Addressing idle and waiting time in short term production planning

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Addressing idle and waiting time in short term production planning

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Abstract. Production systems are facing the increase of economic and sustainability challenges in managing production resources, demand variability and variety, and the increasing shortage of materials. Thus, short-term production planning must include several aspects and consider multiple objective functions simultaneously. In this context, controlling and optimizing waiting and idle times might lead to various benefits, as they are among the main cost sources in production systems and can affect the feasibility of operations from a technological perspective. While waiting time is related to the work in process, idle time refers to a low utilization rate, and both may generate inefficiency and costs. This paper studies how different emphasis to waiting and/or idle time can affect the solution of short-term production planning with several industrially relevant objectives.

Introduction

Short-term production planning deals with scheduling jobs to be produced in the shop floor to optimize one or more criteria. These operations might consider technological constraints related to the jobs to be produced, the processes, and the production resources; optimization criteria are related to costs and challenges the company faces. Among these costs, those related to idle and waiting times are largely important [1]. Long waiting times usually transfer in high work in process (WIP) levels, with consequent high inventory costs and low service level. Instead, long idle times usually imply low utilization rate, possibly due to resource over-sizing, and related costs.

Apart from costs, some industries and technological processes might avoid idle and/or waiting times. For instance, temperature or other characteristics of the materials might require that each operation immediately follows the previous one, thus not allowing any waiting time (*no-wait*) [2]. Similarly, resources might use materials or consumables that become unusable if the machine stays idle for too long (e.g., paint can dry); in such cases, idle time is not allowed (*no-idle*). In addition, interrupting some processes may generate high costs, thus limiting the number of interruptions on some stages can be beneficial, i.e., limiting the occurrences for the machine to move from busy to idle and vice-versa [3]. This occurs, for instance, in casting processes where interrupting a continuous production flow implies maintenance and extensive cleaning, which in turn causes extra costs and delays in the entire production [4].

Although the literature on short-term production addressing idle and waiting time is vast, usually such problems are addressed from the algorithmic point of view. On the contrary, the objective of this paper is to study how different approaches (i.e., different ways of addressing idle and waiting time) can affect the solution of short-term production planning with several industrially relevant objectives. The industrial/managerial implications are the focus of the paper, while the algorithmic side is out of the scope of the paper. The paper studies a permutation flow shop (PFS) production system (i.e., jobs undertake a set of operations on a set of workstations with the same order, and the job sequence on each machine is the same).

Literature Review

The short-term planning of permutation flow shops has been widely studied in the literature. Many optimization criteria have been addressed, such as makespan, total flow time, total tardiness and so on [e.g. 5,6]. As idle and waiting times are the focus of the paper, in the following, only the literature addressing these two performance measures is reviewed.

Most of the literature on short-term production planning addressing idle and waiting time focuses on developing heuristic and meta-heuristic algorithms to solve various problem variants; however, as this paper aims at investigating idle time at the industrial level, the reader is referred to [1,7,8,9] for reviews of the solution methods available in the literature.

When idle time is considered, depending on the technological processes of the shop floor and on the criteria to optimize, it has been assumed either to be avoided (totally or in part) or to be minimized. The *no-idle* PFS scheduling problem is NP-hard, and due to its complexity, many authors developed heuristic and meta-heuristic algorithms to solve it. This problem arises in many real-life production systems such as in the production of integrated circuits, where the costs of steppers are so high that idle time is not desired [7]; also, in fiberglass production and in foundries, some machines (e.g., furnaces, casting machines, ceramic roller kilns) cannot be easily turned off and restarted due to the long machine setup times [10]. Sometimes, only some of the workstations composing the flow shop must respect the no-idle conditions. For instance, in ceramic frit production, only the central fusing kiln has the no-idle constraint; also, in steel production, only the final casting phase needs not to stop (i.e., to be no-idle) while the previous operations can admit idle time [11]. In other cases, idle time can be allowed, but it is linked to higher costs (i.e., there is no technological constraint to avoid idle time); in these cases, some authors have addressed the problem of minimizing the total amount of idle time in the production system [1], or the problem of minimizing the number of interruptions [3]. In such cases, obviously, machines can be idle.
When waiting time is considered, depending on the technological process, jobs can be required not to wait between two consecutive operations. For instance, in steel manufacturing, after being heated to a specific temperature, hot slabs cannot wait before rolling operations; otherwise, their temperature would significantly drop [12]. In general, all the manufacturing processes that require the WIP to be pre-heated to a high temperature may need no-wait conditions [13,14]. Also, robotic cells, which provide a highly coordinated manufacturing process, need to avoid waiting time between consecutive operations [15]. In some cases, avoiding waiting time is an efficient strategy to reduce WIP-related costs [1]. In such cases, the no-wait condition may be downgraded to the minimization of the total waiting time of jobs in the system [1,16], which implies the possibility that jobs wait between consecutive operations to optimize some other performance measure.

Problem formulation

This paper considers a flow shop production system. In this system, there is a set of J jobs to be processed, each requiring a set of M operations. Each operation is allocated to a single machine, and the order in which the operations have to be executed is the same for each job. Thus, the sequence of the operations is the same as the order of the machines, as depicted in Fig. 1. In the system, machines cannot perform more than one operation simultaneously, and jobs cannot be processed by more than one machine simultaneously. The operations, once started, cannot be interrupted (*non-preemption* assumption). For simplicity, a permutation flow shop is considered, in which the sequence of jobs is the same on each machine. Various problem variants are studied according to the assumptions made on idle and waiting time and on the performance measure.

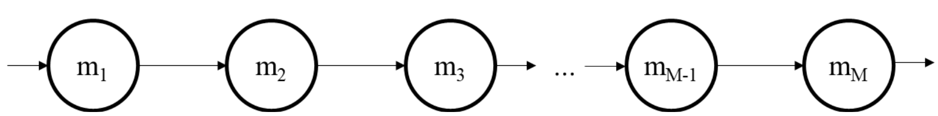


Fig. 1. Flow shop layout

Specifically, the paper addresses the following systems:

- flow shop with allowed idle and waiting times (*general*),
- flow shop with no-idle constraint (*no-idle*),
- flow shop with no-wait constraint (*no-wait*).

For each system, four solutions are found, each minimizing one among the following objective functions (OF):

- *makespan* (*Cmax*), i.e., the completion time of the last job on the last machine;
- *total completion time* (*Ctot*), i.e., the sum of the completion times of all jobs in the sequence;
- *total core idle time* (*Cit*), i.e., the sum of idle times in all machines between the start of the first job of the sequence and the end of the last job;
- *total core waiting time* (*Cwt*), i.e., the sum of waiting times of all jobs between the first and the last operations.

In general, for any problem variant (i.e., for each combination system-OF), the aim is to decide how to process jobs (i.e., to find the job schedule) to optimize the selected OF. As the problem variants are mostly NP-hard, sub-optimal solutions are found in this paper by using a constructive heuristic algorithm. Specifically, the well-known NEH heuristic is adapted to the problem variants. The developed algorithm has the same general structure for all the problem variants, and only limited changes in the sorting rule (as explained in the following) are made to adapt it to each of them. The algorithm works as in the following.

1. Jobs are sorted according to a specific rule depending on which OF is minimized. For makespan and total completion time minimization (NEH_{Cmax}, NEH_{Ctot}), jobs are sorted according to the decreasing sum of processing times; for waiting time minimization (NEH_{Cwt}), jobs are sorted according to the index defined by [17] (that accounts for the variability of processing times); for idle time minimization (NEH_{Cit}), jobs are sorted according to the descending order of the index defined by [18] (that accounts for the variability, skewness and kurtosis of processing times).
2. Each job in the sorted list is inserted in the solution in the position that minimizes OF, thus originating the final schedule.

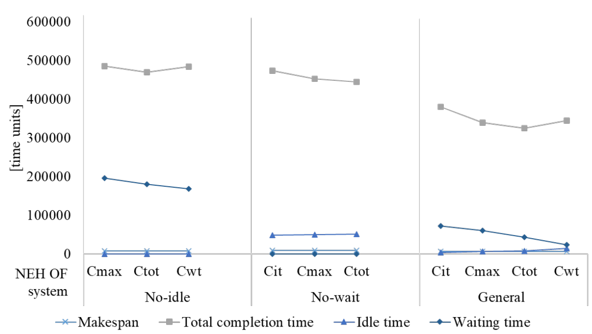
For each solution of each problem variant, all the OFs are evaluated and compared. The comparison aims at evaluating the differences among solutions (in terms of objective functions) found by modelling idle and waiting times in different ways.

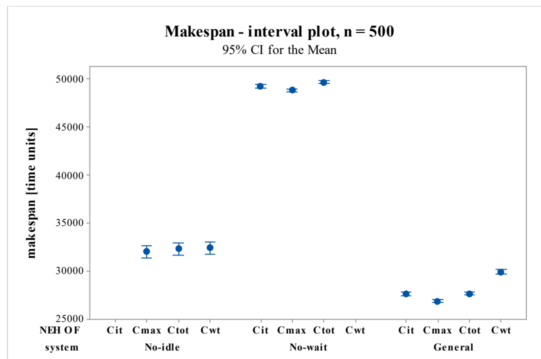
Numerical results

The aim of the experiment is to assess the impact of the way idle and waiting times are modelled on the solution for short-term production planning. To this aim, the NEH is used to find solutions for all the problem variants previously described; the solutions are then compared with respect to their evaluated performance measures (*Cmax, Ctot, Cit, Cwt*). The experiment investigates the trade-off between imposing no-idle/no-wait conditions and paying idle/waiting time. This is particularly relevant for systems characterized by high idle and waiting time costs.

Design of experiment. The Taillard benchmark [19] is used to determine processing times of jobs on the machines. The number of jobs varies between 20 and 500, while the number of machines between 5 and 20. For each problem, 10 instances are available. For each instance, the three systems (general, no-idle, no-wait) are considered, and for each of them, four solutions are found by applying the NEH algorithm with different OFs (NEH_{Cmax}, NEH_{Ctot}, NEH_{Cit}, NEH_{Cwt}); note that in no-idle systems NEH_{Cit} cannot be used, as well as NEH_{Cwt} is not used in no-wait systems. Overall, 4800 experiments are run. For each solution, all the OF values are computed.

Results. Fig. 2 shows, for some of the considered problems, mean values and confidence intervals of some performance measures. Specifically, Fig.2 (a) shows the average values of *Cmax,* *Ctot, Cit, Cwt* of the solutions of the problems with 100 jobs. As an example, starting from the left part of the graph, the grey line shows the average completion time of solutions for no-idle systems found by minimizing *Cmax*, *Ctot* and *Cwt,* respectively; the second grey line shows the same for no-wait systems, and the third for general systems. Instead, Fig. 2 (b) shows the interval plot of makespan for all the problems with 500 jobs, grouped by system variant and NEH OF. As the figures show, for each system, minimizing different objective functions leads to difference system performance. For instance, in general systems, minimizing the waiting time leads to larger *Cmax* values, which, in turns, implies having low utilization levels of machines and lower production rates. Moreover, how idle and waiting times are modelled has an impact on the system performance measures. As Fig. 2 (a) shows, no-idle systems tend to have a larger waiting time than a general system in which idle time is minimized (i.e., general system – NEH_{Cit}). Obviously, if machines cannot be idle because of technological constraints, the consequence of increasing waiting times cannot be avoided. However, if machines can be idle but the idle time related cost is high, then minimizing idle time instead of imposing a no-idle condition can turn into lower waiting time (and, hence, WIP-related) costs. In this case, an economic trade-off should be evaluated.





(a) (b)

Fig. 2. (a) Average values of all performance measures for all problem variants with 100 jobs. (b) 95% confidence intervals of makespan in all problem variants with 500 jobs.

Table 1 shows the average values of all the performance measures, grouped by system, NEH OF, number of jobs and machines. The table shows that, as expected, the larger the instance, the larger the values of each measure. Obviously, for each system, each evaluated performance measure has its lowest value in the solution that minimizes it: for instance, for general systems, the makespan is lower in the solutions of NEH_{Cmax} than the one measured in the other solutions (the example refers to the rows with green borders of the table).

To assess the impact of the way idle and waiting times are modelled on the performance of the system, hypothesis tests are used for comparison. Starting from the *idle time*, it can be modelled either by imposing a no-idle condition, or by minimizing it as OF in a general system. The aim is to understand how the other performance measures (*Cmax, Ctot, Cwt*) change in these two cases. As an example, the blue rows of Table 1 display how makespan changes between a general system with NEH_{Cit} (denoted by $Cmax_{Gen,Cit}$) and a no-idle system with NEH_{Cmax} (denoted by $Cmax_{NI,Cmax}$).

To evaluate the difference, the percentage difference Δ_{Cmax} is computed as:

$$\Delta_{Cmax} = \frac{Cmax_{Gen,Cit} - Cmax_{NI,Cmax}}{Cmax_{Gen,Cit}}. \quad (1)$$

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Table 1. Average performance measures for all problem variants, grouped by system, NEH OF, number of jobs and of machines

	n. jobs	**20**			**50**			**100**			**200**		**500**
	n. machines	**5**	**10**	**20**	**5**	**10**	**20**	**5**	**10**	**20**	**10**	**20**	**20**
Makespan [time units]													
System	**NEH OF**												
No-idle	*Cmax*	1380	2007	3502	3015	3753	5877	5521	6887	9280	12174	15131	32032
	Ctot	1413	1995	3564	3068	3774	5935	5650	6980	9309	12428	15313	32326
	Cwt	1492	2061	3548	3124	3903	6069	5750	7073	9412	12597	15527	32433
No-wait	*Cit*	1494	2169	3302	3345	4578	6374	6381	8448	11361	16125	21225	49280
	Cmax	1433	2006	3043	3312	4386	6090	6344	8291	11081	15810	20770	48835
	Ctot	1490	2092	3194	3440	4549	6263	6502	8585	11364	16114	21121	49696
General	*Cit*	1402	1802	2516	2913	3349	4274	5433	6038	7007	11133	12269	27650
	Cmax	1261	1583	2319	2756	3135	3957	5272	5752	6634	10804	11753	26907
	Ctot	1343	1695	2463	2889	3351	4120	5470	6039	6973	11106	12217	27688
	Cwt	1439	1814	2561	3127	3640	4440	5846	6512	7547	12055	13396	29959
Total completion time [time units]													
No-idle	*Cmax*	18308	31712	60716	91810	130469	235129	310747	449960	697524	1446917	2089681	9931072
	Ctot	17937	30567	61106	87618	126870	233150	293060	435216	680733	1409108	2045126	9695973
	Cwt	19455	31690	61326	92247	133463	240541	312290	449817	692068	1458294	2107398	9848739
No-wait	*Cit*	17998	26441	42571	95621	129115	184689	342539	452853	625838	1698083	2235262	12631925
	Cmax	16602	24704	40486	87432	120392	176732	327895	430746	600214	1610098	2163203	12368030
	Ctot	15670	24252	39944	82172	118434	174832	302911	430587	599178	1586040	2179182	12578382
General	*Cit*	18768	25484	38795	90943	108210	147843	331945	365163	443562	1294577	1462361	7843045
	Cmax	15530	22015	35586	77701	97664	134507	273004	328974	417138	1171820	1385930	7478628
	Ctot	14607	20945	34252	72579	92739	129430	264163	313461	398242	1129317	1314814	7173633
	Cwt	15472	21687	34054	76418	97054	132443	284449	331726	417910	1202852	1403763	7603568
Total core idle time [time units]													
No-wait	*Cit*	1456	7258	25707	3362	16172	57887	6118	29888	109181	55958	203359	465365
	Cmax	1569	7503	26913	3702	16619	59145	6439	30527	109980	56117	204157	466044
	Ctot	1665	7710	27848	4025	17508	60405	6829	32241	113159	58204	209402	481218
General	*Cit*	140	953	4169	433	1312	6468	319	2377	8964	2707	11195	15356
	Cmax	420	2012	7134	660	3044	10961	707	3726	15108	4648	18806	22500
	Ctot	625	2384	8401	970	3853	12511	1102	4978	17444	5874	22108	29321
	Cwt	1056	3488	10629	1894	6602	18320	2666	9374	28849	14480	44620	73747
Total core waiting time [time units]													
No-idle	*Cmax*	4682	13360	32180	24955	49243	128670	62588	167571	357830	395643	920298	3420189
	Ctot	4602	12842	32520	20391	46117	126908	45026	153468	343209	358420	872828	3155334
	Cwt	4154	12960	31769	15171	45069	128630	32280	136670	337244	305421	865828	2923396
General	*Cit*	3880	7016	9717	13437	23579	40602	43084	67241	104676	175804	291344	1087660
	Cmax	2329	4421	6684	13030	17163	30105	39687	55440	86463	168936	262840	1177607
	Ctot	1714	3556	5772	7460	12927	25641	19296	41601	67913	101469	182405	713631
	Cwt	899	2295	4195	2926	7309	16820	8203	19182	42068	45134	100114	340582

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The tested hypothesis is $\Delta_{Cmax} = 0$. Over all the experiments, the average Δ_{Cmax} is -0.1663, and the T-test of the tested hypothesis has a p-value equal to zero, thus the mean percentage difference cannot be considered equal to zero. In practice, the makespan of solutions of no-idle systems in which the NEH_{Cmax} is used ($Cmax_{NI,Cmax}$) is larger than that of a general system that minimizes the idle time ($Cmax_{Gen,Cit}$). This means that imposing a no-idle condition on one hand avoids idle time related costs but, on the other hand, it increases the utilization related costs. Fig. 3 graphically displays the trade-off between these two performance measures. If the no-idle systems (red diamonds) do not have any cost related to idle times, the costs related to the makespan are larger than the general systems (blue circles).

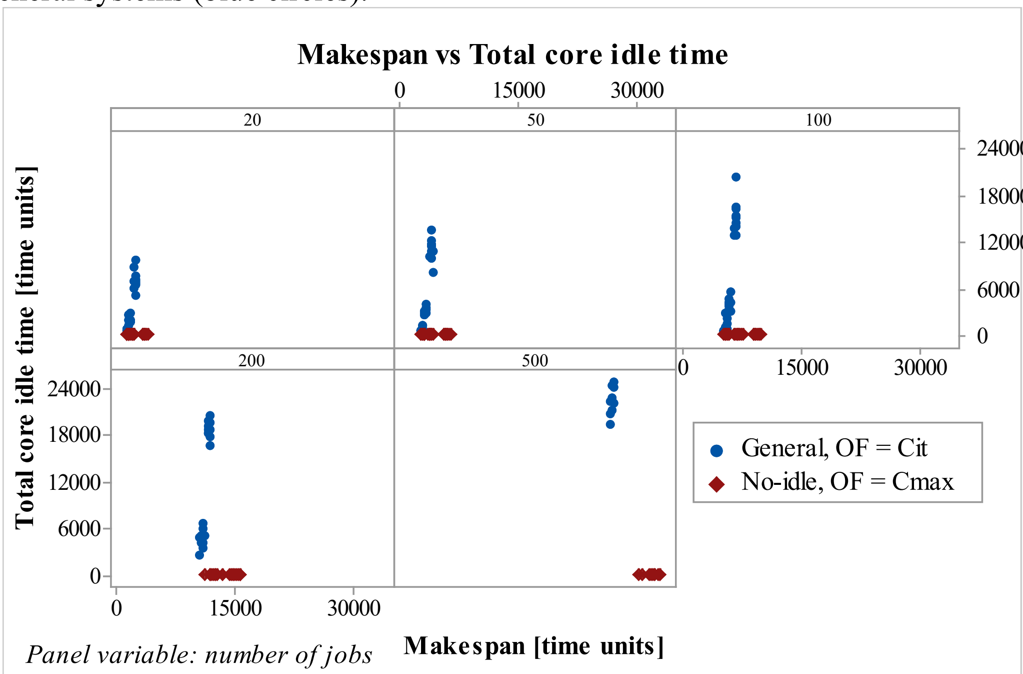

Fig. 3. Dispersion of cmax (x-axis) and cit (y-axis), grouped by number of jobs. Compared systems: general with NEH_{Cit} (blue circles), no-idle with NEH_{Cmax} (red diamonds).

The same analysis has been performed for total completion times and waiting times. In both cases, the difference between the two systems when such performance measures are considered is statistically significant.

The same comparison has been made to address the *waiting time* modelling. The considered systems are: general system with waiting time minimization (*Gen, Cwt*), no-wait systems with their OFs (*NW, Cmax – NW, Ctot – NW, Cit,* alternatively). As an example, let consider the total completion time as the performance measure to be evaluated; then, the compared systems are the ones written with the purple color in Table 1. The percentage difference is computed as:

$$\Delta_{Ctot} = \frac{Ctot_{Gen,Cwt} - Ctot_{NW,Ctot}}{Ctot_{Gen,Cwt}}. \tag{2}$$

Over all the experiments, the average Δ_{Ctot} is equal to -0.2708, and the T-test for the hypothesis $\Delta_{Ctot} = 0$ has a p-value equal to zero, thus the mean percentage difference differs from zero. In practice, minimizing the total completion time in a no-wait system leads to larger completion times than minimizing the total core waiting time in a general system. Fig. 4 graphically shows how the two measures are distributed.

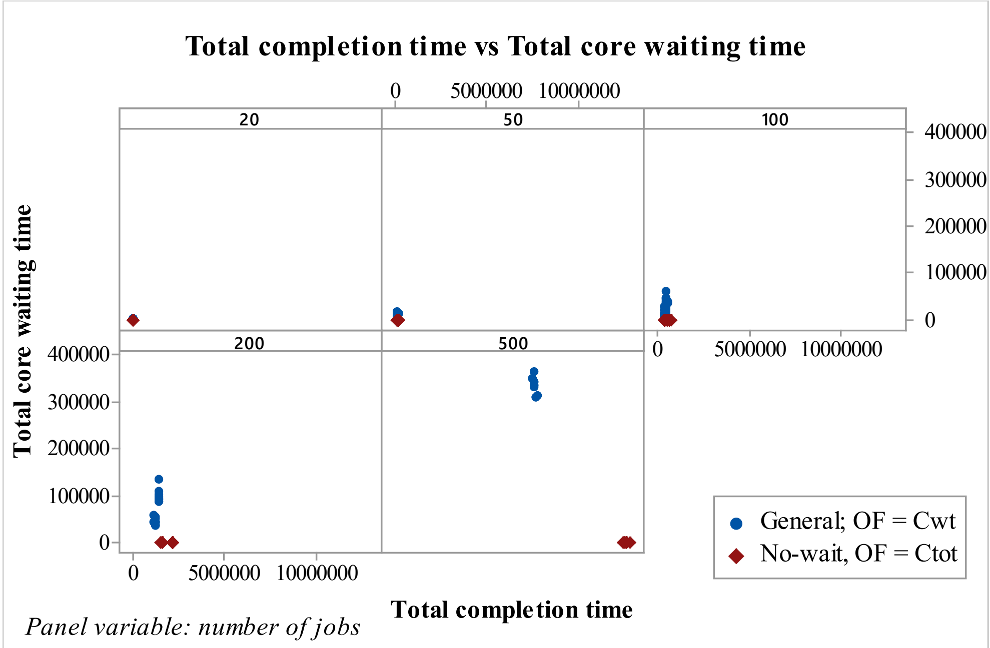

Fig. 4. Dispersion of Ctot (x-axis) and Cwt (y-axis), grouped by number of jobs. Compared systems: general with NEH_{Cwt} (blue circles), no-wait with NEH_{Ctot} (red diamonds).

As the figure shows, imposing the no-wait condition increases the total completion time, leading to larger costs related to flow time, WIP and service level reduction.

Conclusions

Idle and waiting times are very relevant performance measures in production systems, as they are critical in some technological processes, and they both generate costs. In short-term production planning, they can be avoided by imposing no-idle and no-wait conditions, or they can be optimized to reduce them. This paper studies how different ways to model them can generate different schedules with different total costs, thus affecting the solution of short-term production planning. The addressed systems are permutation flow shops with and without no-idle/no-wait conditions, in which several performance measures are optimized. Numerical results on benchmark problems available in the literature show that the way idle and waiting times are modelled significantly impacts on other performance measures such as makespan and total completion time. These are in turns related to utilization, WIP, and flow time costs.

If the technological characteristics of the process or the materials impose no-idle/no-wait conditions, the other performance measures will suffer from these constraints, but no actions can be implemented to improve them. For all the other cases in which idle/waiting times can occur but with high costs, the economic trade-off of allowing some idle/waiting time but reducing makespan and/or total completion time related costs should be considered. The numerical results of the paper specifically show that sometimes allowing (and thus paying) idle/waiting times is beneficial to reduce other cost sources such as utilization and/or flow time, WIP, etc.

Finally, as the used heuristic algorithm, developed for different problems (even though adapted for the considered problem), could have had some effect on the performed comparisons, future research will be devoted to developing more sophisticated ad hoc solution algorithms that include the economic trade-off in finding the optimal solution.

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