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Procedia CIRP 63 (2017) 21 – 26
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The 50th CIRP Conference on Manufacturing Systems

A heuristic approach to solve an industrial scalability problem

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Abstract

In recent years, the rapid change of market demand is increasing the need for scalability as a key characteristic of manufacturing systems. Scalability allows production capacity to be rapidly and cost-effectively reconfigured in different situation with different requirements and constraints. Our industrial partners are facing quarterly scalability problems involving a multi-unit and multi-product manufacturing system. In this paper, an original approach is presented to solve this kind of problems. Starting from the original manufacturing system configuration and process plan, a set of practical principles are introduced to seek for the feasible configurations; a GA is designed to search in the global solution space. A balancing objective function is defined and used to rank the proposed configurations. A real case study with 4-unit / 4-product situation demonstrates both the validity and efficiency of the proposed approach.

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Keywords: Manufacturing System; Reconfiguration; Scalability;

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1. Introduction

In this paper, we tackle the problem of manufacturing system reconfiguration known as “scalability” problem. Scalability may be defined as the ability to adjust the production capacity of a manufacturing system through reconfiguration that has the minimal impact on time and cost [1].

We refer to a case study of our industrial partner that is facing quarterly scalability problems involving a multi-unit and multi-product manufacturing system. In fact, the plant is characterized by four manufacturing units, each of them producing a part in the same part family (engine block). Each unit has several stations with identical machining centers. To face the changeable demand of the different products, engineers usually update the configuration of the stations inside each manufacturing unit. Applying not dedicated reconfiguration approaches, these activity is becoming too time consuming to reach a solution that is usually far from the optimal one, with the consequence of being unprofitable for the company.

Initially introduced by Koren et al. [2], the manufacturing system scalability problem has been extensively reviewed in [3]. Despite the vast literature on reconfigurable manufacturing system, the scalability problem tackle in this paper is not addressed. The most relevant and similar research on the previously stated problem has been presented by Wang and Koren [4]. After a comprehensive definition and modeling of the problem, they introduced a method to design a multi-stage machining line by genetic algorithm (GA). A recent evolution of this research has been presented in [5], in which the mathematical analysis is extended in order to consider buffers. Nevertheless, they refer to a one-product and one-unit case study. Moreover, the approach is based on a complete reconfiguration of the manufacturing system, as it is commonly considered in the literature, thus not considering the real industrial need of small variation with respect to the actual manufacturing system configuration and operations allocation. Section 2 defines an original scalability problem and presents the proposed solution approach. Section 3 introduces the case study and presents the results, while Section 4 is dedicated to the final discussion.

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doi:10.1016/j.procir.2017.03.310

2. Problem definition and solution approach

In the case study we are considering, the company prefers to keep unchanged the number of stations of a unit, which means that the original fixture and certain machining operations should be kept in the original station. Therefore, we address the situation in which the reconfiguration is limited and based on previous and well known and accepted process plans. This situation is not considered in the literature.

In order to model the manufacturing system, each unit is composed by S stations, named S_j with $j = 1..S$. M_j is the number of machining centers allocated to the station S_j. Due to the process plan constrains, each station of each unit is characterized by three sets of operations:

1. fixed operation set, set of operations which must be executed in that station;
2. changeable operation set, set of operations which could be executed in that station, so respecting the technological constraints;
3. not feasible operation set, set of operations which cannot be executed in that station, due to technological constraints.

For each unit and for each new product demand we define the expected cycle time (CT_{Exp}) as the ratio between the available manufacturing time (that consider the reliability of the machining centers, and other factors) and the new product demand (D_{new}). Moreover, the ideal cycle time (CT_{Ideal}) is introduced as the reference value of cycle time for the unit, being the ratio between the total machining time for the part manufactured in the unit and the total number of machining centers in the unit. This cycle time value corresponds to the situation of perfect balancing for the considered unit.

Being this scalability problem a combination of configuration selection and balancing problems, we propose to approach the solution considering two sub-problems. Initially, the total number of identical machining centers M is used to evaluate a configuration, the goal being the minimization of this number. Then, the balancing problem is tackled. Among all the possible objective functions for the balance the system, we consider the sum of square of cycle time deviations. In fact, the far deviate the cycle time of a single station from the average, the more critical the station is. Nevertheless, in the results we report not only the sum of square of the deviations, but also the sum of the absolute deviation, and the cycle time of the bottleneck station.

Approaching the solution as two sub-problems we developed an original approach in which a genetic algorithm to solve the balancing problem is nested in a heuristic approach for the minimization of the total number of machining centers for each unit, as shown in Figure 1.

In order to consider fasten the search of a solution with the minimum number of machining centers, we search the solution among a reduced set of possible configurations which are created considering these two main principles:

I. As the fixed operation set exists for each station, the number of machining centers of each station must guarantee the execution of at least the fixed operation set for the station;
II. The maximum number of machining centers that can be allocated to a station is the largest integer less than or equal to the ratio between the maximum machining time required to perform all operations in both the fixed operation set and the changeable operation set for the station, and the ideal cycle time in the case of perfect balancing.

These two principles enable to avoid searching for a solution among configurations that are clearly non-efficient, that is the case of having free time of a machining center that cannot be used by any operation in the process plan.

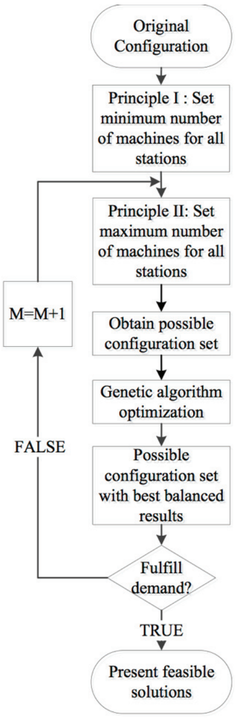

Figure 1. Proposed heuristic approach

Starting from the minimal number of machining centers to fulfill the new demand requirement, the allocation of them to each single station is done considering the heuristic principle, thus generating a small set of possible configurations of the manufacturing unit. For each possible configuration, a genetic algorithm optimization is applied in order to find the best balancing. If the best solution among the considered one is not respecting the new demand requirement, then the total number of machining centers is increased of one machine, and the full search start again. This iterative process is applied until the best feasible solution is found.

The proposed heuristic principles and the iterative approach guarantee the minimization of the number of machining centers, while we expect that the genetic algorithm optimization gives a sub-optimal solution for the balancing problem.

3. Case Study

In this section, a case study is presented to illustrate the reconfiguration process of the manufacturing system driven by two scenarios of product demands. In the considered manufacturing system, there are 4 manufacturing units producing 4 kinds of engine blocks in the same production plant. The 4 units initially consist of 4x9 identical machining centers. This is a choice to facilitate the system reconfigurablility. The information related to the 4 original units is shown in Table 1. A configuration like "1-1-2-1-2-2" means that the unit has 6 stations with 9 machines, and each value stands for the number of parallel machines for each station. Due to the machining constraints of stations, both the minimum operation time to satisfy the fixed operations and the maximum operation time to satisfy the case in which all the changeable operations are added to the station are shown in Table 2.

The manufacturing plant works 300 days a year, 16 hours a day and the inherent availability of each manufacturing unit is estimated as $IA = 90\%$. So the available manufacturing time of each unit (T_A) can be calculated as:

$$T_A = (300 \times 16 \times 3600) \times 90\% = 15552000 \text{ s}$$

Table 1. Information related to the 4 original units

Unit name	Part name	Machining Time/piece [s]	Cycle Time [s]	Production Capacity [parts/y]	Original configuration
I	A	5243.87	636.95	24415	1-1-2-1-2-2
II	B	4807.65	630.80	24654	1-2-2-2-2
III	C	3511.82	415.29	37449	1-2-2-2-2
IV	D	10335.63	1224.7	12699	1-2-2-1-1-2

Table 2. Fixed and changeable operation time for all stations of 4 units

Unit name	Op. Time	S1	S2	S3	S4	S5	S6
I	Min	469.25	260.36	452.52	211.43	602.6	1161.8
	Max	1007.3	1241.0	1433.3	1463.1	1864.4	1594.0
II	Min	284.88	642.60	318.68	661.15	1014.7	
	Max	758.61	1577.8	1084.5	1389.8	1925.3	
III	Min	275.99	152.98	590.91	273.34	666.35	
	Max	695.58	1131.5	1016.4	1657.9	1401.4	
IV	Min	603.57	901.66	1254.1	826.17	382.00	2257.5
	Max	1038.4	3691.9	3045.3	2866.7	3036.2	2660.8

3.1. Scenario I: Reconfigurable Planning for Increased Demand of 4 Units

Due to the 4 increased product demands shown in Table 3 and the available manufacturing time, the upper limit for the cycle time CT_{Exp}, and the minimum number of machining center with the related ideal cycle time CT_{Ideal} can be calculated as follows:

$$CT_{Exp}^{II} = \frac{T_A}{D_{new}} = \frac{(300\times16\times3600)\times0.9}{35000} = 444.34\ s$$

$$M_{min}^{II} = \left\lceil \frac{T_m^{II}\times D_{new}^{II}}{T_A} \right\rceil = \left\lceil \frac{4807.65\times35000}{(300\times16\times3600)\times0.9} \right\rceil = 11$$

$$CT_{Ideal}^{II} = \frac{T_m^{II}}{M_{min}^{II}} = \frac{4807.65}{12} = 400.64\ s$$

Table 3. Reconfiguration information for Scenario I

Unit name	Part name	D_{New}	CT_{Exp}	CT_{Ideal}	M_{min}	Number of machine tools for fixed operations	Additional number of machine tools	Configuration Range	
Unit I	Part A	35000	444.34	436.99	12(+3)	11	+1	min	2-1-2-1-2-3
								max	2-2-3-2-3-3
Unit II	Part B	35000	444.34	400.64	11(+2)	10	+1	min	1-2-2-2-3
								max	1-3-2-3-4
Unit III	Part C	45000	345.60	319.26	11(+2)	10	+1	min	1-2-2-2-3
								max	2-3-3-3-4
Unit IV	Part D	17000	914.82	861.30	12(+3)	10	+2	min	1-2-2-1-1-3
								max	1-4-3-3-3-3

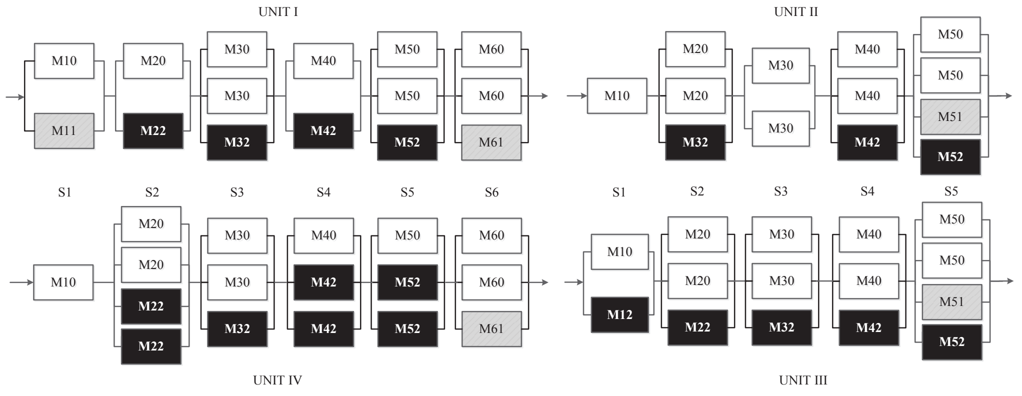

Figure 2. Synthetic representation of all the possible configurations of all the units (Scenario I)

Then, all the principles and the proposed algorithm are followed to obtain the reconfigured plan of the 4 units. As an example, in its original configuration Unit II has 5 stations with a total of 9 identical machining centers ($M_1^{\mathrm{II},0} = 1$, $M_2^{\mathrm{II},0} = 2$, $M_3^{\mathrm{II},0} = 2$, $M_4^{\mathrm{II},0} = 2$, $M_5^{\mathrm{II},0} = 2$). According to Principle I, the minimum number of machining centers for all the stations can be calculated, so the minimum number of machines to finish the fixed operations in each station is $M_1^{\mathrm{II,min}} = 1$, $M_2^{\mathrm{II,min}} = 2$, $M_3^{\mathrm{II,min}} = 2$, $M_4^{\mathrm{II,min}} = 2$, $M_5^{\mathrm{II,min}} = 3$. It means that 1 extra machine tools must be allocated to station 5 with respect to the original configuration. Due to the $M_{min}^{II} - M_{original}^{II} = 2$, at least 1 additional machining center needs to be allocated to guarantee the new production demand. Although apparently the additional machining center could be allocated to the 5 different stations of Unit II, the maximum machine configuration calculated by Principle II provides us only 3 recommended choices, these choices are the possible configuration set for Unit II ($PG_{\mathrm{config}}^{\mathrm{II}}$). In Figure 2, machines in white stand for the original configuration. Machines in gray are the essential machines to satisfy the fixed operation time. Machines in black show the potential number of machining centers we may add to each station.

Finally, the GA algorithm has been used to all configurations in PG_{config}^{II}. Best results from each configuration are ranked in Table 5. Apparently, the result from configuration 3 is far away from CT_{Exp}^{II}, which makes it unfeasible if no extra machine tool is added. The best result is related to configuration 1 since it has the relatively better performance between the two feasible configurations.

Similarly, the three possible configuration set of the remaining units ($PG_{\mathrm{config}}^{\mathrm{I}}$,$PG_{\mathrm{config}}^{\mathrm{III}}$, $PG_{\mathrm{config}}^{\mathrm{IV}}$) can be obtained (Fig 1). Unit I needs 3 additional machines ($M_{11}^{\mathrm{I}}, M_{61}^{\mathrm{I}}$are needed for the fixed operations, while the additional machine could be allocated as M_{22}^{I}, M_{32}^{I}, M_{42}^{I} and M_{52}^{I}). Unit III needs 2 additional machines (M_{51}^{III} is needed for fixed operations, while the additional machine could be allocated as M_{12}^{III}, M_{22}^{III}, M_{32}^{III}, M_{42}^{III} and M_{52}^{I}). Unit IV has a more complex situation. It needs to add 3 machines (M_{61}^{IV} is needed for fixed operations, while 1 machine could be added as M_{32}^{IV} and 2 machines as M_{22}^{IV}, M_{42}^{IV} and M_{52}^{IV}), which makes the number of the possible configurations for Unit IV equal to $C_4^2 + C_3^1 = 9$.

Then, the best results with their configurations of all units are calculated and ranked, as reported from Table 4 to Table 7. As shown in the tables, all units have at least one feasible plan to meet the product demand with the minimum number of machining centers. In conclusion, at the system level the company needs to purchase $3 + 2 + 2 + 3 = 10$ extra machining centers to fulfill the 4 increased demands in this scenario.

Table 4. Ranked results for the possible configuration set (Unit I)

Configuration [Unit I]	Square [s^2]	Balance [s]	Bottleneck [s]	Production [parts/y]
2-2-2-1-2-3	0.2354	1.0072	437.26	35567
2-1-2-2-2-3	0.2383	0.7738	437.42	35554
2-1-2-1-3-3	0.7029	1.6485	437.66	35534
2-1-3-1-2-3	572.37	52.775	454.84	34192

Table 5. Ranked results for the possible configuration set (Unit II)

Configuration [Unit II]	Square [s^2]	Balance [s]	Bottleneck [s]	Production [parts/y]
1-3-2-2-3	17.187	8.7660	437.53	35545
1-2-2-3-3	18.386	9.1015	438.07	35501
1-2-2-2-4	1682.48	85.86382	459.63	33836

Table 6. Ranked results for the possible configuration set (Unit III)

Configuration [Unit III]	Square [s^2]	Balance [s]	Bottleneck [s]	Production [parts/y]
1-2-3-2-3	0.0309	0.2432	319.28	48710
2-2-2-2-3	0.0732	0.4611	319.50	48676
1-2-2-2-4	1423.2	71.644	349.95	44440
1-2-2-3-3	1445.5	73.950	349.95	44440
1-3-2-2-3	1445.5	73.937	349.97	44438

Table 7. Ranked results for the possible configuration set (Unit IV)

Configuration [Unit IV]	Square [s^2]	Balance [s]	Bottleneck [s]	Production [parts/y]
1-2-3-2-3	0.0580	0.3647	861.38	18054
2-2-2-2-3	0.0567	0.4094	861.44	18053
1-2-2-2-4	0.1386	0.7568	861.52	18051
1-2-2-3-3	0.1967	0.9009	861.52	18051
2-2-2-2-3	0.3342	1.1860	861.57	18050
1-2-2-2-4	1469.5	78.946	887.81	17517
1-2-2-3-3	1596.7	86.643	887.86	17516
1-2-2-3-3	1596.7	86.644	887.88	17515
1-3-2-2-3	2187.3	96.488	890.19	17470

3.2. Scenario II: Reconfigurable Planning for Re-balanced Demand of 4 Units

Considering the second scenario in which the 4 product demands are shown in Table 8. Since the demands of Part A and Part D are the same as in scenario 1, the previous optimal results for Unit I and Unit IV are re-used. The search for the best configuration of Unit II and Unit III are performed with the same sequence of steps.

Following the Principle I and II, the minimum and maximum number of machining centers for each station can be calculated (Table 8). Then the possible configuration sets ($PG^{\mathrm{II}}_{\mathrm{config}}$ and $PG^{\mathrm{III}}_{\mathrm{config}}$) can be defined (Figure 3). For Unit II, 6 machine tools with the configuration of “1-1-1-1-2” are needed to satisfy the fixed operations for stations. Because of $M^{II}_{min} = 7$, there is one additional machining center that could be allocated in two possible stations (M^{II}_{22} and M^{II}_{42}, black in Unit II). So Unit II has two possible configurations: “1-2-1-1-2” and “1-1-1-2-2”.

Similarly, 7 machining centers with the configuration of “1-1-2-1-2” are necessary to finish the fixed operations for Unit III. This number corresponds to the minimum number of machining centers ($M^{III}_{min} = 7$), so Unit III has just one possible configuration.

The GA algorithm has been applied to all the 3 configurations in $PG^{\mathrm{II}}_{\mathrm{config}}$ and $PG^{\mathrm{III}}_{\mathrm{config}}$. Results for each configuration are ranked in Table 9 and Table 10. As shown in these tables, both the best results of the two units can satisfy the new product demands. So in this scenario, Unit I and Unit IV still need 6 extra machining centers (3 each). While Unit II and Unit III require a reduction of 2 machining centers each with respect to the original configurations. Therefore, being the machining centers all identical, the overall requirement for the manufacturing system in this scenario is of 2 extra machines.

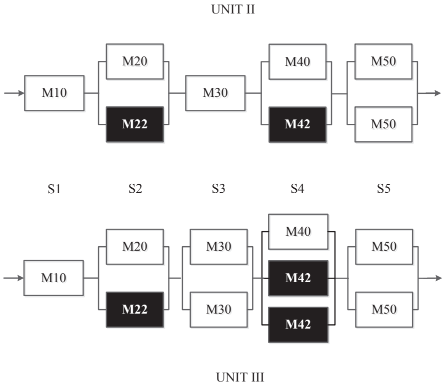

Figure 3. Synthetic representation of all the possible configurations of all the units (Scenario II)

Table 8. Reconfiguration information for Scenario II

Unit name	Part name	D_{New}	CT_{Exp}	CT_{Ideal}	M_{min}	Number of machine tools for fixed operations [Principle I]	Additional number of machine tools [Principle II]	Configuration Range	
Unit I	Part A	35000	444.34	436.99	12(+3)	11	+1	min	2-1-2-1-2-3
								max	2-2-3-2-3-3
Unit II	Part B	22000	706.91	686.81	7(-2)	6	+1	min	1-1-1-1-2
								max	1-2-1-2-2
Unit III	Part C	30000	518.40	501.69	7(-2)	7	0	min	1-1-2-1-2
								max	1-2-2-3-2
Unit IV	Part D	17000	914.82	861.30	12(+3)	10	+2	min	1-2-2-1-1-3
								max	1-4-3-3-3-3

Table 9. Ranked results for the possible configuration set (Unit II)

Configuration [Unit II]	Square [s^2]	Balance [s]	Bottleneck [s]	Production [parts/y]
1-2-1-1-2	114.45	19.334	692.61	22454
1-1-1-2-2	12037	158.03	786.23	19780

Table 10. Ranked results for the possible configuration set (Unit III)

Configuration [Unit III]	Square [s^2]	Balance [s]	Bottleneck [s]	Production [parts/y]
1-1-2-1-2	0.0128	0.2192	501.76	30995

4. Conclusion

This paper present an original approach to solve a scalability problem characterized by a multi-unit and multi-product manufacturing system. In particular, the addressed scalability problem is not considered in the literature being characterized by the fact that the reconfiguration is limited and based on previous and well known and accepted process plans. In fact, the industrial case study refers to those companies which prefer to keep unchanged the number of stations of a manufacturing unit, which means that the original fixture and a given set of machining operations should be kept in the original station.

Heuristic principles driven by process plan operation constraints have been designed to find feasible configuration set with minimum number of machining centers and a GA algorithm has been proposed to search for the optimal balanced solution.

The validation experiments have been executed on Intel i7-4870HQ CPU and 8GB memory. For each configuration, the computational time has been in the range from 16.9 minutes to 47.5 minutes with an average value of 30.9 minutes. This average computational time has been estimated running 4 parallel computations. This means that the overall time to generate the solutions in Scenario 1 has been around 2,5 hours, while around half an hour in Scenario 2.

The experimental results have shown that the scalability problem can be solved efficiently and effectively through the proposed approach.

5. Acknowledgments

This research is supported by National Science and Technology Major Project of the Ministry of Science and Technology of China [Grant No. 2011ZX04015-022].

Acknowledgment is also due to the Recruitment Program of High-end Foreign Experts of the Chinese State Administration of Foreign Experts Affairs.

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