partial solution S' be empty, i.e. there are no disjunctive directed edges yet. The *head* of an operation o is the earliest time, when this operation can start given the directed edges in the DG; it equals to the length of the longest path between source s and o; e.g., $head(o_{tr,1}) = 1$ and $head(o_{tr,2}) = 3$. The *tail* of an operation o is the minimal time that should pass after the completion of o until all the jobs are completed; it equals to the length of the longest path between o and target t in the DG; e.g., $tail(o_{tr,1}) = 2$ and $tail(o_{tr,2}) = 4$. To sequence the operations on the transporter, we have to decide on the direction of disjunctive edge $\{o_{tr,1}, o_{tr,2}\}$ that results in the shortest critical path in the DG. We can do it by solving a single-machine problem $1|r_j, s_{jj'}|L_{max}$ with release times $r_j := head(o_{tr,j})$, processing times $p_j := t_j$, due dates $d_j := M - tail(o_{tr,j})$, and setup times $s_{jj'} := et$. Here, M is the current makespan. Obviously, we want operations with long tails to be completed as early as possible, which results in objective L_{max}. Although $1|r_j, s_{jj'}|L_{max}$ is NP-hard the obtained instances are rather small and can be solved quickly (cf. **?**). In our example, both possible operation sequences of the transporter result in the same objective value ($L_{max} = 11 - M$). We break the ties arbitrarily, e.g., by setting the direction of the respective disjunctive edge to 'up', and update the current partial solution: $S' := S' \cup \{(o_{tr,2}, o_{tr,1})\}$. We perform two more iterations according to the same scheme to receive a feasible schedule; at each iteration we fix the operations' sequence for one machine. SBH has been applied to SchedPT with multiple transporters and an infinite number of transporters, capacitated buffers of machines, time windows as well as restricted waiting times between the operations (cf. Ivens and Lambrecht, 1996; Jeong et al., 1999; Schutten, 1998; Zhang et al., 2014).

A feasible solution for a scheduling problem modeled as a DG is the set of directed disjunctive edges. The makespan of this solution is the length of a *critical* path from s to t. In order to find a better solution all critical paths in the DG need to be reduced in their lengths. Thus, the orientation of at least one of the directed disjunctive edges on a critical path has to be reversed. It is the basic idea of the single-machine lower bounds for job-shop scheduling, of branching strategies and of neighbourhood definitions in local search algorithms, cf. Carlier (1982, 1987); Carlier and Pinson (1989); Brucker et al. (1994), the survey of Błażewicz et al. (1996). It can be extended to a variety of SchedPT settings (cf. Hurink and Knust, 2005) with a single and multiple transporters; with and without input/output stations and including hybrid and flexible shop settings, cf. Elmi and Topaloglu (2013); Lacomme et al. (2013); Rossi (2014); Zeng et al. (2019).

In our simple example from Figure 11b, the critical set of edges contains all the fixed disjunctive edges on the critical path, i.e. $\{(o_{tr,1}, o_{tr,2}), (o_{22}, o_{21})\}$. All the solutions, in which the transporter carries job 1 before job 2 and machine 2 processes job 2 before job 1, have the objective value of at least 13.

4.5 Selected solution approaches based on the transformations to routing problems

Perhaps, the most prominent application of the routing algorithms in SchedPT refers to the ideas of Gilmore and Gomory (1964) for the no-wait and blocking flow-shop settings with zero-sized buffers. Recall that if $b_i^{in} = b_i^{out} = 0$, then the workpiece has to remain at machine i' until the next machine $(i' + 1)$ is free. Gilmore and Gomory (1964) showed how to transform $F2|nwt|C_{max}$ and $F2|b_i^{in} = b_i^{out} = 0|C_{max}$ to a special asymmetric TSP, which is solvable in $O(n \log n)$ (Vairaktarakis, 2003). Observe that $F2|nwt|C_{max}$ and $F2|b_i^{in} = b_i^{out} = 0|C_{max}$ are equivalent as illustrated in Figure 12 in the sense, that each feasible solution of one problem corresponds to a feasible solution of the other problem with the same objective value. The reason for this is that in both cases (including no-wait), we cannot start processing a job j' on machine i', until the next machine $(i' + 1)$ starts the processing the previous job j. In Figure 12, machine 1 cannot start processing job 3 until job 2 starts on machine 2.



(a) A feasible solution for $F2|b_i^{in} = b_i^{out} = 0|C_{max}$. (b) The respective feasible solution for $F2|nwt|C_{max}$.

Figure 12: Illustrative examples of feasible solutions of zero-buffer blocking and no-wait flow shops. Each feasible solution for $F2|nwt|C_{max}$ corresponds to a feasible solution of $F2|b_i^{in} = b_i^{out} = 0|C_{max}$, and *vice versa*. An optimal solution is provided in Figure 13.

So, *w.l.o.g*, let's consider $F2|nwt|C_{max}$. The main idea of Gilmore and Gomory (1964) is very intuitive. Recall that we cannot start processing any j' on machine 1 before machine 2 starts processing the previous job j. Then, we can compute the completion time $C_{2,j'}$ of job j' on machine 2 as follows. If $p_{1,j'} \leq p_{2,j}$, as for jobs $j' = 2$ and $j = 1$ in Figure 12b, then $C_{2,j'} = C_{2,j} + p_{2,j'}$. Otherwise, if $p_{1,j'} > p_{2,j}$ as for jobs $j' = 3$ and $j = 2$ in Figure 12b, then $C_{2,j'} = C_{2,j} + (p_{1,j'} - p_{2,j}) + p_{2,j'}$. Observe that the calculations rely on the parameters of j and j', the parameters of the remaining jobs are *irrelevant*. This allows us to formulate transition costs between jobs $j, j' \in J$ for the TSP-transformation as $c_{j,j'} := C_{2,j'} - C_{2,j} = p_{2,j'} + \max\{0, p_{1,j'} - p_{2,j}\}$.

Finally, observe that $p_{2,j'}$ can be dropped in the computation of each $c_{j,j'}$; then, we have to correct the objective of the respective TSP by adding $\sum_{j \in J} p_{2,j}$ to receive the optimal makespan. In our example in Figure 13, an optimal TSP-tour is $(j_0, j_2, j_3, j_1, j_0)$ with the objective value of 2; this corresponds to the optimal schedule 'process j_2, then j_3, then j_1 on each machine' and to the optimal makespan $2 + 7 = 9$ for the original $F2|nwt|C_{max}$-instance from Figure 12b.

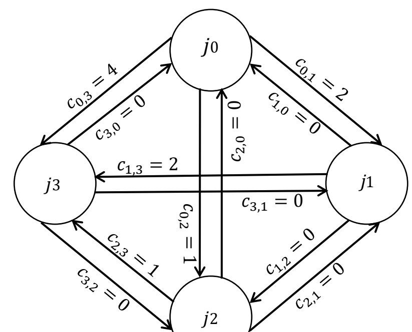


Figure 13: TSP for the instance from Figure 12b. Dummy job j_0 (with zero processing times) was introduced to mark the start of the TSP-tour.

See Bagchi et al. (2006) for a more detailed discussion of the Gilmore-Gomory algorithm in the context of robotic cells. For instance, the sketched TSP-transformation can be extended to the case of multiple machines, though the resulting asymmetric TSP won't be polynomially solvable anymore. The ideas of Gilmore and Gomory (1964) have been extended to two-machine flow-shop SchedPT variants with blocking and a single transporter, including the cases with and without input and output stations, machine- and job-dependent transportation times as well as empty travel and loading/unloading times (see Agnetis et al., 1996; Kise et al., 1991; Levner et al., 1995b; Stern and Vitner, 1990; Steiner and Xue, 2005).

4.6 Final remarks

Solving MIP-formulations of most SchedPT variants is known to be challenging with off-the-shelf solvers. One of the reasons is that, similarly to 'classic' scheduling problems, the LP-relaxations of common modeling approaches are not tight, i.e., the respective polyhedra are far away from the convex hulls spanned over the feasible solutions of the problem (Queyranne and Schulz, 1994). Furthermore, time-index formulations, which are comparatively more effective, quickly get prohibitively large (Van den Akker et al., 2000). As a result, common exact solution procedures for SchedPT are hybrid and integrate enumeration-based techniques with the LP-based solution procedures, as this is the case, for example, in branch-and-price methods or logic-based Benders decompositions (Li et al., 2022; Nishi et al., 2011). Lagrangean relaxation is often employed as part of these methods to get easier-to-solve problems (Nishi et al., 2011; Pan et al., 2022). For instance, by Lagrange-relaxing capacity constraints of the machines and transporters, the overall SchedPT can be sometimes decomposed into a set of 1-job scheduling subproblems.

5 Conclusion and future research directions

We reviewed more than 100 articles on scheduling problems in manufacturing with transportation (SchedPT). To classify the surveyed studies, we extended the state-of-the-art three-field notation. Based on the reviewed literature, we highlight main algorithmic approaches to solve SchedPT. We also collected more than 50 results on polynomially solvable problem variants and performance guarantees.

A number of questions remain for future research.

An interesting line of research takes theoretical and algorithmic results for ‘classical’ scheduling problems and attempts to extend and adapt them to SchedPT. Although much research effort has been spent in this direction, many open questions remain, such as algorithms with performance guarantees for the parallel-machine SchedPT.

Based on the reviewed literature, a relatively small share of articles considers limited space of input and output buffers of the machines, although buffer capacity remains a common bottleneck in manufacturing processes. Among manufacturing settings, especially reconfigurable manufacturing systems have received less attention so far, notwithstanding the general large interest of practitioners and in the academic community. Furthermore, studies that include multiple machines and multiple transporters are still underrepresented (cf. Figure 6) and promise to become a fruitful area of research. Especially the cases of heterogenous transporters, which in practice often differ not only in their velocity (transportation time), but also functionality, capacity and energy-consumption, have to be addressed. An interesting lane of studies is to integrate a more detailed transporter routing into SchedPT to anticipate possible delays due to congestion and collision avoidance, which is relevant for many factories, especially due to limited factory space.

On-going customization and digitization in companies emphasize the importance of research on online-versions of SchedPT, including design of well-performing policies, competitive ratio and average performance analysis. Furthermore, poor data quality remains a challenge for many manufacturing enterprises. Therefore, approaches on how to deal with incomplete and noisy information as well as smart data collection strategies remain of high interest (Otto and Otto, 2014). Automation of production processes coupled with digitization offer an opportunity for more integrated operational planning. Still, only few studies on advanced solution approaches, especially decompositions, for larger production units exist (cf. Carlier et al., 2010; Li et al., 2022; Nishi et al., 2011; Pan et al., 2022) and further research in this area is of high importance.

A characteristic challenge of scheduling in manufacturing is the variety of relevant problem variants and constraints. Only on the technological side, the range of available solutions is vast. Just consider, e.g., different transporter technologies, which may include single and multiple grippers for handover of the jobs as well as swapping handover devices; transporters may be flexible in their movement, may only follow marked lines or wires, be track-mounted or even share the same track with other transporters. Companies not only combine heterogeneous transporters and machines, but also face a range of industry- and factory-specific constraints. Developing a customized solution approach case by case for each enterprise would be a lengthy and slow undertaking. To face this challenge, we need on one side more well-documented case studies and benchmark data sets. On the other side, further consolidation work should be done in summarizing and formalizing major classes of problem formulations and mathematical types of constraints as well as advising on the priorities in their analysis.

Acknowledgments

This work was supported by the Deutsche Forschungsgemeinschaft (DFG - German Research Foundation) as part of the SuPerPlan project GZ: OT 500/4-1.

References

Aanen, E., Gaalman, G. J., and Nawijn, W. M. (1993). A scheduling approach for a flexible manufacturing system. *International Journal of Production Research*, 31(10):2369–2385.

Abdelmaguid, T. F., Nassef, A. O., Kamal, B. A., and Hassan, M. F. (2004). A hybrid GA/heuristic approach to the simultaneous scheduling of machines and automated guided vehicles. *International Journal of Production Research*, 42(2):267–281.

Adams, J., Balas, E., and Zawack, D. (1988). The shifting bottleneck procedure for job shop scheduling. *Management Science*, 34(3):391–401.

Agnetis, A. and Arbib, C. (1997). Concurrent operations assignment and sequencing for particular assembly problems in flow lines. *Annals of Operations Research*, 69:1–31.

Agnetis, A., Pacciarelli, D., and Rossi, F. (1996). Lot scheduling in a two-machine cell with swapping devices. *IIE Transactions*, 28(11):911–917.

Aguirre, A. M., Méndez, C. A., and Castro, P. M. (2014). A hybrid scheduling approach for automated flowshops with material handling and time constraints. *International Journal of Production Research*, 52(9):2788–2806.

Ahmadi-Javid, A. and Hooshangi-Tabrizi, P. (2015). A mathematical formulation and anarchic society optimisation algorithms for integrated scheduling of processing and transportation operations in a flow-shop environment. *International Journal of Production Research*, 53(19):5988–6006.

Allahverdi, A. (2015). The third comprehensive survey on scheduling problems with setup times/costs. *European Journal of Operational Research*, 246(2):345–378.

Allahverdi, A., Gupta, J., and Aldowaisan, T. (1999). A review of scheduling research involving setup considerations. *Omega*, 27:219–239.

Allahverdi, A., Ng, C. T., Cheng, T. C. E., and Kovalyov, M. Y. (2008). A survey of scheduling problems with setup times or costs. *European Journal of Operational Research*, 187(3):985–1032.

Anwar, M. F. and Nagi, R. (1998). Integrated scheduling of material handling and manufacturing activities for just-in-time production of complex assemblies. *International Journal of Production Research*, 36(3):653–681.

Archetti, C., Peirano, L., and Speranza, M. G. (2021). Optimization in multimodal freight transportation problems: A survey. *European Journal of Operational Research*, 299(1):1–20.

Averbakh, I. and Berman, O. (1996). Routing two-machine flowshop problems on networks with special structure. *Transportation Science*, 30(4):303–314.

Averbakh, I. and Berman, O. (1999). A simple heuristic for m-machine flow-shop and its applications in routing-scheduling problems. *Operations Research*, 47(1):165–170.

Averbakh, I., Berman, O., and Chernykh, I. (2005). A 6/5-approximation algorithm for the two-machine routing open-shop problem on a two-node network. *European Journal of Operational Research*, 166(1):3–24.

Averbakh, I., Berman, O., and Chernykh, I. (2006). The routing open-shop problem on a network: Complexity and approximation. *European Journal of Operational Research*, 173(2):531–539.

Babu, A. G., Jerald, J., Haq, A. N., Luxmi, V. M., and Vigneswaralu, T. P. (2010). Scheduling of machines and automated guided vehicles in FMS using differential evolution. *International Journal of Production Research*, 48(16):4683–4699.

Bagchi, T. P., Gupta, J. N., and Sriskandarajah, C. (2006). A review of TSP based approaches for flowshop scheduling. *European Journal of Operational Research*, 169(3):816–854.

Balas, E. (1969). Machine sequencing via disjunctive graphs: An implicit enumeration algorithm. *Operations Research*, 17(6):941–957.

Baumann, P. and Trautmann, N. (2014). A hybrid method for large-scale short-term scheduling of make-and-pack production processes. *European Journal of Operational Research*, 236(2):718–735.

Bilge, Ü. and Ulusoy, G. (1995). Time window approach to simultaneous scheduling of machines and material handling system in an FMS. *Operations Research*, 43(6):1058–1070.

Błażewicz, J., Domschke, W., and Pesch, E. (1996). The job shop scheduling problem: Conventional and new solution techniques. *European Journal of Operational Research*, 93:1–33.

Błażewicz, J., Ecker, K. H., Pesch, E., Schmidt, G., Sterna, M., and Weglarz, J. (2019a). *Handbook on Scheduling*. Springer.

Błażewicz, J., Ecker, K. H., Pesch, E., Schmidt, G., Sterna, M., and Weglarz, J. (2019b). Scheduling in flexible manufacturing systems. In *Handbook on Scheduling*, pages 671–711. Springer.

Błażewicz, J., Pawlak, G., and Walter, B. (2002). Scheduling production tasks in a two-stage FMS. *International Journal of Production Research*, 40(17):4341–4352.

Botta-Genoulaz, V. (2000). Hybrid flow shop scheduling with precedence constraints and time lags to minimize maximum lateness. *International Journal of Production Economics*, 64(1):101–111.

Boudhar, M. and Haned, A. (2009). Preemptive scheduling in the presence of transportation times. *Computers & Operations Research*, 36(8):2387–2393.

Boysen, N., Briskorn, N., and Meisel, F. (2017). A generalized classification scheme for crane scheduling with interference. *European Journal of Operational Research*, 258:343–357.

Bożek, A. and Werner, F. (2018). Flexible job shop scheduling with lot streaming and sublot size optimisation. *International Journal of Production Research*, 56(19):6391–6411.

Brauner, N. (2008). Identical part production in cyclic robotic cells: Concepts, overview and open questions. *Discrete Applied Mathematics*, 156(13):2480–2492.

Brucker, P., Jurisch, B., and Sievers, B. (1994). A branch and bound algorithm for the job-shop scheduling problem. *Discrete Applied Mathematics*, 49(1-3):107–127.

Brucker, P. and Knust, S. (2009). Complexity results for scheduling problems. http://www2.informatik.uni-osnabrueck.de/knust/class/.

Brucker, P., Knust, S., Cheng, T. C. E., and Shakhlevich, N. V. (2004). Complexity results for flow-shop and open-shop scheduling problems with transportation delays. *Annals of Operations Research*, 129(1-4):81–106.

Brucker, P., Knust, S., and Wang, G. (2005). Complexity results for flow-shop problems with a single server. *European Journal of Operational Research*, 165(2):398–407.

Buzacott, J. and Yao, D. (1986). Flexible manufacturing systems: A review of analytical models. *Management Science*, 32:890–905.

Cao, J. and Bedworth, D. D. (1992). Flow shop scheduling in serial multi-product processes with transfer and set-up times. *International Journal of Production Research*, 30(8):1819–1830.

Carlier, J. (1982). The one machine sequencing problem. *European Journal of Operational Research*, 11:42–47.

Carlier, J. (1987). Scheduling jobs with release dates and tails on identical machines to minimize the makespan. *European Journal of Operational Research*, 29:298–306.

Carlier, J., Haouari, M., Kharbeche, M., and Moukrim, A. (2010). An optimization-based heuristic for the robotic cell problem. *European Journal of Operational Research*, 202(3):636–645.

Carlier, J. and Pinson, E. (1989). An algorithm for solving the job-shop problem. *Management Science*, 35:164–176.

Castillo-Salazar, J. A., Landa-Silva, D., and Qu, R. (2016). Workforce scheduling and routing problems: Literature survey and computational study. *Annals of Operations Research*, 239(1):39–67.

Chan, F. (2004). A comprehensive survey and future trend of simulation study on FMS scheduling. *Journal of Intelligent Manufacturing*, 15:87–102.

Chen, B. and Lee, C. Y. (2008). Logistics scheduling with batching and transportation. *European Journal of Operational Research*, 189(3):871–876.

Chen, B., Potts, C. N., and Woeginger, G. J. (1998). A review of machine scheduling: Complexity, algorithms and approximability. In Du, D. Z. and Pardalos, P. M., editors, *Handbook of Combinatorial Optimization: Volume1–3*, pages 1493–1641. Springer.

Chen, Z. L. (2010). Integrated production and outbound distribution scheduling: Review and extensions. *Operations Research*, 58(1):130–148.

Chernykh, I., Kononov, A., and Sevastyanov, S. (2013). Efficient approximation algorithms for the routing open shop problem. *Computers & Operations Research*, 40(3):841–847.

Crama, Y. (1997). Combinatorial optimization models for production scheduling in automated manufacturing systems. *European Journal of Operational Research*, 99(1):136–153.

Crama, Y., Kats, V., Van de Klundert, J., and Levner, E. (2000). Cyclic scheduling in robotic flowshops. *Annals of Operations Research*, 96(1):97–124.

Dang, Q. V., Nguyen, C. T., and Rudová, H. (2019). Scheduling of mobile robots for transportation and manufacturing tasks. *Journal of Heuristics*, 25(2):175–213.

Dawande, M., Geismar, H. N., Sethi, S. P., and Sriskandarajah, C. (2005). Sequencing and scheduling in robotic cells: Recent developments. *Journal of Scheduling*, 8(5):387–426.

Dessouky, Y. M., Roberts, C. A., Dessouky, M. M., and Wilson, G. (1996). Scheduling multi-purpose batch plants with junction constraints. *International Journal of Production Research*, 34(2):525–541.

Dosa, G. and Tuza, Z. (2018). Multiprofessor scheduling. *Discrete Applied Mathematics*, 234:195–209.

Ebrahimi, A., Jeon, H. W., Lee, S., and Wang, C. (2020). Minimizing total energy cost and tardiness penalty for a scheduling-layout problem in a flexible job shop system: A comparison of four metaheuristic algorithms. *Computers & Industrial Engineering*, 141:106295.

Edis, E. B., Oguz, C., and Ozkarahan, I. (2013). Parallel machine scheduling with additional resources: Notation, classification, models and solution methods. *European Journal of Operational Research*, 230(3):449–463.

El Amraoui, A. and Elhafsi, M. (2016). An efficient new heuristic for the hoist scheduling problem. *Computers & Operations Research*, 67:184–192.

ElMaraghy, H. A. (2005). Flexible and reconfigurable manufacturing systems paradigms. *International Journal of Flexible Manufacturing Systems*, 17(4):261–276.

Elmi, A. and Topaloglu, S. (2013). A scheduling problem in blocking hybrid flow shop robotic cells with multiple robots. *Computers & Operations Research*, 40(10):2543–2555.

Fahimnia, B., Farahani, R. Z., Marian, R., and Luong, L. (2013). A review and critique on integrated production-distribution planning models and techniques. *Journal of Manufacturing Systems*, 32(1):1–19.

Fazlollahtabar, H. and Saidi-Mehrabad, M. (2015). Methodologies to optimize automated guided vehicle scheduling and routing problems: A review study. *Journal of Intelligent & Robotic Systems*, 77:525–545.

Feng, J., Che, A., and Chu, C. (2015). Dynamic hoist scheduling problem with multi-capacity reentrant machines: A mixed integer programming approach. *Computers & Industrial Engineering*, 87:611–620.

Feng, Y., Li, G., and Sethi, S. P. (2018). A three-layer chromosome genetic algorithm for multi-cell scheduling with flexible routes and machine sharing. *International Journal of Production Economics*, 196:269–283.

Fragapane, G., Hvolby, H., Sgarbossa, F., and Strandhagen, J. O. (2022a). Autonomous mobile robots in sterile instrument logistics: An evaluation of the material handling system for a strategic fit framework. *Production Planning & Control*, in press.

Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., and Strandhagen, J. (2022b). Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Annals of Operations Research*, 308:125–143.

Gamberi, M., Manzini, R., and Regattieri, A. (2009). An new approach for the automatic analysis and control of material handling systems: Integrated layout flow analysis (ILFA). *The International Journal of Advanced Manufacturing Technology*, 41:156–167.

Geissbauer, R., Schrauf, S., Berttram, P., and Cheraghi, F. (2017). Digital factories 2020: Shaping the future of manufacturing. Technical report, PricewaterhouseCoopers GmbH.

Gilmore, P. C. and Gomory, R. E. (1964). Sequencing a one state-variable machine: A solvable case of the traveling salesman problem. *Operations Research*, 12(5):655–679.

Glass, C. A., Shafransky, Y. M., and Strusevich, V. A. (2000). Scheduling for parallel dedicated machines with a single server. *Naval Research Logistics*, 47(4):304–328.

Graham, R. L., Lawler, E. L., Lenstra, J. K., and Kan, A. H. G. R. (1979). Optimization and heuristic in deterministic sequencing and scheduling: A survey. *Annals of Discrete Mathematics*, 5:287–326.

Gunasekaran, A., Martikainen, T., and Yli-Olli, P. (1993). Flexible manufacturing systems: An investigation for research and applications. *European Journal of Operational Research*, 66(1):1–26.

Gutin, G. and Punnen, A. P. (2006). *The traveling salesman problem and its variations*, volume 12. Springer.

Hall, N. G., Kamoun, H., and Sriskandarajah, C. (1998). Scheduling in robotic cells: Complexity and steady state analysis. *European Journal of Operational Research*, 109(1):43–65.

Hall, N. G., Potts, C. N., and Sriskandarajah, C. (2000). Parallel machine scheduling with a common server. *Discrete Applied Mathematics*, 102(3):223–243.

Haned, A., Soukhal, A., Boudhar, M., and Huynh Tuong, N. (2012). Scheduling on parallel machines with preemption and transportation delays. *Computers & Operations Research*, 39(2):374–381.

He, X., Dong, S., and Zhao, N. (2020). Research on rush order insertion rescheduling problem under hybrid flow shop based on NSGA-III. *International Journal of Production Research*, 58(4):1161–1177.

Hottenrott, A. and Grunow, M. (2019). Flexible layouts for the mixed-model assembly of heterogeneous vehicles. *OR Spectrum*, 41:943–979.

Hottenrott, A., Schiffer, M., and Grunow, M. (2022). Flexible assembly layouts in smart manufacturing: An impact assessment for the automotive industry. *IISE Transactions*, in press.

Hurink, J. and Knust, S. (2001). Makespan minimization for flow-shop problems with transportation times and a single robot. *Discrete Applied Mathematics*, 112(1-3):199–216.

Hurink, J. and Knust, S. (2002). A tabu search algorithm for scheduling a single robot in a job-shop environment. *Discrete Applied Mathematics*, 119(1-2):181–203.

Hurink, J. and Knust, S. (2005). Tabu search algorithms for job-shop problems with a single transport robot. *European Journal of Operational Research*, 162(1):99–111.

Ivens, P. and Lambrecht, M. (1996). Extending the shifting bottleneck procedure to real-life applications. *European Journal of Operational Research*, 90(2):252–268.

Jeong, H. I., Park, J., and Leachman, R. C. (1999). A batch splitting method for a job shop scheduling problem in an MRP environment. *International Journal of Production Research*, 37(15):3583–3598.

Jiang, E. D. and Wang, L. (2019). An improved multi-objective evolutionary algorithm based on decomposition for energy-efficient permutation flow shop scheduling problem with sequence-dependent setup time. *International Journal of Production Research*, 57(6):1756–1771.

Johnson, S. M. (1954). Optimal two-and three-stage production schedules with setup times included. *Naval Research Logistics Quarterly*, 1(1):61–68.

Karuno, Y., Nagamochi, H., and Ibaraki, T. (2002). Better approximation ratios for the single-vehicle scheduling problems on line-shaped networks. *Networks*, 39(4):203–209.

Khramova, A. P. and Chernykh, I. (2021). A new algorithm for the two-machine open shop and the polynomial solvability of a scheduling problem with routing. *Journal of Scheduling*, 24(4):405–412.

King, R. E., Hodgson, T. J., and Chafee, F. W. (1993). Robot task scheduling in a flexible manufacturing cell. *IIE Transactions*, 25(2):80–87.

Kise, H., Shioyama, T., and Ibaraki, T. (1991). Automated two-machine flowshop scheduling: A solvable case. *IIE Transactions*, 23(1):10–16.

Kizilay, D., Van Hentenryck, P., and Eliiyi, D. T. (2020). Constraint programming models for integrated container terminal operations. *European Journal of Operational Research*, 286(3):945–962.

Knust, S. (2010). *Shop-Scheduling Problems with Transportation*. PhD thesis, Universität Osnabrück.

Koren, Y., Wang, W., and Gu, X. (2017). Value creation through design for scalability of reconfigurable manufacturing systems. *International Journal of Production Research*, 55(5):1227–1242.

Kovalyov, M. Y., Pesch, E., and Ryzhikov, A. (2018). A note on scheduling container storage operations of two non-passing stacking cranes. *Networks*, 71(3):271–280.

Kulak, O. (2005). A decision support system for fuzzy multi-attribute selection of material handling equipments. *Expert Systems with Applications*, 29:310–319.

Lacomme, P., Larabi, M., and Tchernev, N. (2013). Job-shop based framework for simultaneous scheduling of machines and automated guided vehicles. *International Journal of Production Economics*, 143(1):24–34.

Lati, N. and Gilad, I. (2010). Minimising idle times in cluster tools in the semiconductor industry. *International Journal of Production Research*, 48(21):6443–6459.

Lawler, E., Lenstra, J., Rinnooy Kan, A., and Shmoys, D. (1991). *The Traveling Salesman Problem: A Guided Tour of Combinatorial Optimization*. Wiley.

Lee, C. Y. and Chen, Z. L. (2001). Machine scheduling with transportation considerations. *Journal of Scheduling*, 4(1):3–24.

Lee, C. Y., Leung, J. Y., and Yu, G. (2006). Two machine scheduling under disruptions with transportation considerations. *Journal of Scheduling*, 9(1):35–48.

Lee, C. Y. and Strusevich, V. A. (2005). Two-machine shop scheduling with an uncapacitated interstage transporter. *IIE Transactions*, 37(8):725–736.

Lei, C., Zhao, N., Ye, S., and Wu, X. (2020). Memetic algorithm for solving flexible flow-shop scheduling problems with dynamic transport waiting times. *Computers & Industrial Engineering*, 139:105984.

Levner, E., Kogan, K., and Levin, I. (1995a). Scheduling a two-machine robotic cell: A solvable case. *Annals of Operations Research*, 57(1):217–232.

Levner, E., Kogan, K., and Maimon, O. (1995b). Flowshop scheduling of robotic cells with job-dependent transportation and set-up effects. *Journal of the Operational Research Society*, 46(12):1447–1455.

Li, F., Zhang, L., Liao, T. W., and Liu, Y. (2019a). Multi-objective optimisation of multi-task scheduling in cloud manufacturing. *International Journal of Production Research*, 57(12):3847–3863.

Li, X., Otto, A., and Pesch, E. (2017). Two-way bounded dynamic programming approach for operations planning in transshipment yards. *Transportation Science*, 51:325–342.

Li, X., Otto, A., and Pesch, E. (2019b). Solving the single crane scheduling problem at rail transshipment yards. *Discrete Applied Mathematics*, 264:134–147.

Li, Y., Côté, J. F., Callegari-Coelho, L., and Wu, P. (2022). Novel formulations and logic-based Benders decomposition for the integrated parallel machine scheduling and location problem. *INFORMS Journal on Computing*, 34(2):1048–1069.

Lian, X., Zheng, Z., Wang, C., and Gao, X. (2021). An energy-efficient hybrid flow shop scheduling problem in steelmaking plants. *Computers & Industrial Engineering*, 162:107683.

Liou, C. D. and Hsieh, Y. C. (2015). A hybrid algorithm for the multi-stage flow shop group scheduling with sequence-dependent setup and transportation times. *International Journal of Production Economics*, 170:258–267.

Liu, J. and MacCarthy, B. L. (1997). A global MILP model for FMS scheduling. *European Journal of Operational Research*, 100(3):441–453.

Liu, S. Q. and Kozan, E. (2017). A hybrid metaheuristic algorithm to optimise a real-world robotic cell. *Computers & Operations Research*, 84:188–194.

Lushchakova, I. N., Soper, A. J., and Strusevich, V. A. (2009). Transporting jobs through a two-machine open shop. *Naval Research Logistics*, 56(1):1–18.

Maggu, P. L. and Das, G. (1980). On $2 \times n$ sequencing problem with transportation times of jobs. *Pure and Applied Mathematika Sciences*, 12(1):1–6.

Maggu, P. L., Smghal, M. L., Mohammad, N., and Yadav, S. K. (1982). On n-job, 2-machine flow-shop scheduling problem with arbitrary time lags and transportation times of jobs. *Journal of the Operations Research Society of Japan*, 25(3):219–227.

Mehrabi, M. G., Ulsoy, A. G., and Koren, Y. (2000). Reconfigurable manufacturing systems: Key to future manufacturing. *Journal of Intelligent Manufacturing*, 11(4):403–419.

Mejía, G. and Yuraszeck, F. (2020). A self-tuning variable neighborhood search algorithm and an effective decoding scheme for open shop scheduling problems with travel/setup times. *European Journal of Operational Research*, 285(2):484–496.

Mönch, L., Fowler, J. W., Dauzère-Pérès, S., Mason, S. J., and Rose, O. (2011). A survey of problems, solution techniques, and future challenges in scheduling semiconductor manufacturing operations. *Journal of Scheduling*, 14(6):583–599.

Morris, J. S. and Tersine, R. J. (1990). A simulation analysis of factors influencing the attractiveness of group technology cellular layouts. *Management Science*, 36(12):1567–1578.

Naderi, B. and Azab, A. (2021). Production scheduling for reconfigurable assembly systems: Mathematical modeling and algorithms. *Computers & Industrial Engineering*, 162:107741.

Naderi, B., Zandieh, M., and Shirazi, M. A. (2009). Modeling and scheduling a case of flexible flowshops: Total weighted tardiness minimization. *Computers & Industrial Engineering*, 57(4):1258–1267.

Nishi, T., Hiranaka, Y., and Grossmann, I. E. (2011). A bilevel decomposition algorithm for simultaneous production scheduling and conflict-free routing for automated guided vehicles. *Computers & Operations Research*, 38(5):876–888.

Nossack, Y., Briskorn, D., and Pesch, E. (2018). Container dispatching and conflict-free yard crane routing in an automated container terminal. *Transportation Science*, 52:1059–1076.

Nouri, H. E., Driss, O. B., and Ghédira, K. (2016a). A classification schema for the job shop scheduling problem with transportation resources: State-of-the-art review. In Silhavy, R., Senkerik, R., Oplatkova, Z. K., Silhavy, P., and Prokopova, Z., editors, *Artificial Intelligence Perspectives in Intelligent Systems*, pages 1–11. Springer.

Nouri, H. E., Driss, O. B., and Ghédira, K. (2016b). Simultaneous scheduling of machines and transport robots in flexible job shop environment using hybrid metaheuristics based on clustered holonic multiagent model. *Computers & Industrial Engineering*, 102:488–501.

Olsen, T. and Tomlin, B. (2020). Industry 4.0: Opportunities and challenges for Operations Management. *Manufacturing & Service Operations Management*, 22:1–222.

Otto, C. and Otto, A. (2014). Multiple-source learning precedence graph concept for the automotive industry. *European Journal of Operational Research*, 234(1):253–265.

Pan, Q. K. (2016). An effective co-evolutionary artificial bee colony algorithm for steelmaking-continuous casting scheduling. *European Journal of Operational Research*, 250(3):702–714.

Pan, R., Wang, Q., Li, Z., Cao, J., and Zhang, Y. (2022). Steelmaking-continuous casting scheduling problem with multi-position refining furnaces under time-of-use tariffs. *Annals of Operations Research*, 310(1):119–151.

Panwalkar, S. S. (1991). Scheduling of a two-machine flowshop with travel time between machines. *Journal of the Operational Research Society*, 42(7):609–613.

Paraskevopoulos, D. C., Laporte, G., Repoussis, P. P., and Tarantilis, C. D. (2017). Resource constrained routing and scheduling: Review and research prospects. *European Journal of Operational Research*, 263(3):737–754.

Paulli, J. (1995). A hierarchical approach for the FMS scheduling problem. *European Journal of Operational Research*, 86(1):32–42.

Pinedo, M. L. (2012). *Scheduling*, volume 29. Springer.

Qin, H., Fan, P., Tang, H., Huang, P., Fang, B., and Pan, S. (2019). An effective hybrid discrete grey wolf optimizer for the casting production scheduling problem with multi-objective and multi-constraint. *Computers & Industrial Engineering*, 128:458–476.

Qiu, L., Hsu, W. J., Huang, S. Y., and Wang, H. (2002). Scheduling and routing algorithms for AGVs: a survey. *International Journal of Production Research*, 40(3):745–760.

Queyranne, M. and Schulz, A. S. (1994). *Polyhedral approaches to machine scheduling*. Berlin: TU, Fachbereich 3.

Rahimi, V., Arkat, J., and Farughi, H. (2020). A vibration damping optimization algorithm for the integrated problem of cell formation, cellular scheduling, and intercellular layout. *Computers & Industrial Engineering*, 143:106439.

Rebaine, D. and Strusevich, V. A. (1999). Two-machine open shop scheduling with special transportation times. *Journal of the Operational Research Society*, 50(7):756–764.

Rossi, A. (2014). Flexible job shop scheduling with sequence-dependent setup and transportation times by ant colony with reinforced pheromone relationships. *International Journal of Production Economics*, 153:253–267.

Rossi, A. and Lanzetta, M. (2020). Integration of hybrid additive/subtractive manufacturing planning and scheduling by metaheuristics. *Computers & Industrial Engineering*, 144:106428.

Roy, B. and Sussmann, B. (1964). Les problemes d'ordonnancement avec contraintes disjonctives (Scheduling problems with disjunctive constraints). *Note D. S.*, 9.

Saidi-Mehrabad, M., Dehnavi-Arani, S., Evazabadian, F., and Mahmoodian, V. (2015). An Ant Colony Algorithm (ACA) for solving the new integrated model of job shop scheduling and conflict-free routing of AGVs. *Computers & Industrial Engineering*, 86:2–13.

Sarin, S. C., Kalir, A. A., and Chen, M. (2008). A single-lot, unified cost-based flow shop lot-streaming problem. *International Journal of Production Economics*, 113(1):413–424.

Sawik, T. (1998). A lexicographic approach to bi-objective loading of a flexible assembly system. *European Journal of Operational Research*, 107(3):656–668.

Sawik, T. (2000). An LP-based approach for loading and routing in a flexible assembly line. *International Journal of Production Economics*, 64(1-3):49–58.

Schulz, A., Fliedner, M., Fiedrich, B., and Pfeiffer, C. (2021). Levelling crane workload in multi-yard rail-road container terminals. *European Journal of Operational Research*, 293(3):941–954.

Schutten, J. M. (1998). Practical job shop scheduling. *Annals of Operations Research*, 83:161–177.

Sevastianov, S. V. and Woeginger, G. J. (1998). Makespan minimization in open shops: A polynomial time approximation scheme. *Mathematical Programming*, 82(1):191–198.

Shabtay, D., Arviv, K., Stern, H., and Edan, Y. (2014). A combined robot selection and scheduling problem for flow-shops with no-wait restrictions. *Omega*, 43:96–107.

Shams, H. and Salmasi, N. (2014). Parallel machine scheduling problem with preemptive jobs and transportation delay. *Computers & Operations Research*, 50:14–23.

Soukhal, A. and Martineau, P. (2005). Resolution of a scheduling problem in a flowshop robotic cell. *European Journal of Operational Research*, 161(1):62–72.

Stecke, K. E. (2013). Flexible Manufacturing Systems. In Gass, S. and Fu, M., editors, *Encyclopedia of Operations Research and Management Science.*, pages 588–593. Springer.

Steiner, G. and Xue, Z. (2005). Scheduling in reentrant robotic cells: Algorithms and complexity. *Journal of Scheduling*, 8(1):25–48.

Stern, H. I. and Vitner, G. (1990). Scheduling parts in a combined production-transportation work cell. *Journal of the Operational Research Society*, 41(7):625–632.

Stevens, J. W. and Gemmill, D. D. (1997). Scheduling a two-machine flowshop with travel times to minimize maximum lateness. *International Journal of Production Research*, 35(1):1–15.

Strusevich, V. A. (1999). A heuristic for the two-machine open-shop scheduling problem with transportation times. *Discrete Applied Mathematics*, 93(2-3):287–304.

Sule, D. R. (1994). *Manufacturing Facilities: Location, Planning and Design*. PWS Publishing Company.

Sun, D., Tang, L., Baldacci, R., and Lim, A. (2021a). An exact algorithm for the unidirectional quay crane scheduling problem with vessel stability. *European Journal of Operational Research*, 291(1):271–283.

Sun, Y., Chung, S. H., Wen, X., and Ma, H.-L. (2021b). Novel robotic job-shop scheduling models with deadlock and robot movement considerations. *Transportation Research Part E: Logistics and Transportation Review*, 149:102273.

Tang, L., Guan, J., and Hu, G. (2010). Steelmaking and refining coordinated scheduling problem with waiting time and transportation consideration. *Computers & Industrial Engineering*, 58(2):239–248.

Tang, L. and Liu, P. (2009). Flowshop scheduling problems with transportation or deterioration between the batching and single machines. *Computers & Industrial Engineering*, 56(4):1289–1295.

Tompkin, J. and White, J. (1984). *Facilities Planning*. Wiley.

Ulusoy, G. and Bilge, Ü. (1993). Simultaneous scheduling of machines and automated guided vehicles. *International Journal of Production Research*, 31(12):2857–2873.

Ulusoy, G., Sivrikaya-Şerifoĝlu, F., and Bilge, Ü. (1997). A genetic algorithm approach to the simultaneous scheduling of machines and automated guided vehicles. *Computers & Operations Research*, 24(4):335–351.

Vairaktarakis, G. L. (2003). Simple algorithms for Gilmore–Gomory's traveling salesman and related problems. *Journal of Scheduling*, 6(6):499–520.

Van den Akker, J., Hurkens, C. A., and Savelsbergh, M. W. (2000). Time-indexed formulations for machine scheduling problems: Column generation. *INFORMS Journal on Computing*, 12(2):111–124.

Vis, I. F. (2006). Survey of research in the design and control of automated guided vehicle systems. *European Journal of Operational Research*, 170(3):677–709.

Wang, L., Wang, J. J., and Jiang, E. (2021). Decomposition based multiobjective evolutionary algorithm with adaptive resource allocation for energy-aware welding shop scheduling problem. *Computers & Industrial Engineering*, 162:107778.

Woeginger, G. J. (1997). A polynomial-time approximation scheme for maximizing the minimum machine completion time. *Operations Research Letters*, 20(4):149–154.

Yan, P., Liu, S. Q., Sun, T., and Ma, K. (2018). A dynamic scheduling approach for optimizing the material handling operations in a robotic cell. *Computers & Operations Research*, 99:166–177.

Yang, D. L. and Chern, M. S. (2000). Two-machine flowshop group scheduling problem. *Computers & Operations Research*, 27(10):975–985.

Yang, Y., Chen, Y., and Long, C. (2016). Flexible robotic manufacturing cell scheduling problem with multiple robots. *International Journal of Production Research*, 54(22):6768–6781.

Yu, W., Hoogeveen, H., and Lenstra, J. K. (2004). Minimizing makespan in a two-machine flow shop with delays and unit-time operations is NP-hard. *Journal of Scheduling*, 7(5):333–348.

Zeng, C., Tang, J., and Fan, Z. P. (2019). Auction-based cooperation mechanism for cell part scheduling with transportation capacity constraint. *International Journal of Production Research*, 57(12):3831–3846.

Zhang, Q., Manier, H., and Manier, M. A. (2012). A genetic algorithm with tabu search procedure for flexible job shop scheduling with transportation constraints and bounded processing times. *Computers & Operations Research*, 39(7):1713–1723.

Zhang, Q., Manier, H., and Manier, M. A. (2014). A modified shifting bottleneck heuristic and disjunctive graph for job shop scheduling problems with transportation constraints. *International Journal of Production Research*, 52(4):985–1002.

Zhang, S., Li, X., Zhang, B., and Wang, S. (2020). Multi-objective optimisation in flexible assembly job shop scheduling using a distributed ant colony system. *European Journal of Operational Research*, 283(2):441–460.

Zhang, S. and Wong, T. N. (2016). Studying the impact of sequence-dependent set-up times in integrated process planning and scheduling with E-ACO heuristic. *International Journal of Production Research*, 54(16):4815–4838.

Zhang, X. and van de Velde, S. (2010). On-line two-machine open shop scheduling with time lags. *European Journal of Operational Research*, 204(1):14–19.

Zhang, X. and van de Velde, S. (2015). Two-machine interval shop scheduling with time lags. *Journal of Scheduling*, 18(4):359–368.

Zheng, Y., Xiao, Y., and Seo, Y. (2014). A tabu search algorithm for simultaneous machine/AGV scheduling problem. *International Journal of Production Research*, 52(19):5748–5763.

Zhong, W. and Chen, Z. L. (2015). Flowshop scheduling with interstage job transportation. *Journal of Scheduling*, 18(4):411–422.

Appendix A

In the article, we outlined the extensions to the three-field notation that cover the aspects of transportation. In this appendix, we explain the remaining abbreviations used in Table 1, which stem from the conventional notation (see Błażewicz et al., 2019a; Graham et al., 1979; Pinedo, 2012).

Machine layout ($\alpha 1 \in \{1, P, F, HF, J, FJ, O\}$): Section 3 provides a brief overview of the material flow in the considered layouts.

$\alpha 1 = 1$: Single machine.

$\alpha 1 = P$: Parallel machines.

$\alpha 1 = F$: Flow shop.

$\alpha 1 = HF$: Hybrid flow shop.

$\alpha 1 = J$: Job shop.

$\alpha 1 = FJ$: Flexible job shop.

$\alpha 1 = O$: Open shop.

Number of machines/stages ($\alpha 2 \in \{const, m\}$):

$\alpha 2 = const$: The number of machines equals $const \in \mathbb{N}$.

$\alpha 2 = m$: The system can have any number of machines (or stages in a hybrid system).

Processing time ($\beta 1 \in \{\circ, p_{ij} = p\}$):

$\beta 1 = \circ$: Processing times can be arbitrary.

$\beta 1 = p_{ij} = p$: Constant processing time for all jobs on all machines.

Time-window parameters ($\beta 2 \in \{\circ, r_j, \tilde{d}_j\}$):

$\beta 2 = \circ$: No time windows / time windows are irrelevant.

$\beta 2 = r_j$: Jobs have job-specific release times.

$\beta 2 = \tilde{d}_j$: Jobs have deadlines, d_j denotes the time by which job j must leave the system.

Other constraints ($\beta 7 \in \{\circ, prmp, brkdwm, nwt, prmu, batch(i), prec, mlrs, rcrc, M_j\}$):

$\beta 7 = \circ$: There are no other constraints in the problem.

$\beta 7 = prmp$: Preemption. Jobs are allowed to be interrupted at any point in time and receive the remaining processing from the current or some other machine later on.

$\beta 7 = brkdwn$: Breakdowns or machine availability constraint. Some machines are not available for a given period of time.

$\beta 7 = nwt$: No-wait. Jobs are not allowed to wait between two successive machines.

$\beta 7 = prmu$: Permutation. Jobs visit machines in the same order (a job cannot pass another while waiting in a queue).

$\beta 7 = batch(i)$: Machine i is a batching machine and is able to process several jobs simultaneously.

$\beta 7 = prec$: Precedence constraints between jobs. One or more jobs may have to be completed before certain jobs are allowed to start their processing.

$\beta 7 = mlrs$: Multiple resources: Some jobs need two or more resources simultaneously for their processing.

$\beta 7 = rcrc$: Recirculation or reentrant system. A job may visit a machine more than once.

$\beta 7 = M_j$: Machine eligibility for job j. In a hybrid flow shop, not all the machines of the same stage can process job j.

Objective ($\gamma \in \{C_{max}, L_{max}, T_{max}, \sum C_j, \sum T_j, \sum w_j T_j\}$):

$\gamma = C_{max}$: Makespan.

$\gamma = L_{max}$: Lateness.

$\gamma = T_{max}$: Tardiness.

$\gamma = \sum C_j$: Total completion time.

$\gamma = \sum T_j$: Total tardiness.

$\gamma = \sum w_j T_j$: Total weighted tardiness.

Appendix B

Annals of Operations Research	Journal of Operations Management	OR Spectrum
Computers & Industrial Engineering	Journal of Scheduling	Production and Operations Management
Computers & Operations Research	Journal of the Operational Research Society	SIAM Journal on Applied Mathematics
Discrete Applied Mathematics	Management Science	SIAM Journal on Computing
European Journal of Applied Mathematics	Manufacturing & Service Operations Management	SIAM Journal on Optimization
European Journal of Operational Research	Mathematical Methods of Operations Research	Studies in Applied Mathematics
IISE Transactions (former IIE Transactions)	Mathematical Programming	Transportation Research Parts A
IMA of Applied Mathematics	Mathematics of Operations Research	Transportation Research Parts B
INFORMS Journal on Computing	Naval Research Logistics	Transportation Research Parts C
International Journal of Production Economics	Networks	Transportation Research Parts D
International Journal of Production Research	Omega	Transportation Research Parts E
Journal of Business Economics	Operations Research	Transportation Science
Journal of Heuristics	Operations Research Letters	

Table 8: List of the considered journals.

Appendix C

Studies on SchedPT variants in flexible manufacturing systems (FMS)		
Aanen et al. (1993)	Crama (1997)	Nishi et al. (2011)
Abdelmaguid et al. (2004)	Dang et al. (2019)	Paulli (1995)
Agnetis et al. (1996)	King et al. (1993)	Stern and Vitner (1990)
Babu et al. (2010)	Kise et al. (1991)	Ulusoy and Bilge (1993)
Bilge and Ulusoy (1995)	Lacomme et al. (2013)	Ulusoy et al. (1997)
Błażewicz et al. (2002)	Liu and MacCarthy (1997)	Zheng et al. (2014)
Studies on SchedPT variants in robotic cells (RC)		
Carlier et al. (2010)	Levner et al. (1995a)	Steiner and Xue (2005)
El Amraoui and Elhafsi (2016)	Levner et al. (1995b)	Sun et al. (2021a)
Elmi and Topaloglu (2013)	Liu and Kozan (2017)	Yan et al. (2018)
Feng et al. (2015)	Shabtay et al. (2014)	Yang et al. (2016)
Lati and Gilad (2010)	Soukhal and Martineau (2005)	
Studies on SchedPT variants in flexible assembly lines (FAL)		
Agnetis and Arbib (1997)	Hottenrott et al. (2022)	Zhang et al. (2020)
Anwar and Nagi (1998)	Sawik (1998)	
Hottenrott and Grunow (2019)	Sawik (2000)	
Studies on routing-scheduling SchedPT variants (RS)		
Averbakh and Berman (1996)	Averbakh et al. (2006)	Khramova and Chernykh (2021)
Averbakh and Berman (1999)	Chernykh et al. (2013)	
Averbakh et al. (2005)	Karuno et al. (2002)	
Studies on SchedPT variants in cellular manufacturing (CM)		
Feng et al. (2018)	Rahimi et al. (2020)	Zeng et al. (2019)
Studies on SchedPT variants in reconfigurable manufacturing systems (RMS)		
Naderi and Azab (2021)		
Further studies on SchedPT variants featuring specific industries		
Aguirre et al. (2014)	Li et al. (2019a)	Rossi and Lanzetta (2020)
Baumann and Trautmann (2014)	Pan (2016)	Tang et al. (2010)
Dessouky et al. (1996)	Pan et al. (2022)	Wang et al. (2021)
Lian et al. (2021)	Qin et al. (2019)	

Note: Only papers with an explicit and prominent reference to the respective manufacturing setting are included. See Section 1.2 and Figure 9 for the details on the classification.

Table 9: Articles classified by the studied manufacturing setting.