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A survey of scheduling problems with uncertain interval/bounded processing/setup times

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ABSTRACT

Scheduling plays an important role in service and manufacturing environments for the delivery of reliable products on time. The scheduling literature reveals that the vast majority of the investigated scheduling problems are for the deterministic case where all parameters of jobs are known in advance and are fixed. However, in some real-world environments, the assumption of fixed parameters of jobs is not valid since job parameters are uncertain. An uncertain parameter can be modelled as having a probability distribution, or it can be modelled as a fuzzy number, or it can be modelled as a random variable within some interval with lower and upper bounds, distribution free. If the uncertain parameter, e.g., processing time, is modelled as a random variable within some lower or upper bounds, it is called interval or bounded processing time. The objective of this paper is to survey the investigated scheduling problems with interval or bounded processing/setup times. The scheduling literature is reviewed, the addressed problems are analyzed, and classified based on shop environments (single machine, parallel machine, flowshop, job shop), performance measures, the approach taken in the papers to solve the considered problem, and interval/bounded processing times or setup times. Some future research opportunities with interval/bounded processing/setup times are presented.

1. Introduction

This paper reviews scheduling literature on scheduling problems with uncertain processing or setup times. Even though ignoring setup times is valid for some manufacturing settings it is not valid for some other manufacturing settings. Kopanos et al. (2009) reported that setup times play an important role in some manufacturing environments, however, a review of the literature on scheduling problems indicates that more than 90% of the literature on scheduling problems ignores setup times, Allahverdi (2015). On the other hand, millions of dollars per year were saved by considering setup times in their scheduling by many companies, e.g., Trovinger and Bohn (2005), Loveland et al. (2007). Furthermore, Sabouni and Logendran (2013a, b) and Gelogullari and Logendran (2010) pointed out the importance of explicitly considering setup times in the manufacturing of printed circuit boards. Therefore, explicit consideration of setup times are crucial for some manufacturing environments.

The review of scheduling literature reveals that the assumption of deterministic processing/setup times is common, Ying and Lin (2018), An et al. (2016), Keshavarz and Salmasi (2013), and Seidgar et al. (2014). However, some real world manufacturing environments are often subject to a wide range of uncertainties, Honkomp et al. (1997), Wang and Choi (2012), Gonzalez-Neira et al. (2017a), and Zhu and Zhou (2020). Therefore, the assumption of deterministic processing/setup times for some manufacturing environments may not be realistic as there are several factors causing uncertainty in processing/setup times. Some factors are conditions of tools, untested processing technology, unsteady operating

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conditions of machines, diverse proficiency levels of workers, disruptions in manufacturing systems, machine operator fatigue, Tayanithi et al. (1992), Zhu and Zhou (2020). Moreover, the originally estimated processing/setup time may not be precise as there may be late materials, absent workers, and so on. Therefore, uncertainty in the processing/setup times must be incorporated and production control must consider uncertainty in processing/setup times in advance to avoid any possible inconvenience. Furthermore, for some scheduling environments, past data may not be available for new jobs, thus making it hard to forecast their precise durations.

Different methods have been used to describe the uncertainty in the scheduling regarding a given parameter: fuzzy description, probability description, and interval or bounded description, Gonzalez-Neira et al. (2017b). In the fuzzy description approach, fuzzy sets theory is utilized. Behnamian (2016) provides a comprehensive survey on the scheduling problems using a fuzzy description approach. In the probability description approach, the uncertainties are modeled with a probability distribution function. The probabilistic description approach is mainly used when there is enough historical data to estimate the probabilities. On the other hand, in the interval or bounded approach, a bounded interval is used when the distribution of the data is not known, the only known information is the lower and upper bounds. This paper reviews the scheduling literature utilizing the interval or bounded approach for uncertain processing times or uncertain setup times.

In some manufacturing environments, processing/setup times may be modelled as random variables with a specific probability distribution. However, this assumption may not be effective for some manufacturing environments. For instance, we may not have enough previous information to define the probability distribution for processing or setup times. As pointed out by Kouvelis and Yu (1997), the distributional assumption is inappropriate for some manufacturing environments since factors such as worker skill levels and tool conditions control the uncertainty of processing/setup times. Matsveichuk et al. (2009) pointed out that it is hard to obtain a reliable probability distribution for random processing times in some manufacturing environments.

The processing times and/or setup times, in manufacturing of rockets, planes, and complex machines, can be modelled as random variables with some lower and upper bounds, Xie and Chen (2018). We review scheduling literature which address the scheduling problems with uncertain processing/setup times. The only known information about job processing/setup times are some lower and upper bounds. The distribution of processing/setup times within these lower and upper bounds are unknown. Notation is described in the next section, the results are summarized in the section after notation, and future research opportunities are presented in the conclusion section.

2. Notation

Let $t_{i,j}$ denote processing time of job i (i I={1,2, …,n}) on machine j (j J={1,2, …,m}). The lower bound $LBt_{i,j} \geq 0$ and the upper bound $UBt_{i,j} \geq LBt_{i,j}$ of $t_{i,j}$ is the only known information. Therefore, $t_{i,j}$ satisfies $LBt_{i,j} \leq t_{i,j} \leq UBt_{i,j}$. Similarly, let $s_{i,j}$ denote setup time of job i on machine j. Hence, $s_{i,j}$ satisfies $LBs_{i,j} \leq s_{i,j} \leq UBs_{i,j}$ where $LBs_{i,j}$ and $UBs_{i,j}$ denote the lower bound and upper bound on $s_{i,j}$. The notation used in the paper is given in Table 1 where the first column gives the notation used in the paper while the second column gives the description.

Table 1
Notation used in the paper

Notation	Description
PM	Performance measure
DR	Dominance Relation
H	Heuristic or algorithm
ST	Stability approach
ES	Branch-and-Bound or Mixed Integer Linear Programming
1	Single machine
F	Flowshop
Fm	m-machine flowshop
J	Job shop
FJ	Flexible job shop
P	Parallel machines
Fno-wait	Flowshop with no-wait constraint
Fm, no-wait	M-machine flowshop with no-wait constraint
Δt	Uncertain processing time, i.e., $t_{i,j}$ satisfies $LBt_{i,j} \leq t_{i,j} \leq UBt_{i,j}$
Δs	Uncertain setup time, i.e, $s_{i,j}$ satisfies $LBs_{i,j} \leq s_{i,j} \leq UBs_{i,j}$
C_{max}	Makespan
L_{max}	Maximum lateness
$\sum C_j$	Total completion time
$\sum F_j$	Total flow time
$\sum T_j$	Total tardiness
$\sum U_j$	Total number of late jobs
$\sum w_j C_j$	Total weighted completion time
$\sum w_j U_j$	Total weighted number of late jobs
$\sum w_j L_j$	Total weighted late jobs
NTJ	Number of tardy jobs

3. Results

The literature is classified based on shop environment, performance measures considered, the approach taken to address the considered problem, and uncertainty in processing or setup times.

Table 2
Summary of the conducted research on uncertain processing/setup times.

	Shop					Approach		
Reference	Environment	Δt	Δs	PM	ST	DR	H	ES
Allahverdi (2022a)	F2, no-wait		√	$\sum C_j$			√	
Allahverdi (2022b)	F4	√		$\sum C_j$			√	
Allahverdi (2022c)	F2, no-wait		√	$\sum C_j$		√		
Aydilek et al. (2022)	F2, no-wait		√	L_{max}		√	√	
Diaz et al. (2022)	J	√		$\sum T_j$	√		√	
Allahverdi (2021)	F4	√		C_{max}			√	
Allahverdi and Allahverdi (2021a)	F4	√		$\sum C_j$			√	
Allahverdi and Allahverdi (2021b)	F4	√		C_{max}			√	
Allahverdi and Allahverdi (2021c)	F4	√		$\sum C_j$		√	√	
Allahverdi and Allahverdi (2021d)	F4	√		$\sum C_j$			√	
Allahverdi et al. (2021)	F2, no-wait		√	L_{max}		√	√	
Aydilek et al. (2021)	F2		√	$\sum C_j$			√	
Allahverdi and Allahverdi (2020a)	F2, no-wait		√	$\sum C_j$		√	√	
Allahverdi and Allahverdi (2020b)	F4	√		C_{max}		√	√	
Drwal and Józefczyk (2020)	1	√		$\sum w_j U_j$				√
Sotskov et al. (2020)	J	√		C_{max}	√	√		
Zhu and Zhou (2020)	FJ	√		C_{max}			√	
Sotskov et al. (2019a)	J	√		C_{max}	√			
Sotskov et al. (2019b)	1	√		$\sum C_j$			√	
Sotskov and Egorova (2019)	1	√		$\sum C_j$		√		
Allahverdi and Allahverdi (2018a)	F2, no-wait		√	L_{max}		√		
Allahverdi and Allahverdi (2018b)	F2, no-wait		√	$\sum C_j$		√		
Allahverdi and Allahverdi (2018c)	F2, no-wait		√	L_{max}		√		
Allahverdi and Allahverdi (2018d)	F4	√		C_{max}		√		
Allahverdi and Allahverdi (2018e)	F4	√		$\sum C_j$		√		
Lai et al. (2018)	1	√		$\sum w_j C_j$		√		
Sotskov and Egorova (2018)	1	√		$\sum C_j$	√			
Xie and Chen (2018)	FJ	√		C_{max}			√	
Aydilek et al. (2017)	1	√		$\sum U_j$		√	√	
Drawl (2017)	1	√		$\sum w_j L_j$			√	
Drwal and Rischke (2016)	P	√		$\sum C_j$				
Pereira (2016)	1	√		C_{max}				√
Aydilek et al. (2015)	F2	√	√	C_{max}		√	√	
Ying et al. (2015)	F2	√		C_{max}			√	
Allahverdi et al. (2014)	1	√		$\sum w_j C_j$			√	
Siepak and Józefczyk (2014)	P	√		$\sum F_j$			√	
Sotskov et al. (2014)	F2	√		C_{max}		√		
Xu et al. (2014)	P	√		$\sum F_j$				√
Aydilek et al. (2013)	F2		√	C_{max}			√	
Aydilek and Allahverdi (2013)	F2	√		C_{max}			√	
Sotskov et al. (2013)	1	√		$\sum w_j C_j$			√	
Xu et al. (2013)	P	√		C_{max}			√	
Sotskov and Lai (2012)	1	√		$\sum w_j C_j$		√	√	
Allahverdi and Aydilek (2010a)	F2	√		L_{max}			√	
Allahverdi and Aydilek (2010b)	F2	√		C_{max}			√	
Aydilek and Allahverdi (2010)	F2	√		$\sum C_j$			√	
Sotskov et al. (2010)	1	√		$\sum w_j C_j$			√	
Allahverdi (2009)	F3	√	√	L_{max}		√		
Matsveichuk et al. (2009a)	F2	√		C_{max}			√	
Matsveichuk et al. (2009b)	F2	√		C_{max}		√		
Ng et al. (2009)	F2	√		C_{max}		√		
Sotskov et al. (2009)	1	√		$\sum w_j C_j$		√	√	
Allahverdi (2008)	F3	√	√	C_{max}		√		
Sotskov and Egorova (2008)	1	√		$\sum w_j C_j$		√		
Allahverdi (2007)	F3	√	√	$\sum C_j$		√		
Leshchenko and Sotskov (2007)	F2	√		C_{max}		√		
Allahverdi (2006a)	F2	√	√	L_{max}		√		
Allahverdi (2006b)	F2	√	√	$\sum C_j$		√		
Leshchenko and Sotskov (2006)	F2	√		C_{max}		√		
Allahverdi (2005)	F2	√	√	C_{max}		√		
Leshchenko and Sotskov (2005)	J	√		C_{max}		√		
Sotskov et al. (2004)	F2	√		$\sum C_j$		√		
Lai et al. (2004)	J	√		$\sum F_j$			√	
Allahverdi and Sotskov (2003)	F2	√		C_{max}		√		
Allahverdi et al. (2003)	F2		√	C_{max}, $\sum C_j$		√		
Lai et al. (1997)	J	√		C_{max}		√		

Table 2 summarizes the conducted research on scheduling problems addressing the uncertainty on processing/setup times. The first column in the table describes references which are ordered first based on the year the paper was published, then, alphabetically ordered based on the last name of the authors. The second column indicates the shop environment studied. The third and fourth columns in the table show if the uncertain processing times or uncertain setup times is considered in the paper, respectively. The fifth column indicates the performance measure studied. The last four columns in the table demonstrate which approach is taken to address the considered problem. Fig. 1 shows the percentage of research conducted with respect to performance measures. C_{max} performance measure was addressed about 42% of the conducted research on processing/setup times. On the other hand, $\sum C_j$ performance measure was studied about 28%. Both performance measures of $\sum w_jC_j$ and L_{max} were considered about 11%. The performance measure $\sum F_j$ was addressed 5% while other performance measures ($\sum U_j$, $\sum T_j$, $\sum w_jC_j$, $\sum w_jL_j$) were considered about 2%.

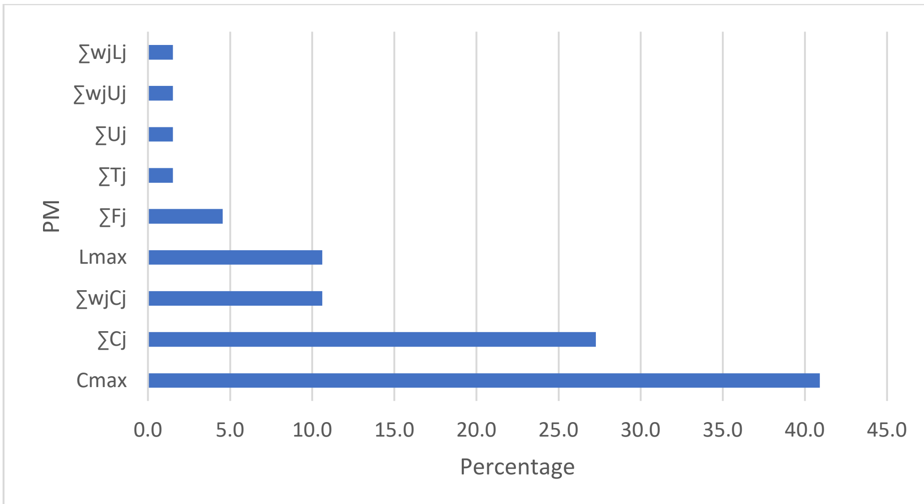

Fig. 1. Percentage of addressed problems with respect to PM.

The percentage of research conducted with respect to the shop environment is given in Fig. 2. About 50% of the conducted research on uncertain processing/setup times studied flowshop environments. About 21% of the research considered a single machine environment while 12% of the research investigated no-wait flowshop environment. About 9%, 6%, and 2% of the research studied job shop, parallel machines, and flexible job shop environments, respectively.

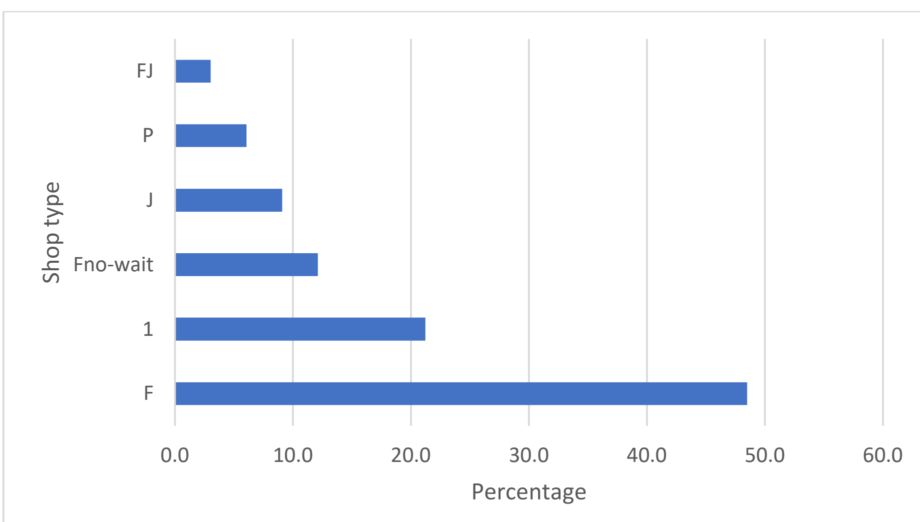

Fig. 2. Percentage of addressed problems with respect to shop type.

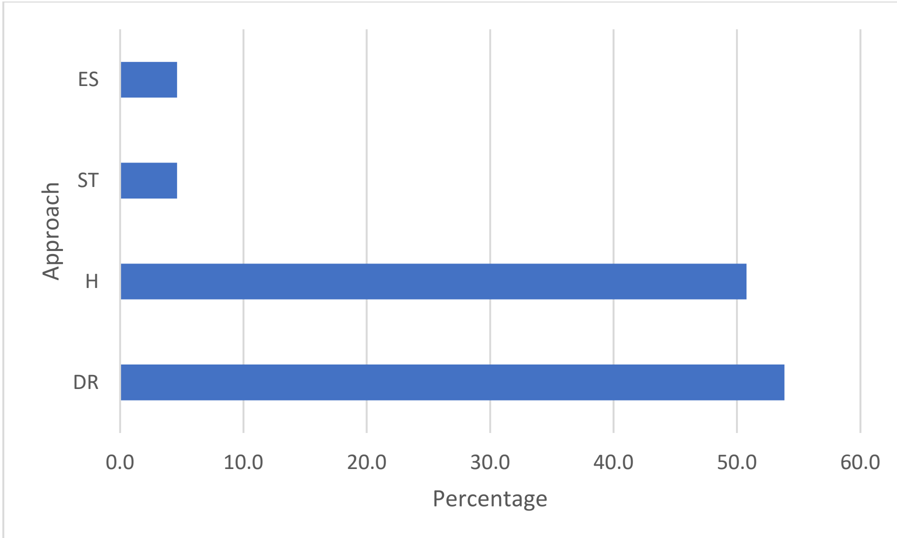

Fig. 3. Percentage of addressed problems with respect to approach used.

Fig. 3 indicates the percentage of research conducted with respect to the approach used in the reviewed papers. Developing a dominance relation approach was considered in about 54% of the papers while establishing an algorithm or heuristic approach was explored in about 51% of the papers. It should be noted that some papers both developed dominance relations and established an algorithm or heuristic. On the other hand, the stability approach was used in about 5% of the papers. Finally, Branch-and-Bound or Mixed Integer Linear Programming was considered in about 5% of the papers. About 83% of the papers considered uncertain processing times while 28% of the papers studied uncertain setup times. It should be stated that some papers investigated both uncertain processing times and uncertain setup times.

4. Conclusions and Future Research Opportunities

This paper reviewed the scheduling literature utilizing the interval/bounded approach for uncertain processing times or uncertain setup times. The reviewed problems are classified based on shop environments (single machine, parallel machine, flowshop, job shop), performance measures, interval processing times, or interval setup times.
Regarding the shop environment, about 50% of the papers considered a flowshop environment followed by 22% for a single machine environment. The other shop environments received much less attention from the researchers. Given that other shop environments are common in practice and uncertainty in processing or setup times apply for some of these shop environments, more work is needed on these problems.

When the approach taken to address these problems is considered, developing dominance relations received the highest attention among the researchers investigating uncertain bounded processing/setup times. It should be noted that dominance relations help reduce the search space but it is hard to find the optimal solution with the dominance relations. Therefore, the dominance relations should be used along with implicit enumeration techniques such as dynamic programming and Branch-and-Bound algorithms. Therefore, another avenue of research is to develop implicit enumeration techniques by utilizing the already developed dominance relations.

Regarding performance measures, more emphasis is given to completion time based performance measures such as makespan and total completion time while much less emphasis is given to those problems with due date related performance measures such as number of tardy jobs. Hence, more research is needed for due date related performance measures. It should be noted that only one paper of the reviewed papers, Diaz et al. (2022), addressed uncertain bounded processing with total tardiness performance measure which is a very important performance measure. For the importance of the performance measure of total tardiness, see Pessoa et al. (2022), Min and Kim (2022), Yamada et al. (2021). Therefore, more research is needed on scheduling problems with uncertain processing/setup times to minimize total tardiness.

The reviewed papers addressing uncertain bounded setup times modeled setup times as sequence independent. This is certainly true for some manufacturing environments. However, there are many other manufacturing environments where setup times are sequence-dependent, e.g., see Toksarı and Toğa (2022), Alimian et al. (20220, Allali et al. (2022), Rifai et al. (2021), Mara et al. (2021). Therefore, another avenue of research is to address problems with uncertain bounded sequence-dependent setup times.

Regarding shop environments, about 60% of the research considered flowshop environments while about 20% studied single machine environments. Other shop environments, such as job shop and parallel machine environments, received much less attention. Hence, there is a need to study more scheduling problems with uncertain bounded processing/setup times for other shop environments.

The objective of the current paper was to review papers addressing scheduling problems with uncertain bounded processing/setup times. It was observed that there are few papers which study scheduling problems with uncertain bounded due dates, e.g., Diaz et al. (2022), Drwal (2018). Therefore, there is a need to address more scheduling problems with uncertain bounded due dates.

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