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ORIGINAL ARTICLE

Controllable processing time policies for job shop manufacturing system

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Abstract The research presented concerns the policy to manage a job shop in which the machines have controllable processing times. A controllable processing time means that it can be reduced processing time by using additional resources. The model proposed is based on a multi-agent architecture that supports the manufacturing system. The policy proposed concerns the evaluation of the workload of the resources. It is necessary to define the following issues for the controllable time process of a resource: the condition of start and the duration of the process time reduction. Two approaches are proposed to assign the resources to the machines. The first approach concerns the reduction of the processing time one machine at time, while the second approach distributes the additional resources proportionally among the machines. A simulation environment is developed to test the proposed approach in several dynamic conditions. The simulation results show that the control of the processing times proposed allows to improve significantly the performance.

Keywords Multi-agent architecture · Job shop · Controllable processing time · Discrete event simulation

1 Introduction

The research on the manufacturing systems considers that the processing times are fixed. In real applications, the processing time is related to the amount and type of resources used. For example, the processing times of milling or cutting operations depends on the cutting tools, the facilities to process many parts at the same time, add a tool spindle in the machine, etc. Therefore, the reduction of the processing time depends on the investment in additional resources. The possibility to reduce the processing time allows to improve the performance of the manufacturing systems when exception occurs. The exceptions can be internal as machine failure or external as demand fluctuations. Janiak [7] described an industrial application of a scheduling problem with controllable processing times in steel mills. The preheating time and the rolling time are inversely proportional to the gas flow intensity. Kayan and Aktur [11] determined the upper and lower bounds for the processing time of each job under controllable machining conditions. The proposed bounding scheme is used to find a set of discrete efficient points on the efficient frontier for a bi-criteria scheduling problem on a single CNC machine. Kaspi and Shabtay [10] minimized the expected cost per unit under three different tool replacement strategies: failure replacement, opportunistic replacement, and integrated replacement. The replacement strategies determined the processing time of the manufacturing machines.

Several scientific works have demonstrated that the problem is a *Np-hard* problem, [1,2]. In these cases, the problem can be resolved when the number of machines and the maximum number of operations per job are fixed [8,9]

In this paper, two approaches are proposed to control the processing time of the machines of job shop manufacturing systems. The policies proposed can be integrated in a multi-agent architecture with the other activities as the scheduling process. The problem discussed concerns the following issues: the machines of the manufacturing system that need the reduction of the processing time; the amount of resources for the reduction activity; the time of the reduction of the processing time.

The approach proposed can be applied in a real industrial case because the computational time is limited and the number of machines and jobs are not fixed at priori.

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The paper is organized as follows. Section 2 presents an overview of the literature; the multi-agent architecture and the proposed approaches are described in Section 3. The simulation environment is presented in Section 4, while Section 5 provides a discussion of the simulation results. Finally, conclusions and future research paths are drawn in Section 6.

2 Literature review

Many authors have addressed the controllable processing time problem in manufacturing systems. The papers focused mainly on mathematical optimal solutions that can be used in very limited real application cases. Few researchers investigated approaches that can be supported by multi-agent architecture and implemented in several manufacturing systems.

Jansen et al. [9] considered two models of controllable processing times: continuous and discrete. For both models, they presented polynomial time approximation schemes when the number of machines and the number of operations per job are fixed.

Shabtay and Steiner [20] presented a survey of results for scheduling problems with controllable processing times. The survey argued that although the field has attracted a lot of attention from researchers in the last 25 years, there are still many open questions and a lot of problems that have not been studied. Some problems have already been considered in the literature, but their complexity remains unsolved.

Shabtay and Steiner [21] studied the earliness-tardiness scheduling problem on a single machine with due date assignment and controllable processing times. We analyze the problem with three different due date assignment methods and two different processing time functions. For each combination of these, we provide a polynomial-time algorithm to find the optimal job sequence, due date values and resource allocation minimizing an objective function which includes earliness, tardiness, due date assignment, makespan, and total resource consumption costs.

Gürel et al. [6] showed that if the processing times are controllable then an anticipative approach can be used to form an initial schedule so that the limited capacity of the production resources are utilized more effectively. They considered a non-identical parallel machining environment, where processing times can be controlled at a certain compression cost. When there is a disruption during the execution of the initial schedule, a match-up time strategy is utilized such that a repaired schedule has to catch-up initial schedule at some point in future.

Their computational results show that the match-up time strategy is very sensitive to initial schedule and the proposed anticipative scheduling algorithm can be very helpful to reduce rescheduling costs.

Selim and Taylan [19]) developed a control approach for cutting force control of CNC machine. The process time depends on the cutting force because of the tool wear. The developed approach is applied to a milling machine center (only one machine). Examples taken from experimental tests have shown that the developed approach is effective for the uncertain CNC machine.

Nearchou [16] considered the single machine scheduling problem of jobs with controllable processing times and compression costs and the objective to minimize the total weighted job completion time plus the cost of compression. An appropriate problem representation scheme is developed together with a multi-objective procedure to quantify the trade-off between the total weighted job completion time and the cost of compression. The four heuristics are evaluated and compared over a large set of test instances ranging from five to 200 jobs. The experiments showed that a differential evolution algorithm is superior (with regard to the quality of the solutions obtained) and faster (with regard to the speed of convergence) to the other approaches.

Choi et al. [5] considered the problem of scheduling a set of independent jobs on a single machine so as to minimize the total weighted completion time, subject to the constraint that the total compression cost is less than or equal to a fixed amount. The complexity of this problem is mentioned as an open problem. In this note, they showed that the problem is NP-hard.

Luo et al. [14] investigated the optimal resource allocation for hybrid flow shop in one-of-a-kind production to achieve an optimal resource allocation plan ensuring that all jobs are finished in a given time interval with a minimum number of resources and without any buffer overflow. A real industrial application is implemented for Gienow Windows and Doors Ltd. based on this model and algorithm. Experimental results show that this method is effective. Behnamian and Fatemi Ghomi [4] also studied the hybrid flow shop scheduling problem. They proposed a robust hybrid metaheuristic approach to minimize makespan and total resource allocations costs.

Yildiz et al. [24] dealed with a bi-criteria scheduling problem arising in an *m-machine* robotic cell consisting of CNC machines producing identical parts. Such machines by nature possess the process flexibility of altering processing times by modifying the machining conditions at differing manufacturing costs. They characterized the set of all non-dominated solutions for two specific pure cycles that have emerged as prominent ones in the literature. They proved that either of these pure cycles is non-dominated for the majority of attainable cycle time values. For the remaining regions, we provide the worst case performance of one of these two cycles.

Akturk et al. [3] studied the scheduling under controllable machining conditions. Scheduling with tool changes, particularly due to tool wear, has just begun to receive attention. Though machining conditions impact tool wear and induce tool change, the two issues have not been considered together. They are able to solve the problem exactly for up to 30 jobs using a mixed integer linear programming formulation. For larger problems, they turn to approximate solution via heuristics. They examined a number of different schemes. The best of these schemes are used in a problem space genetic algorithm; this produces quality solutions in a time-efficient manner, as is evidenced from an extensive computational study conducted by us.

Turkcan et al. [22]) considered flexible manufacturing system loading, scheduling, and tool management problems simultaneously. The objective was to determine relevant tool management decisions, which are machining conditions selection and tool allocation, and to load and schedule parts on non-identical parallel CNC machines. The proposed heuristics are used in a problem space genetic algorithm in order to generate a series of approximately efficient solutions.

Liu et al. [13] considered the two-agent scheduling problems with deteriorating jobs and group technology on a single machine, where the objective is to minimize the total completion time of the first agent with the restriction that the maximum cost of the second agent cannot exceed a given upper bound. The job processing times and group setup times are both function of their starting times. They proposed the optimal properties and present the optimal polynomial time algorithms for two scheduling problems, respectively.

Mokhtari et al. [15] proposed a resource-dependent processing time for permutation in flow shop scheduling problem in which the processing time of a job depends on the amount of additional resources assigned to that job. A hybrid discrete differential evolution algorithm and a variable neighborhood search were combined to solve the two problems simultaneously.

Niu et al. [17] considered the job shop scheduling problem with discretely controllable processing time combining two kinds of sub-problems: the job shop scheduling problem and the discrete time–cost tradeoff problem. It is proposed that a search-based metaheuristic can be used with limited number of machines due to the computational complexity.

Uruk et al. [23] considered a two-machine flow shop scheduling problem with identical jobs. The overall problem is to determine the assignment of the flexible operations to the machines and processing times for each operation to minimize the total manufacturing cost and makespan simultaneously. They used a heuristic procedure that is constructed to solve larger instances in a reasonable time.

Based on the above literature review, the following limitations can be drawn:

(a) The approaches proposed in literature can be used in limited manufacturing systems, because the computation complexity is very high. This restriction reduces the possibility to introduce the approaches proposed in real industrial cases.

(b) The approaches proposed in literature are tested in manufacturing system where the exceptions and rapidity of alterations were not investigated. The most tests are conducted in static conditions. Moreover, the performance measures investigated are often limited.

The research proposed in this paper resulted to the above limitations in the following issues:

(a) The proposed approaches have a low computational complexity and they can be applied in generic manufacturing systems. The low computational complexity is due to the evaluation of the manufacturing resources state in terms of the congestion state to take the decisions. The use of a multi-agent architecture allows to integrate the controllable processing times with the scheduling of a manufacturing system. Moreover, a wider range of performance measures is analyzed.

(b) A simulation environment is used to test the proposed approaches when some exceptions occur (for example, demand fluctuations) and the rapidity changes are investigated.

3 The research context and controllable process time policies

The manufacturing system consists of a given number of machines; each machine is able to perform a particular set of manufacturing operations. In such a system, the parts visit the manufacturing machines according to their routing. The assumptions of the manufacturing system are the following:

- Each part performs *m* operations;
- Each typology part has been given process order, processing time, and due date;
- Orders for production of different parts arrive randomly;
- Operations cannot be pre-empted:
- Each machine can process only one task at once;
- The queues are managed by the First In First Out policy in order to investigate only the proposed strategy;
- Each machine can breakdown randomly.

In this research, the material handling time is included in the machining time, and the handling resources are always available.

The multi-agent architecture consists of three types of agent. A machine agent (MA) is associated to each workstation; it is an intelligent entity whose principle aim is to schedule the resource tasks in order to improve the machine performance. A time-controlled agent (TCA) is associated to the group of machines with the same characteristics to control the processing time; it manages the tools to control the processing time of the machines (for example, cutting tools, material handling, etc.). Moreover, when a new part enters the system, the corresponding part agent is created; it analyses the part status locating the following activities to be scheduled and performs the strategy to assign the part to the workstation.

The coordination mechanism among the agents to assign the parts to the machines is deeply described in Renna [18]. The objective of this paper is the control of the processing time.

The activities of the TCA agent concerns are: it evaluates the conditions in which the machines ask for the reduction of the processing time; the "strength" of the processing time reduction; the period of the processing time reduction. The information of the control system are the following:

- $J=1,\ldots J$; it is the index of the machines.
- *Resources*; it is the amount of resources (tools, material handling, etc.) available to reduce the processing time of the machines. It is related to the manufacturing system.
- $\mathit{Reducetime}_j$; it defines the reduction of the processing time for the machine j. This parameter relates the resources used to the effective processing time reduction.
- $\mathit{WaitingTime}_j$; it is the sum of the standard processing time of the parts in queue in the resource j.
- Setup_j; it is the setup time necessary to make the machine j operative with the reduction of the processing time.
- $\mathit{resourceM}_j$; it is the resource assigned to the machine j.

Each MA agent evaluates the WaitingTime of the machine managed and transmits this information to the TCA agent. The WaitingTime is the sum of the processing time of the parts that wait in queue of the machine. The TCA agent performs the following activities (see Fig. 1):

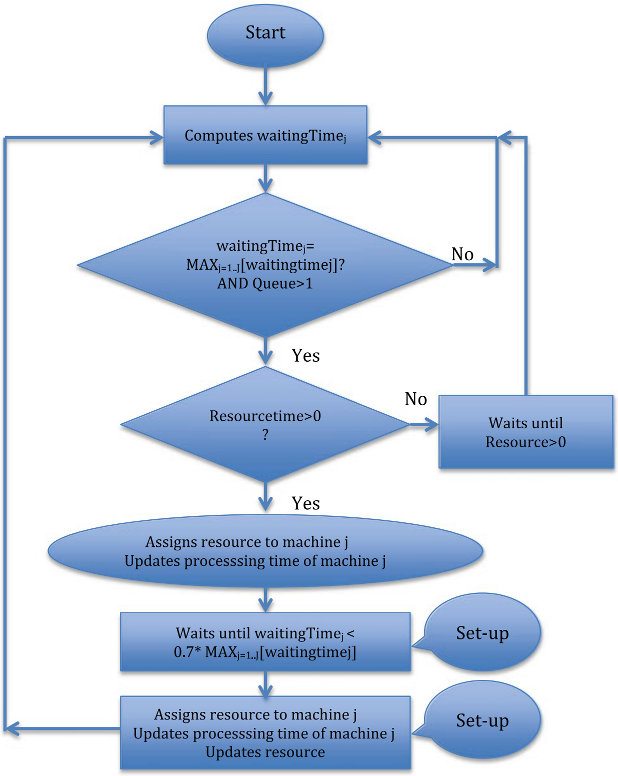

Fig. 1 Flow chart of the control process time policy

(a) The TCA agent collects all the WaitingTime parameters of the machines controlled. Then, the TCA agent has to select in what machine the reduction of the processing time will be performed. The machine selected needs to satisfy two conditions: it has the higher WaitingTime and the number of parts in the queue is greater than one. The second condition is necessary to avoid the reduction activity in case of only one part in the queue. If the machine with the higher WaitingTime has one part in the queue means that the manufacturing system does not need to reduce the processing times.

(b) The TCA agent verifies that the resources available are greater than one; in affirmative case, the process goes on. In case of resources not available, the requirement of the machine goes in wait state (see step *e*).

(c) The TCA agent uses the resources to reduce the processing time of the machine. The first approach proposed is the following. The TCA agent assigns all the resources to the machine; then, the agent update to zero the resources available for the other machines and communicates to the MA agent the new processing time of the machine and the setup activity to perform. After the setup, the machine can operate with reduced processing time. This approach is designated as "approach 1" in the rest of the paper.

(d) The MA of the machine with the reduction of the processing time transmits to the TCA when the WaitingTime of this machine is lower than a threshold (in this paper it is fixed to 70 %) of the higher WaitingTime of the machines supervised by the TCA. When this event occurs, the machine releases the resources after a setup time and the processing time changes back to the standard processing time. The threshold of 70 % is used to avoid continuous intervention on the machines with reduction of the global performance.

(e) This step concerns the case when the requirement of the machine is in the wait state, because the resources were not available. When the resources are available, the TCA agent starts from step (a) for this machine.

An alternative approach is the assignment of the resource proportionally among the machine resources. The approach modifies step (c) of the process described above.

The TCA agent computes the following expression:

$$resourceM_j = Min\left[1 + \left(indwait_j\right)^+; \max\ res;\ resources\right] \qquad (1)$$

The *indwait* is the following expression:

$$indwait_j = \frac{WaitingTime_j}{\sum_j WaitingTime_j} \times K \qquad (2)$$

The value of indwait_j evaluates the waiting time of the machine *j* compared to the entire manufacturing system. The coefficient *k* (*in this paper is fixed to 3.33*) is used to amplify the index in order to obtain a value comparable with the resource available. This allows to set the indwait by one parameter *k* with no change the evaluation of the waiting time.

Therefore, the resourceM_j is the amount of resources assigned to machine j. The means of the expression is the following: the value 1 is added to assure at least 1 of the resource assigned to the resource (in case the indwait is lower than 0.5, the indwait is 0). The value maxres (in this paper is fixed to 5) is used to limit the amount of resource assigned to the machine j; this avoids the assignment of the total resources to the machine. The value resources is used to assure that the resources assigned is effectively available. This approach is designed as “approach 2” in the rest of the paper.

The approach 1 converges all the resources available on one machine reducing the number of machines to setup with high reduction of working time; while the approach 2 reduce the working time of several resources (the distribution on several resources leads to a lower reduction of the working time) increasing the machines to setup.

4 Simulation environment

The objective of the simulation experiments is to measure the performance of the proposed approach benchmarked to the workload approach in a very dynamic environment. The author selected the Arena® discrete event simulation platform by Rockwell Software Inc. it was used to develop the simulation model of the presented approaches. Arena®—based on the known SIMAN simulation language—is well suited for modeling shop floors of production systems in which each entity (part) follows a manufacturing route through production resources (servers, material handling systems, buffers, and so forth), [12].

Table 1 Part mix

	Part 1	Part 2	Part 3	Part 4
Mix	40 %	40 %	10 %	10 %
Workload	Low	High	Low	High
Due date	Normal	Normal	Rush	Rush

Table 2 Part routing and processing time

	WS 1	WS 2	WS 3	Workload
Part 1	10	10	10	Medium
Part 2	20	20	–	High
Part 3	–	10	10	Low
Part 4	20	–	20	High

The manufacturing system consists of three machines; each machine is able to perform a set of technological operations. The manufacturing system is called to manufacture a set of four different parts. Table 1 reports the mix, the workload on the manufacturing machines and the due date assignment of each part typology.

Each part visits the machines according to the routing (see Table 2). It has been considered a different workload requested by the parts.

The due date is obtained by the following expression:

$$due\ date = totalprocessingtime \times due\ date_{index} \qquad (3)$$

The due date is obtained by the technological working time multiplied with a due date index; this index is 5 for “*normal*” orders, while it is 2 for “*rush orders*”.

Parts enter the system following an exponential arrival stream whose inter-arrival times are reported in Table 3. The simulations are performed for an inter-arrival time that assures a medium level of manufacturing system congestion: 16 is the parameter of the exponential distribution.

In order to emulate a dynamic environment, the manufacturing characteristics (machine breakdown, inter-arrival, and mix) changing during the production run consisting of three alternating stages.

Specifically, concerning the machine breakdowns, it has been assumed that all the manufacturing machines are subject to faults, and failures occur in accordance with exponentially

Table 3 Alternating stages data

	Stage 1	Stage 2	Stage 3
Inter-arrival	10	20	10
Mix 1	0.2	0.1	0.1
Mix 2	0.4	0.3	0.1
Mix 3	0.2	0.5	0.2
Mix 4	0.2	0.1	0.6
MTBF 1	4,000	1,000	500
MTBF 2	1,000	3,000	1,000
MTBF 3	500	2,000	4,000

Table 4 Resource available

	Resource available
Res 1	3
Res 2	5
Res 3	7
Res 4	9
Res 5	12
Res 6	15
Res 7	18

distributed time between failures, with mean time between failure MTBF=2,000 unit times equal for all machines. Repairing times are constant for all machines as 200 unit times.

In static conditions, the simulation data used is the data above described.

The proposed approaches are tested in static and highly dynamic situations; the dynamicity of the manufacturing system is characterized by the stage length. The simulation length is fixed to 43,200 time units, the length of the each stage characterizes the dynamicity of the manufacturing system. Three stage lengths are considered; the simulations data for each stage are reported in Table 3. Three stage lengths are considered: 4,320, 2,160, and 1,080 unit times. The stage length of 4,320 unit times is the low dynamicity; in this case, the data change every 4,320 unit times, therefore the stages alternate 10 times. The medium dynamicity is characterized by the 2,160 unit times; in this case the stages alternate 20 times. The stage length of 1,440 leads to alternate the stages 30 times; this characterizes the higher dynamicity of the manufacturing system.

The experimental classes tested are static and have three degrees of dynamicity. The simulations are conducted for two processing time policies and the case of no policy. Moreover, the control policies are evaluated for several values of resource time available to reduce the processing times. Table 4 reports the seven cases evaluated.

Then, several causes of dynamicity are considered: production mix, machines breakdown, and inter-arrival times. Table 5 reports the cases considered with the simulations experiments performed.

For each experiment class, a number of replications able to assure a 5 % confidence interval and 95 % of confidence level for each performance measure have been conducted.

The performance measures investigated are the following:

- Throughput time for each part $p=1,2,3,4$ (*thr. time p*); these index evaluate if some typology of product get main benefits than others.
- Average throughput time (*average thr. time*);
- Throughput (*thr.*);
- Work in process (*WIP*);
- Average utilization of the manufacturing system (*av. utilization*);
- Total tardiness time of the parts (*tardiness*);
- The average utilization of the resource time (*av. res. time*); it measures the utilization of the resources used to reduce the processing time.
- The average reduction of the processing time of the machines j=1,2,3 (*reduction j*); these indexes evaluate the distribution of the reduction processing time among the machine.
- Total number of processing time adjusting (*tot. adj.*); this index measures the number of changeover; therefore it is an evaluation of the variable costs related to the control policy.

5 Result and analysis

The first experimental class conducted concerns the static conditions for the manufacturing system. Table 6 reports the simulation results in terms of percentage differenced compared to the case with no policy.

In static conditions, the control of the processing time leads to obtain relevant benefits. In particular, the performance measures with the higher improvement are the average throughput time and the tardiness. The difference between the two control policies is the number of adjustments. The approach 2 allows to keep high level of performance reducing the number of adjustments: one every 1,610 unit times. This allows to reduce the costs of the processing time policy. The reduction of the adjustments reduces the number of set-ups and therefore, the average utilization of

Table 5 Alternating stages data

	Experimental classes
Static	1 (no policy)+(7 resources available×2 policies)=15
Dynamic production mix	(1 (no policy)+(7 resources available×2 policies))×3 stages length=45
Dynamic mix and machine breakdowns	(1 (no policy)+(7 resources available×2 policies))×3 stages length=45
Dynamic mix, machine break downs, and inter-arrival	(1 (no policy)+(7 resources available×2 policies))×3 stages length=45
Number of experimental classes	150

Table 6 Simulation results: static conditions

	Approach 1	Approach 2
Average thr. time (%)	−63.60	−76.29
Thr. time 1 (%)	−62.07	−76.47
Thr. time 2 (%)	−69.15	−77.10
Thr. time 3 (%)	−43.75	−71.64
Thr. time 4 (%)	−54.20	−73.57
Thr. (%)	0.27	0.54
WIP (%)	−63.76	−76.31
Av. utilization (%)	1.95	−29.76
Tardiness (%)	−91.61	−93.84
Res. time	12	12
Tot. adj. (time between each adjustment)	1,659.2 (26)	26.84 (1,610)
Av. red. (%)	36	30
Av. res. time (%)	92	76

the manufacturing systems. The approach 1 leads to a greater number of set-ups because the resources are allocated to one machine with high reduction of processing time; then, in few times another machine becomes the machine with the greater waiting time and the resources will be assigned to this machine. This leads to continuous setups due to the oscillation of the waiting time of the machines.

The benefits in terms of throughput time reduction is rather uniformly among the part typologies for the approach 2; while the approach 1 distributes the benefits in a unbalanced way. Both the approaches have the better results with 12 resources time available.

Figure 2 shows the average throughput time when the number of resource time changes (see Table 4). The other relevant performance measures have the same trend. The approach 1 reduces the benefit with low and high resource time available; while the approach 2 reduces the performance only for low resource time available. Therefore, the approach 2 is more robust when the resource available changes.

Table 7 reports the simulation results when mix fluctuations occur. The approach 2 leads always to better results; the benefits are obtained reducing drastically the number of machine changes. The higher dynamicity (low stage length factor) reduces the benefits of the process control times. Therefore, the control approaches work better when the mix fluctuations are characterized by low dynamicity. This means that the distribution of the resources among the manufacturing machines is the better strategy when mix changes.

Table 8 reports the simulation results when mix and machine breakdowns fluctuations occur.

The trend of the performance measures is very similar to the case with mix fluctuations. The introduction of fluctuations of the machine breakdown improves the benefits of the proposed approaches. The control policy works better when internal exceptions occur as the machine breakdowns. Moreover, the effect of the dynamicity on the performance measures is lower than the case with only mix fluctuations.

Table 9 reports the simulation results when mix, machine breakdowns, and inter-arrival fluctuations occur. The approach 1 is better than the approach 2 when inter-arrival fluctuations occur. In this case, the allocation of the resources on one machine with high reduction of processing time is the better strategy to react when the inter-arrival time fluctuates. The performance measures have limited variation when the dynamicity of the fluctuations changes.

Table 10 reports the average of the simulation results for each typology of fluctuation. As the reader can notice, the introduction of fluctuations leads to increase the benefits of control processing time methodology. The control policy of processing time is better when several alterations can affect the manufacturing system. The benefits of the proposed approaches are relevant in each condition tested.

Fig. 2 Performace vs resource time (see Table 4)

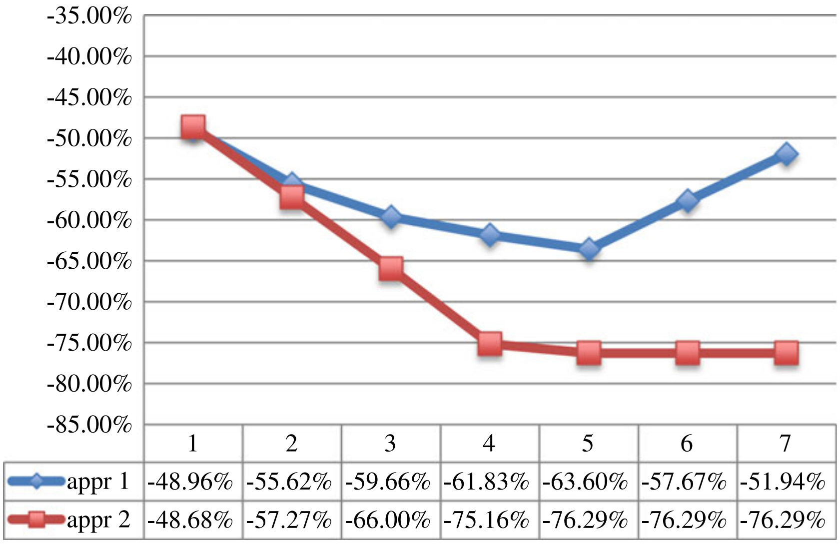

Table 7 Simulation results: mix fluctuations

Dynamicity	Low		Medium		High	
	Approach 1	Approach 2	Approach 1	Approach 2	Approach 1	Approach 2
Average thr. time (%)	−79.53	−80.49	−74.20	−75.79	−67.79	−71.97
Thr. time 1 (%)	−76.83	−80.54	−72.95	−76.92	−67.88	−73.04
Thr. time 2 (%)	−70.56	−75.02	−64.00	−70.17	−59.67	−67.11
Thr. time 3 (%)	−81.58	−83.98	−76.87	−79.86	−70.12	−76.56
Thr. time 4 (%)	−84.22	−80.70	−78.68	−74.94	−71.00	−70.41
Thr. (%)	2.19	2.46	0.54	1.91	0.27	0.27
WIP (%)	−79.70	−80.45	−74.27	−75.94	−67.86	−71.97
Av. utilization (%)	−14.75	−29.03	−5.43	−30.77	−5.91	−1.41
Tardiness (%)	−94.92	−91.53	−93.04	−89.17	−89.80	−87.37
Res. time	12	12	12	12	12	12
Tot. adj. (time between each adjustment)	1,530 (28)	26.84 (1,610)	1,515 (29)	26.84 (1,610)	1,487 (29)	25 (1,728)
Av. red. (%)	36	30	36	30	36	30
Av. res. time (%)	90	76	90	77	90	77

From the simulation results, the following issues can be drawn:

- The approach 2 is the better approach in the cases of mix and breakdown fluctuations. The main advantage of this approach is the limitation of the number of machine set-ups to change the processing times. This allows to reduce the costs related to the control process policy. Moreover, the approach 2 is more robust to the resources available to reduce the processing time of the manufacturing resources. Therefore, the proportionally distribution of the resources time among the machines is the better strategy.
- The approach 1 leads to the better results only in the case of inter-arrival fluctuations. In this condition, the approach 1 outperforms the approach 2 over the 10 % for the main performance measures. The main limit of this approach is the higher number of set-ups. Therefore, this policy is characterized by higher costs than the approach 2.
- The simulations allow to define the value of resource time to acquire to obtain the better performance measures. In the design stage, the simulation environment supports the decision of the resource time acquisition. Moreover, the simulation allows to evaluate the performance measures when the resources time available change.

Table 8 Simulation results: mix fluctuations and machine breakdowns

Dynamicity	Low		Medium		High	
	Approach 1	Approach 2	Approach 1	Approach 2	Approach 1	Approach 2
Average thr. Time (%)	−81.86	−83.34	−76.16	−78.23	−69.98	−74.13
Thr. time 1 (%)	−79.57	−82.84	−74.71	−78.75	−69.77	−75.11
Thr. time 2 (%)	−77.12	−80.92	−70.26	−74.78	−63.52	−68.76
Thr. time 3 (%)	−84.24	−86.71	−79.05	−82.57	−73.05	−78.81
Thr. time 4 (%)	−84.33	−82.27	−78.43	−76.35	−71.60	−72.63
Thr. (%)	1.91	2.19	1.36	1.36	1.08	1.08
WIP (%)	−81.86	−83.34	−76.00	−78.07	−69.94	−74.07
Av. utilization (%)	−6.02	−29.17	−5.05	−29.82	−5.05	−29.82
Tardiness (%)	−95.21	−93.15	−93.25	−90.50	−90.51	−88.91
Res. time	12	12	12	12	12	12
Tot. adj. (time between each adjustment)	1,457.50 (30)	26.84 (1,610)	1,480 (29)	26.54 (1,627)	1,478 (29)	24.92 (1,734)
Av. red. (%)	36	30	36	30	36	30
Av. res. time (%)	91	76	90	77	90	77

Table 9 Simulation results: mix fluctuations, machine breakdowns, and inter-arrival

Dynamicity	Low		Medium		High	
	Approach 1	Approach 2	Approach 1	Approach 2	Approach 1	Approach 2
Average thr. time (%)	−96.74	−80.86	−96.64	−86.29	−96.61	−90.98
Thr. time 1 (%)	−96.32	−79.35	−96.40	−85.15	−96.53	−90.52
Thr. time 2 (%)	−96.48	−85.67	−96.22	−89.91	−95.97	−92.02
Thr. time 3 (%)	−96.53	−78.55	−96.13	−82.82	−96.16	−89.09
Thr. time 4 (%)	−97.32	−80.30	−97.34	−86.86	−97.28	−91.80
Thr. (%)	2.74	−10.96	18.42	17.22	5.48	−10.96
WIP (%)	−96.97	−80.54	−96.65	−86.26	−96.63	−91.05
Av. utilization (%)	−13.51	−22.31	−11.97	−21.62	−14.83	−23.57
Tardiness (%)	−99.08	−81.20	−99.08	−87.43	−99.13	−93.10
Res. time	12	12	12	12	12	12
Tot. adj. (time between each adjustment)	1,610.90 (27)	26.84 (1,610)	1,666.60 (26)	26.54 (1,706)	1,681.80 (26)	20.76 (2,081)
Av. red. (%)	37	30	37	31	36	30
Av. res. time (%)	92	7	93	77	93	79

- The benefits of the control policies are reduced when the dynamicity of the manufacturing system is very high. In this condition, the control policies have more difficult to adapt to the continuous variations of the manufacturing system parameters. However, the control policies investigated lead to better performance measures.

6 Conclusions and future development

The research presented two approaches for processing time control in a manufacturing system. The approaches can be supported by a multi-agent architecture. The approaches are based on the evaluation of the workload of the manufacturing resources that compete to acquire the resources to reduce the processing time. The first approach concerns the reduction of the processing time to one manufacturing resource at times. The second approach is based on a proportional distribution of the resources among the machines. A simulation environment has been developed to test the proposed approach in several conditions and in a very dynamic environment with internal (machine breakdowns) and external (mix and inter-arrival time) changes. The simulation results were compared to a manufacturing system without processing time control. The simulation results show that the control processing time policies proposed allow to improve significantly the performance measures of the manufacturing system. The policy based on the proportional distribution leads to better results in case of mix and breakdowns, but the policy based on one machine at times is better when the inter-arrival of the parts change. The policy based on the distribution among the machines allows to reduce drastically the number of set-ups; therefore, this approach allows to reduce the costs related to this policy. Moreover, the policies propose are characterized by a low computational complexity and they can be supported by a multi-agent architecture. The simulations allow to evaluate the real benefits in several manufacturing conditions reducing the risk related to the control processing time policies.

Future development paths concern on the evaluation of distribution of the resources to reduce the processing time with methodologies based on artificial intelligence and the

Table 10 Simulation results: mix fluctuations, machine breakdowns, and inter-arrival

Dynamicity	Mix		Mix and breakdown		Mix, breakdown and inter-arrival	
	Approach 1	Approach 2	Approach 1	Approach 2	Approach 1	Approach 2
Average thr. time (%)	−68.87	−71.00	−76.00	−78.57	−96.66	−86.04
Thr. (%)	1.00	1.55	1.45	1.54	8.88	−1.57
WIP (%)	−73.94	−76.12	−75.93	−78.49	−96.75	−85.95
Av. utilization (%)	−8.70	−20.40	−5.37	−29.60	−13.44	−22.50
Tardiness (%)	−92.59	−89.36	−92.99	−90.85	−99.10	−87.24

development of a fuzzy engine combined with the genetic algorithms to determine the resources to allocate. These approaches will be investigated to evaluate if the greater complexity leads to improve significantly the performance of the manufacturing system.

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