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ORIGINAL ARTICLE

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Assessment of manufacturing systems reconfiguration smoothness

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Abstract The effect of the configuration selection on the smoothness and easiness of manufacturing systems reconfiguration process cannot be neglected, especially when dealing with reconfigurable manufacturing systems (RMS). The term "*reconfiguration smoothness*" is introduced in this paper to address this issue. In order to evaluate the level of reconfiguration smoothness (RS), a metric was developed to provide a relative measure of the expected cost, time, and effort required to convert from one configuration to another. This metric is composed of three components representing different levels of reconfiguration, namely; market-level reconfiguration smoothness (TRS), system-level reconfiguration smoothness (SRS), and machine-level reconfiguration smoothness (MRS). Rules are introduced to guide the development of execution plans for system-level reconfiguration, which we call "*reconfiguration planning*". These plans help reduce the physical effort of reconfiguring the system. A case study is presented to demonstrate the use of the developed metric followed by sensitivity analysis to show the effect of changing different metric parameters. The results show how the developed metric provides a powerful relative assessment tool for the transitional smoothness between a current configuration and a number of candidate feasible configurations for the next period. This can affect the configuration selection decisions at the beginning of each configuration period.

Keywords Configuration selection · Reconfigurable manufacturing systems · Reconfiguration planning · Reconfiguration smoothness

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1 Introduction

The history of manufacturing systems shows their evolution over the years in response to an increasingly dynamic and global market with greater need for flexibility and responsiveness (Fig. 1). Unpredictable market changes cause frequently varying manufacturing systems requirements. Reconfigurable manufacturing systems (RMS) were proposed to meet these requirements and provide a degree of capacity scalability and functional adaptability.

Most manufacturing industries now use a portfolio of dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS) to produce their products. RMS is intended to combine the high throughput of DML with the flexibility of FMS and react to changes quickly and efficiently [2]. There are many aspects of manufacturing systems reconfiguration that present important research challenges. They include reconfiguration of the factory communication software, new machine controllers, building blocks, and configuration of modular machines, modular processes, and configuration of the production system [3]. The main focus of the research presented in this paper is the selection of system-level configurations.

A distinguishing feature of RMS is that its configuration evolves over time in order to provide the functionality and capacity needed, when it is needed. These configuration changes can be in the form of adding/removing machines to/from the system, adding/removing axes/spindles to/from machine tools, changing configuration of machine tools, changing the system layout or changing the material handling systems. Figure 2 shows an example of system-level reconfiguration.

The effort required to reconfigure the system according to the anticipated demand scenarios has to be taken into consideration in the process of selection of reconfigurable manufacturing systems (RMS) configuration [4, 5]. This paper introduces the term "*reconfiguration smoothness*" to reflect the cost, time, and effort required to reconfigure the system. A reconfiguration smoothness (RS) metric is developed and presented.

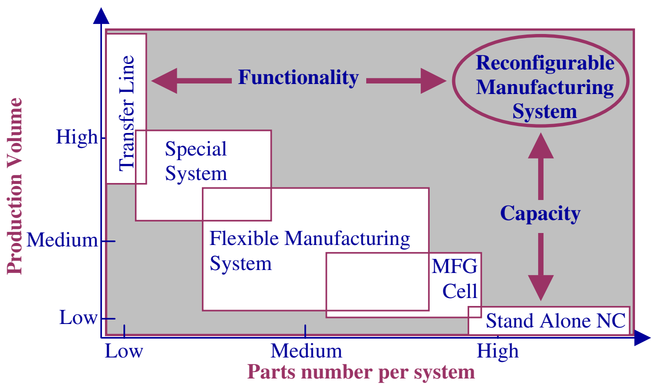

Fig. 1 Functionality & capacity of manufacturing systems (adopted from [1])

The next section reviews related literature. Section 3 presents some basic assumptions with regards to the configuration structure and the kinds of available information. Section 4 demonstrates the concept of "*reconfiguration smoothness*" from a stochastic perspective. Section 5 describes in detail the developed reconfiguration smoothness metric (RS) with all its components. Section 6 presents a case study to demonstrate the use of the developed metric followed by sensitivity analysis to show the effect of changing different metric parameters on its value. In Sect. 7, the paper concludes with a summary and an outlook on future research issues.

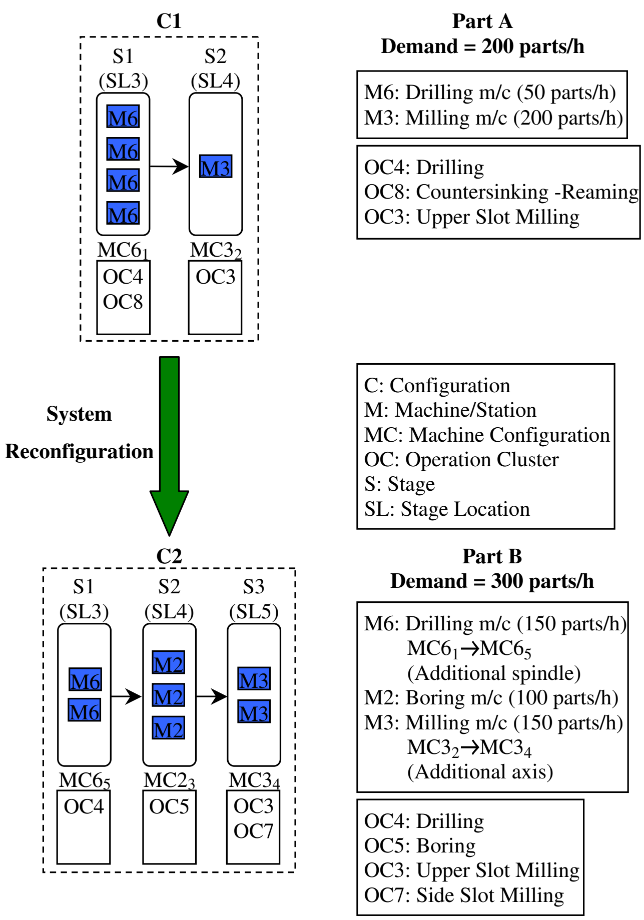

Fig. 2 System reconfiguration example

2 Literature review

Makino and Trai [6] classified reconfigurable systems into two categories: statically reconfigurable systems, which are based on the concept of building blocks, where the stations of the system are designed to be easily moved around, and dynamically reconfigurable systems, which attain their reconfigurability by using advanced material handling systems like automated guided vehicles (AGVs) or traveling robots rather than the use of traditional conveyor systems.

ElMaraghy [1] and Shabaka and ElMaraghy [7] divided manufacturing systems reconfiguration activities into two types: hard or soft. Examples of hard (physical) reconfiguration activities include adding/removing of machines, adding/removing of machine modules, and changing material handling systems. Examples of soft (logical) reconfiguration activities include re-programming of machines, re-planning, re-scheduling, re-routing, and increasing/decreasing of shifts or number of workers.

Kusiak and Lee [8] and Lee [9, 10] discussed reconfigurability in the design of products and manufacturing systems. They defined reconfigurability as the ability of a manufacturing system to be reconfigured at a low cost and in a short period of time. They introduced rules to be applied in the early stages of system design in order to minimize the number of machine relocations. However, they focused more on appropriate product design as a means of attaining reconfigurability.

Kuo [11] and Yamada et al. [12] optimized the equipment layout assignment for RMS with the objective of minimizing the total transportation time. Kuo [11] used distributed colored timed Petri net (DCTPN) to model the RMS while Yamada et al. [12] used an algorithm based on particle swarm optimization (PSO).

Abdi and Labib [13–15] discussed strategic issues of system design and products grouping and selection. They introduced an analytical hierarchical process (AHP) model for designing RMSs based on a case study. They focused on decisions regarding selecting system type followed by the grouping of products into families and selecting a family for each system configuration.

The following sub-sections provide an in depth review of the approaches that dealt with the selection of systems configuration in the RMS context.

2.1 A framework for a stochastic model of an RMS

Xiaobo et al. [16] proposed a framework for a stochastic model of an RMS. This framework involves three issues identified by the authors as the most important, namely; the optimal configurations in the design, the optimal selection policy in the utilization, and the performance measure in the improvement of these systems. They stated that a reconfigurable manufacturing system (RMS) manages to satisfy customers, with each family of products corresponding to one configuration of the RMS. Xiaobo et al. [17] formulated the problem of selecting the optimal configuration for each product, based on their stochastic model, and devised two algorithms to solve it. They also formulated the selection of the product family to be produced next by the RMS as an optimization problem and devised two procedures to solve it [18]. A semi-Markov process for obtaining the performance measure of an RMS according to the service levels of different product families was formulated and two solution approaches were proposed [19].

Ohiro et al. [20] proposed a modification to improve the work done by Xiaobo et al. [16–19] through involving the overall state of the system, regarding the quantity of orders, in choosing the best configuration instead of associating each product family with only a single optimal configuration regardless of the system state. The results, Ohiro et al. introduced [20], show the superiority of their model.

This research work does not clarify the information needed to define a configuration and assess its feasibility for a certain product family. These types of information are essential for choosing optimal feasible configurations for each product family. Accordingly, this work neglects the effect of the configuration selection on the smoothness and easiness of the subsequent reconfiguration process, which has to be taken into consideration especially when dealing with RMS.

2.2 System performance analysis approach

Spicer et al. [21] defined machining system configuration as the arrangement of the machines (parallel, series, hybrid,…etc.) and the interconnections among them (with or without crossover) (Fig. 3). They showed that, for the same number of machines, pure parallel configurations have the best performance regarding throughput and scalability but with more quality streams than other configurations.

Koren et al. [22] used the same system configuration definition as [21] to demonstrate that the system configuration has a significant impact on six key performance criteria; investment cost of machines and tools, quality, throughput, capacity scalability, number of product types and system conversion time. Yang and Hu [23] studied the effect of different configurations (parallel, series,…etc.) on the system productivity using machine level reliability models for a six CNC using machine manufacturing system. Maier-Speredelozzi [24] studied the effect of different configurations on the manufacturing systems convertibility after developing convertibility metrics for manufacturing systems. Zhong et al. [25] presented methodologies for evaluating system performance with respect to productivity, quality, scalability, and convertibility for different machining system configurations. Maier-Speredelozzi and Hu [26] adapted the analytic hierarchy process (AHP) for use in problems where manufacturing system configurations are selected considering multiple performance criteria.

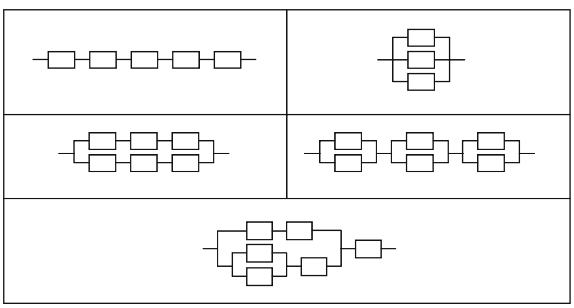

Fig. 3 Alternative system configurations [21]

The trend in the work done by this research group tends to narrow the scope of the system configuration definition to just the physical layout (parallel, series, hybrid,…etc.). This scope should be widened to include other important information such as the configuration topology (e.g., the number of stages, which operations will be performed together within each stage, precedence relationships between stages, number of stations within a stage, types of stations selected) as well as the material handling systems. These other aspects of configuration have a great influence on the overall system performance and accordingly on the configuration selection decisions. In addition, this research work neglects the effect of the configuration selection on the smoothness and easiness of the subsequent reconfiguration process, which is essential as mentioned earlier.

2.3 Multi-part optimal line design

Tang et al. [27] introduced an approach that coupled line-balancing, machine selection, and throughput analysis for designing manufacturing lines that produce multiple parts. They utilized a genetic algorithm formulation to capture the configuration and task allocation for a multiple-parts line and used the minimal ratio of cost to throughput as the criterion for the fitness function. They utilized a throughput analysis engine; namely performance analysis of manufacturing systems (PAMS), which is based on the work done by Yang et al. [28].

This research work neglects the effect of the configuration selection on the smoothness and easiness of the reconfiguration process especially when dealing with RMS. In addition, it only deals with deterministic analysis, which is not sufficient and will affect the evaluation of the alternative configurations from the perspective of smoothness of reconfiguration if taken into consideration.

2.4 Alternative configuration path generation

Son [29] and Son et al. [30] developed a methodology to design economical reconfigurable machining systems (RmSs), given a deterministic demand scenario for the early stage of configuration design. This methodology generates configuration paths for changing demand by considering reconfigurations between demand periods, using a configuration similarity index, as well as the cost efficiencies for each demand period utilizing genetic algorithms (GAs). The used index is based on the level of similarity between any two consecutive configurations and is divided into three components; resource similarity defining commonality in resources between the two configurations, structural similarity defining the precedence relationship between operations, and operation similarity defining operation assignments to stations.

This work deals only with deterministic analysis which is not sufficient when dealing with such a changing environment and expectations of some different scenarios that might occur. In addition, the configuration similarity index defined, although promising, has to be enhanced to be more reflective of the cost, time, and effort of reconfiguration as it is lacking many important elements that would affect the cost and effort of the physical reconfiguration process such as the number of machines to be relocated (not just the difference in the number of machines being used), number of machine modules to be added or removed from the system and the number of flow paths between different stages. In addition, this index does not reflect the different levels of reconfiguration, which will affect the influence of each component on the index evaluation.

2.5 Design methodology for scalable machining systems

Spicer [31] developed a methodology to design scalable machining systems using an integer linear programming (ILP) based partial enumerative procedure. It attempts to optimize the total life cycle cost of the system configuration including investment cost, operating cost in addition to reconfiguration cost. In evaluating the reconfiguration cost, the author assumed that all used reconfigurable machine tools (RMTs) have identical machine bases and all the added or removed modules are identical. In addition, he only considered two main components of reconfiguration cost, namely; labor cost and lost capacity cost.

The assumptions made by the author in this work are far from reality where you can have different types of RMTs accompanied by different types of modules to be used for different process types like milling, drilling, turning, boring,…etc. In addition there are various cost components to be considered when evaluating the reconfiguration cost such as the investment cost of new equipment, the costs involved in the different activities of buying or selling of machines and/or machine modules, the costs of changing the material handling equipment used in different configurations in addition to the cost of training of workers to use the new equipment being added to the system and many other components. Therefore, in this work, the estimation of the reconfiguration cost is not realistic and difficult to validate. It does not provide accurate insight about the amount of effort required to reconfigure the system because it is based on assumptions that are far from realistic technological facts. In addition, this work is based on deterministic analysis, which is not sufficient when dealing with dynamic demand expectations.

2.6 Summary of the literature review

Most of the work done to date, in that field of research, either handled the configuration problem from one perspective of configuration, namely; physical layout [21–26] or dealt with the configuration as a parameter without defining it [16–20]. Another major shortcoming in most of the work done is neglecting the effect of the configuration selection on the smoothness of the subsequent reconfiguration process, which was only tackled by Son [29, 30] but with a very basic configuration similarity model that needs major enhancements, and by Spicer [31] but with an unrealistic reconfiguration cost model.

Another important drawback of the research work that considered the reconfiguration process as part of the configuration selection process [29–31] was dealing with the problem from a deterministic perspective, which is not sufficient especially when taking into consideration the anticipated demand and consequently the expected configuration and reconfiguration requirements.

In conclusion, the smoothness of the anticipated reconfiguration process between any two consecutive configurations should be considered as a part of the configuration selection process. It is difficult to evaluate the exact cost and time of the reconfiguration process. Therefore, there is a need for a metric that provides a way of comparing the cost, effort, and time required to reconfigure the system. This metric will help in comparing different feasible configuration alternatives that are not only capable of satisfying the demand requirements, but will also lead to a smooth reconfiguration process considering the future demand expectations. This metric should consider the different types of activities involved in any reconfiguration process. In addition, the evaluation of the reconfiguration smoothness has to be considered from a stochastic perspective to be able to handle the different future demand expectations.

3 Basic assumptions

3.1 Configuration structure

An RMS should be able to provide exactly the capacity and functionality to satisfy given demands for a group of products. Therefore, RMSs have similar characteristics to dedicated manufacturing systems within a configuration period (CP) because these RMSs should be designed to be dedicated around the products for each CP with exact capacity and functionality. High production volume in addition to high level of capacity scalability, one of the main characteristics of RMS, should be considered when deciding upon an RMS's basic structure.

Flow lines, as one form of RMS structures, can satisfy the high production volume requirements. In addition, flow lines can have stages with multiple parallel stations (machines). This facilitates scalability required for RMSs and synchronizes the different stages in order to maximize utilization of the available machines/stations. This will reduce the effect of breakage of any of the machines thus the use of buffers is not essential. Therefore, the configuration structure of the RMS, used in this paper, will be that of a flow line allowing paralleling of identical stations/machines with identical operation assignment in different stages. Figure 4 shows an example of a selected configuration in a specific configuration period (CP).

Therefore, a selected configuration is a series of stages (groups of parallel identical machines/stations). Each stage contains information such as stage location (relative to the available space for the flow line), machine/station type (stage type) and its selected machine configuration, number of machines/stations and the assigned operation clusters (operations). In Fig. 4, S stands for stage, L stands for location, M stands for machine/station, MCi_j stands for machine configuration j corresponding to machine/station i, and OS stands for an operation clusters setup. An operation clusters setup (OS) is a set (one or more) of operation clusters (OCs) that can be performed together on a specific machine with a specific machine configuration. An operation cluster (OC) is a set of operations (OPs), which are always machined together with a specific order due to different types of constraints. These constraints can be logical constraints (L) such as clustering drilling, reaming and possibly boring operations together when producing a hole. They can also be datum tolerance constraints (D), which means that some operations must be carried out on the same machine to preserve the required tolerance accuracy because of having some operations located and carried out with reference to others. A machine configuration (MC) is a feasible configuration for the machine/station capable of performing a specific operation clusters setup (OS). Only one machine configuration (MC) can be assigned for a machine/station in a selected configuration.

3.2 Configuration periods (CPs)

The criteria of configuration selection should include the smoothness of the anticipated reconfiguration process from an existing configuration to the next anticipated configuration. More than one configuration period (CP) are considered. The number of the CPs is a function of the availability of anticipated information regarding the demand requirements for each of the following CPs. This information includes the product mix (product types) and the production volume requirements for each product within each CP.

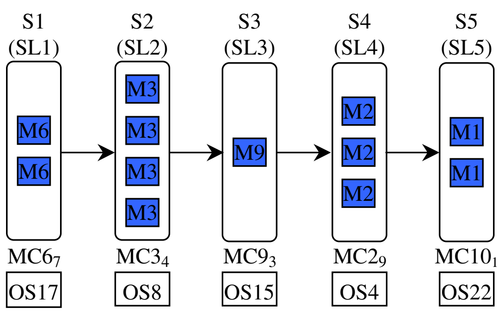

Fig. 4 An example of a selected configuration in a specific configuration period (CP)

More than one scenario for the anticipated demand requirements should be involved in the expectations when dealing with such a dynamic and changing environment. This can only be done through analysis of stochastic nature. Therefore, it is assumed in this paper to have expectations for more than one demand scenario (DS) accompanied by their probability of occurrence for each of the CPs following the current CP, the CP of interest. Figure 5 demonstrates an example of the type of information that can be involved in the stochastic analysis regarding the different demand scenarios (DSs) at each configuration period (CP).

There is only one scenario for the first CP, as can be seen from Fig. 5, because this CP is the current one and the one of interest and at the time of selecting its optimal configuration we should be able to know deterministically the demand requirements. On the other hand, for the CPs following the first one, there might be more than one anticipated demand scenario. DS_{ij} stands for demand scenario number j in configuration period number i, whereas P_{ij} stands for its probability of occurrence. The number in front of each product type represents the production volume requirement of that specific product type within its corresponding demand scenario (DS).

3.3 Input description

3.3.1 Demand scenarios (DSs)

These are the current demand scenario (DS_{11}) and the expected DSs for the following configuration periods (CPs)

CP1

DS_{11}	$P_1 = 1.00$	
Product	A	1000
	B	2000
	C	0

CP2

DS_{21}	$P_{21} = 0.60$	
Product	A	1000
	B	3000
	C	0

DS_{22}	$P_{22} = 0.40$	
Product	A	1500
	B	0
	C	2500

CP3

DS_{31}	$P_{31} = 0.45$	
Product	A	2000
	B	1500
	C	1500

DS_{32}	$P_{32} = 0.30$	
Product	A	2000
	B	0
	C	2500

DS_{33}	$P_{33} = 0.25$	
Product	A	0
	B	3000
	C	1500

CP4

DS_{41}	$P_{41} = 0.50$	
Product	A	3000
	B	1000
	C	2000

DS_{42}	$P_{42} = 0.50$	
Product	A	2000
	B	2500
	C	1500

Fig. 5 Example for demand scenarios (DSs) at different configuration periods CPs

accompanied by their probabilities of occurrence. This should include information regarding the product mix and production volume requirements (Fig. 5). The top-level management supplies such information according to the market requirements and the goals of the enterprise.

3.3.2 Operations (OPs), operation clusters (OCs), & precedence graphs (PGs)

OPs are the sets of operations required to produce each of the required parts. OCs are the sets of operations (OPs) to be machined together. These must be accompanied by operations precedence graphs that define sequential constraints between the different OPs and subsequently between different OCs.

3.3.3 Machines/stations (Ms)

This is the set of alternative reconfigurable machine/station types that are available/obtainable for use in the system. These Ms should be accompanied by the machine configurations (MCs) that can be used with each type.

3.3.4 Machine configurations (MCs)

These are the sets of feasible machine configurations for each machine/station (M) with which it can perform one or more operation clusters (OCs). Only one machine configuration (MC) can be assigned for a machine/station in a selected configuration. These MCs are accompanied by their corresponding feasible OCs and the number of removable modules (axes, spindles, …etc.) that constitute each of them. MCi_j represents the number of removable modules that constitute machine/station i in case of having machine configuration j. In addition, each couple of MCs for the same machine/station (M) should be accompanied by the configuration distance between them in terms of the number of modules that have to be added/removed to/from any of them to obtain the other. MCi_{j2-j1} represents the number of modules added to machine/station i to change from machine configuration j1 to machine configuration j2. MCi_{j1-j2} represents the number of modules removed from machine/station i to change from machine configuration j1 to j2.

3.3.5 Operation time for each M-MC-OS combination

The operation time for a machine/station type (M) with machine configuration (MC) to perform an operation clusters setup (OS), a set of one or more operation clusters (OCs) that can be performed together, should be provided. This enables the estimation of the production rate for this M-MC-OS combination.

3.3.6 Space limitations

The limitations regarding the space allocated for the flow line (configuration) include the length and width available for the configuration. The length can be translated to the number of stage locations (NSL), which determine the maximum number of stages. The width can be translated to the maximum number of parallel machines/stations within a stage.

4 Reconfiguration smoothness (RS)

The anticipated reconfiguration process has to be considered in the process of selection of RMS configurations. The term "*reconfiguration smoothness*", being introduced, reflects the easiness and smoothness of transforming the system from one configuration to the next. This is essential to evaluate in order to be able to select system configurations that not only satisfy the current demand requirements but also will be easily and smoothly reconfigured to satisfy the anticipated demand requirements in future periods within the planning horizon of the manufacturing systems.

A metric was developed in order to measure the level of reconfiguration smoothness (RS). This metric provides a relative measure of the expected cost, time, and effort required to change from one configuration to another rather than estimating the exact time and cost of the reconfiguration process, which is difficult to evaluate. This metric will be used to evaluate the degree of closeness between any two possible consecutive configurations.

The purpose of evaluating the reconfiguration smoothness is to compare different candidate feasible configurations for future CPs based on the easiness of reconfiguration from a current configuration. These RS evaluations will be provided to the higher-level management to support their decision-making regarding the configuration selection.

5 Reconfiguration smoothness (RS) metric

The proposed reconfiguration smoothness metric is composed of three components representing different levels of reconfiguration, namely; market-level reconfiguration smoothness (TRS), system-level reconfiguration smoothness (SRS) and machine-level reconfiguration smoothness (MRS). Accordingly, RS between configurations C_1 and C_2 is defined as follows:

$$RS = \alpha TRS + \beta SRS + \gamma MRS, \tag{5.1}$$

where $\alpha+\beta+\gamma=1$ and the three components TRS, SRS, and MRS all lie between 0 and 1 to make the value of RS lie between 0 and 1. When the two configurations C_1 and C_2 are identical, RS becomes 0.

It is recommended that $\beta>\gamma>\alpha$ as these weights reflect the relative amount of cost, time, and effort required for performing the activities corresponding to the three components associated with any reconfiguration process. Generally, the system-level activities are the most expensive as they mostly involve hard-type reconfiguration activities, e.g., adding/removing of machines/stations. This is followed by the machine-level activities, which involve both hard-type reconfiguration activities, e.g., adding/removing of machine modules and soft-type reconfiguration activities, e.g., changing of operation clusters setup assignments. This is followed by the market-level activities, which mostly involve soft-type reconfiguration activities e.g. buying/selling of machines/stations and/or machine modules. The following sub-sections describe the three components TRS, SRS and MRS in detail.

5.1 Market-level reconfiguration smoothness (TRS)

The market-level reconfiguration smoothness (TRS) reflects the cost, time, and effort required to perform market-level activities that are associated with the reconfiguration process. These types of activities are performed outside the boundaries of the manufacturing system and are mostly soft-type reconfiguration activities. They include marketing activities, bidding activities, financial activities, logistic activities, shipping activities, and all other activities that are associated with: (a) buying/renting of new machines/stations and/or machine modules that are required by the new configuration (C_2), and (b) selling/returning of machines/stations and/or machine modules that were utilized by the previous configuration (C_1) and are no longer required by the new configuration (C_2).

TRS is divided into two components namely; TRS_m representing changes related to use of machines/stations and TRS_d representing changes related to use of machine modules. Therefore, TRS is defined as follows:

$$\mathrm{TRS} = \varepsilon \mathrm{TRS_m} + (1-\varepsilon)\mathrm{TRS_d}, \tag{5.2}$$

where ε lies in [0 1] and,

$$\begin{aligned}\mathrm{TRS_m} &= \delta \frac{\text{Number of Added Machines}}{\text{Total Number of Machines}} + (1-\delta)\frac{\text{Number of Removed Machines}}{\text{Total Number of Machines}} \\ &= \delta \frac{\sum_{Mi \in M_2 - M_1} Mi}{\sum_{Mi \in M_1 \cup M_2} Mi} + (1-\delta)\frac{\sum_{Mi \in M_1 - M_2} Mi}{\sum_{Mi \in M_1 \cup M_2} Mi},\end{aligned} \tag{5.3}$$

$$\begin{aligned}\mathrm{TRS_d} &= \delta \frac{\text{Number of Added Machine Modules}}{\text{Total Number of Machine Modules}} + (1-\delta)\frac{\text{Number of Removed Machine Modules}}{\text{Total Number of Machine Modules}} \\ &= \delta \frac{\sum_{Mi \in M_1 \cap M_2} MCi_{j2-j1}}{\sum_{Mi \in M_1 \cap M_2}\left(MCi_{j1} + MCi_{j2-j1}\right)} + (1-\delta)\frac{\sum_{Mi \in M_1 \cap M_2} MCi_{j1-j2}}{\sum_{Mi \in M_1 \cap M_2}\left(MCi_{j1} + MCi_{j2-j1}\right)},\end{aligned} \tag{5.4}$$

where M_1 and M_2 are the sets of machines/stations that are utilized in configurations C_1 and C_2 respectively and δ lies in [0 1].

It is recommended that $\varepsilon > 0.5$ because the TRS activities associated with machines/stations are more cost, time, and effort consuming than those associated with machine modules. It is recommended as well that $\delta > 0.5$ because, generally, the activities associated with buying/renting are more cost, time, and effort consuming than those associated with selling/returning of either machines/stations or machine modules.

5.2 System-level reconfiguration smoothness (SRS)

The system-level reconfiguration smoothness (SRS) reflects the cost, time, and effort required to perform system-level activities that are associated with the reconfiguration process. These types of activities are performed within the boundaries of the manufacturing system but at a level higher than machines. They mostly include hard-type reconfiguration activities like installation/un-installation of machines/stations and/or whole stages, installation/un-installation of material handling equipment corresponding to installed/un-installed stages, changing the number of material handling flow paths between stages and relocating of material handling equipment according to changes in stage locations. In addition, they include soft-type reconfiguration activities like increasing/decreasing the number of assigned operators.

All these activities, hard and soft, are included in addition to all other activities that are associated with: (a) adding/removing of machines/stations and/or whole stages to/from the system, (b) moving (relocating) of machines/stations and/or whole stages from their original location to other locations within the system, and (c) increasing/decreasing number of material flow paths between stages which is a function of the number of machines/stations in each stage.

SRS is divided into three components namely; SRS_s representing changes related to stages, SRS_m representing changes related to machines/stations and SRS_f representing changes related to number of material flow paths. Therefore, SRS is defined as follows:

$$SRS = \phi SRS_s + \varphi SRS_m + \lambda SRS_f, \tag{5.5}$$

where $\varphi+\phi+\lambda=1$ and,

$$SRS_s = \pi\frac{\text{Number of Installed Stage Types}}{\text{Total Number of Stage Types}} + (1-\pi)\frac{\text{Number of Un} - \text{Installed Stage Types}}{\text{Total Number of Stage Types}}$$

$$= \pi\frac{\sum_{Si\in S_2-S_1} Si + \sum_{Si\in S_m} Si}{\sum_{Si\in S_1\cup S_2} Si} + (1-\pi)\frac{\sum_{Si\in S_1-S_2} Si + \sum_{Si\in S_m} Si}{\sum_{Si\in S_1\cup S_2} Si}, \tag{5.6}$$

$$SRS_m = \pi\frac{\text{Number of Installed Machines}}{\text{Total Number of Machines}} + (1-\pi)\frac{\text{Number of Un} - \text{Installed Machines}}{\text{Total Number of Machines}}$$

$$= \pi\frac{\sum_{Mi\in M_2-M_1} Mi + \sum_{Mi\in M_m} Mi}{\sum_{Mi\in M_1\cup M_2} Mi} + (1-\pi)\frac{\sum_{Mi\in M_1-M_2} Mi + \sum_{Mi\in M_m} Mi}{\sum_{Mi\in M_1\cup M_2} Mi} \tag{5.7}$$

$$SRS_f = \theta\frac{\text{Number of Added Material Flow Paths}}{\text{Total Number of Material Flow Paths}} + (1-\theta)\frac{\text{Number of Removed Material Flow Paths}}{\text{Total Number of Material Flow Paths}}$$

$$= \theta\frac{\sum_{i=1}^{NS_2-1}\max[(NM_{i_2} * NM_{i+1_2} - NM_{i_1} * NM_{i+1_1}), 0]}{\sum_{i=1}^{\max(NS_1,NS_2)-1}\max[(NM_{i_1} * NM_{i+1_1}), (NM_{i_2} * NM_{i+1_2})]}$$

$$+(1-\theta)\frac{\sum_{i=1}^{NS_1-1}\max[(NM_{i_1} * NM_{i+1_1} - NM_{i_2} * NM_{i+1_2}), 0]}{\sum_{i=1}^{\max(NS_1,NS_2)-1}\max[(NM_{i_1} * NM_{i+1_1}), (NM_{i_2} * NM_{i+1_2})]}, \tag{5.8}$$

where S_1 and S_2 are the sets of stage types that are utilized in configurations C_1 and C_2 respectively, S_m is the set of stages that are moved (relocated) in reconfiguration from configuration C_1 to configuration C_2, S_i is any stage type i, M_m is the set of machines/stations that are moved (relocated) in reconfiguration from configuration C_1 to configuration C_2, NS_1 and NS_2 are the numbers of stages used in configurations C_1 and C_2 respectively, NM_{i_1} and NM_{i_2} are the numbers of machines in stage i in configurations C_1 and C_2 respectively and the weights π, υ & θ lie in [0 1].

It is recommended that φ>ϕ>λ as these weights reflect the relative amount of cost, time, and effort for performing activities corresponding to the four SRS components. Generally, activities associated with changes related to stages are the most expensive with regards to time, cost, and effort as they involve both hard-type reconfiguration concerning the type of material handling equipment used and soft-type reconfiguration concerning the number of operators assigned. This is followed by the activities associated with changes related to machines/stations, which is followed by activities associated with changes in material flow paths.

It is recommended that π>0.5 because, generally, the activities associated with adding a new/relocated stage or machine are more cost, time, and effort consuming than those associated with removing a new/relocated stage or machine because adding involves calibration, setup and other ramp up activities. It is recommended, as well that θ>0.5 because increasing the number of flow paths between stages is obviously more complicated with regards to material handling design and installation than decreasing them.

From the above analysis, regarding the system-level reconfiguration smoothness (SRS), there is a need for information about the location of each stage in each of the two consecutive configurations and the number of machines or whole stages that have to be moved/relocated in order to reconfigure from configuration C_1 to configuration C_2. Such information is available if a specific reconfiguration execution plan is known. Therefore, some rules should be set for deciding how the reconfiguration will take place at the system-level. Sub-section 5.4 presents some rules that have been developed to guide reconfiguration planning.

5.3 Machine-level reconfiguration smoothness (MRS)

The machine-level reconfiguration smoothness (MRS) reflects the cost, time, and effort required to perform machine-level activities that are associated with the reconfiguration process. These types of activities are performed inside the boundaries of the manufacturing system and are all within the limits at the machine-level. They include hard-type reconfiguration activities like adding/removing of machine modules and/or machine fixtures to/from pre-existing machines/stations in the system. In addition, they include soft-type reconfiguration activities like adding/removing operation clusters setup assignments to/from pre-existing machines/stations with same machine configurations and accordingly changing of setups and control systems for these machines/stations.

All these activities, hard and soft, are included in addition to all other activities that are associated with: (a) adding/removing of machine modules due to reconfiguration of machines/stations that will remain in the system, and (b) adding/removing of operation clusters setup assignments to/from machines/stations that will remain in the system keeping their same configurations. MRS is divided into two components namely; MRS_d representing changes related to utilization of machine modules (changes in machine configurations) and MRS_o representing changes related to operation cluster assignments. Therefore, MRS is defined as follows:

$$\mathrm{MRS} = \nu \mathrm{MRS_d} + (1-\nu)\mathrm{MRS_o}, \tag{5.9}$$

where ν lies in [0 1] and,

$$\begin{aligned}\mathrm{MRS_d} &= \sigma \frac{\text{Number of Added Machine Modules}}{\text{Total Number of Machine Modules}} + (1-\sigma)\frac{\text{Number of Removed Machine Modules}}{\text{Total Number of Machine Modules}} \\ &= \sigma \frac{\sum_{Mi\in M_1\cap M_2} MCi_{j2-j1}}{\sum_{Mi\in M_1\cap M_2}\left(MCi_{j1}+MCi_{j2-j1}\right)} + (1-\sigma)\frac{\sum_{Mi\in M_1\cap M_2} MCi_{j1-j2}}{\sum_{Mi\in M_1\cap M_2}\left(MCi_{j1}+MCi_{j2-j1}\right)},\end{aligned} \tag{5.10}$$

$$\begin{aligned}\mathrm{MRS_o} &= \sigma \frac{\text{Number of OS Assignments Added to Machines Keeping their Configurations}}{\text{Total Number of OS Assignments for Machines Keeping their Configurations}} \\ &\quad +(1-\sigma)\frac{\text{Number of OS Assignments Removed from Machines Keeping their Configurations}}{\text{Total Number of OS Assignments for Machines Keeping their Configurations}} \\ &= \sigma \frac{\sum_{osj\in OS_{i,k}(2)-OS_{i,k}(1)\&Mi\in M_1\cap M_2} OSj}{\sum_{osj\in OS_{i,k}(1)\cup OS_{i,k}(2)\&Mi\in M_1\cap M_2} OSj} + (1-\sigma)\frac{\sum_{osj\in OS_{i,k}(1)-OS_{i,k}(2)\&Mi\in M_1\cap M_2} OSj}{\sum_{osj\in OS_{i,k}(1)\cup OS_{i,k}(2)\&Mi\in M_1\cap M_2} OSj},\end{aligned} \tag{5.11}$$

where $OS_{i,k}$ (1) and $OS_{i,k}$ (2) are the sets of operation clusters setups that are assigned to machine/station i with machine configuration k in configurations C_1 and C_2 respectively and σ lies in [0 1].

It is recommended that ν>0.5 because the MRS activities associated with machine reconfiguration (adding/removing of modules) already encompass the activities associated with changes in operation cluster assignments and more. It is recommended, as well, that σ>0.5 because, generally, the activities associated with adding either machine modules or operation cluster assignments are more cost, time, and effort consuming than those associated with removing of either machine modules or operation cluster assignments.

Generally, the weights to be assigned for the various metric components are best left for the user, e.g., the facilities planning engineer, to determine according to the situation. This is due to the fact that the relative influence, on reconfiguration smoothness, of the different types and levels of reconfiguration activities, expressed by these weights, is case-based and cannot be generalized to accommodate all practical situations. It is also function of the infrastructure setup in the facility and the degree of modularity of the controllers being used on both the system-level and the machine-level. For example, it is easier to relocate a machine in a facility where the electric supply infrastructure is modular. However, the suggested recommendations provide guidelines for determining values of these weights for the majority of situations.

5.4 Reconfiguration planning

There are normally different alternative plans for reconfiguring the manufacturing system. There is a need for some rules to help plan the reconfiguration process and, accordingly, determine some parameters required to fully define the reconfiguration smoothness metric (RS). In addition, these rules will help the decision-makers with regards to the reconfiguration process and how it can be pursued. Minimizing the effort of reconfiguration must be taken into consideration in developing these rules. The following are the rules developed for reconfiguration planning in the order of application to break possible ties:

- Maximize the number of stage types that keep their locations.
- Maximize the number of machines that keep their locations.
- Minimize the number of empty stage locations between consecutive stages.
- Maximize the number of machines that keep their configurations.
- Maximize the number of machines that keep their operation clusters setup assignment.

The first two rules are concerned with minimizing the physical movement/relocation of stage types and machines respectively, which are considered system-level reconfiguration activities (the most expensive reconfiguration activities). The space limitations in terms of the available stage locations have to be considered when applying the first rule. The third rule, on the other hand, is concerned with minimizing the material handling effort by minimizing the distances between consecutive stages. Finally, the fourth and fifth rules are concerned with minimizing the machine-level reconfiguration activities whether it is hard (machine reconfiguration) or soft (change in operation clusters setup assignments).

5.5 Example on reconfiguration planning & RS evaluation

An example is presented to demonstrate the concept of reconfiguration planning, implementation of the developed rules and the use of the reconfiguration smoothness metric.

Consider the system reconfiguration example presented in Fig. 2. First, the reconfiguration planning rules are applied to decide the steps of reconfiguration from C_1 to C_2. The first rule aims at maximizing the number of stage types that keep their locations. Stage type M6 may be kept in its location (SL3) and stage type M3 moved from SL4 to the next location (SL5) in order to allow stage type M2 to be placed in location SL4. Alternatively, stage type M3 may be kept in SL4 and stage type M6 moved from SL3 to the prior location (SL2) in order to allow stage type M2 to be placed in location SL3. Figure 6 demonstrates the two alternative reconfiguration possibilities. The application of the first rule is not sufficient for differentiating the two because for both, only one stage type will keep its location. Therefore, the second rule is used. This rule aims at maximizing the number of machines that keep their locations. Here, the first alternative is better because it means keeping two machines of type M6 in their location while the other alternative means keeping only one machine of type M3 in its location. Therefore the first reconfiguration alternative is chosen as shown in Fig. 6.

Now, the reconfiguration smoothness between C_1 and C_2 can be evaluated, according to the first reconfiguration alternative, using the metric. In doing that, values were chosen for the different metric weights according to the suggested recommendations.

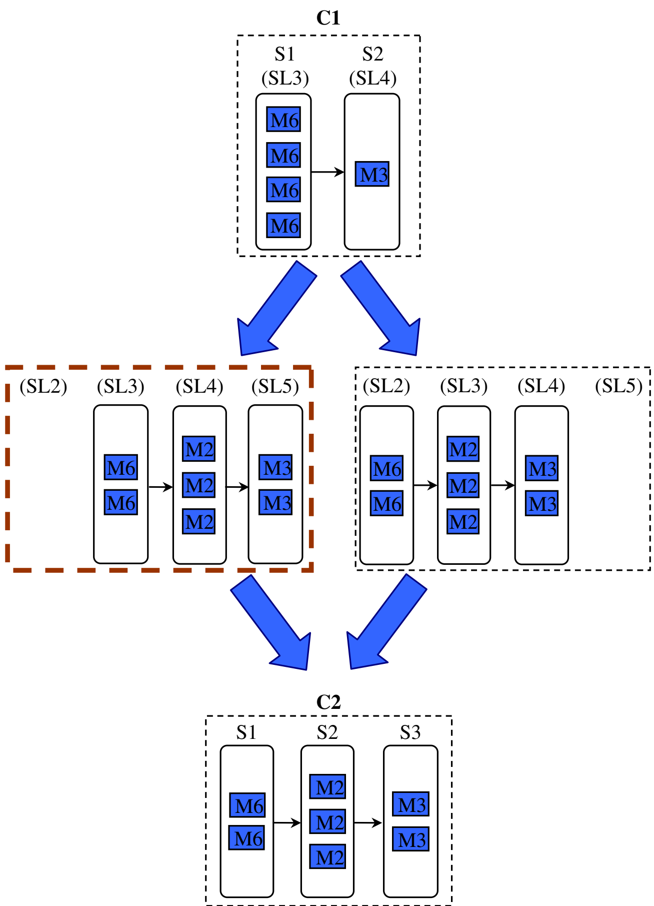

Fig. 6 Alternative reconfiguration plans

RS evaluation of (C_1–C_2) for the first reconfiguration alternative:

- Market-level reconfiguration smoothness (TRS) [Eqs. (5.2)–(5.4)]:

$$TRS_m = \frac{2}{3}\left(\frac{4}{9}\right) + \frac{1}{3}\left(\frac{2}{9}\right) = \frac{10}{27},$$

$$TRS_d = \frac{2}{3}\left(\frac{1+2(1)}{(3+1)+2(1+1)}\right) + \frac{1}{3}\left(\frac{0}{(3+1)+2(1+1)}\right) = \frac{1}{4}$$

$$\therefore TRS = \frac{2}{3}\left(\frac{10}{27}\right) + \frac{1}{3}\left(\frac{1}{4}\right) = \frac{107}{324} = 0.3302.$$

- System-level reconfiguration smoothness (SRS) [Eqs. (5.5)–(5.8)]:

$$SRS_s = \frac{2}{3}\left(\frac{1+1}{3}\right) + \frac{1}{3}\left(\frac{0+1}{3}\right) = \frac{5}{9},$$

$$SRS_m = \frac{2}{3}\left(\frac{4+1}{9}\right) + \frac{1}{3}\left(\frac{2+1}{9}\right) = \frac{13}{27},$$

$$SRS_f = \frac{2}{3}\left(\frac{(6-4)+(6-0)}{6+6}\right) + \frac{1}{3}\left(\frac{0}{6+6}\right) = \frac{4}{9}$$

$$\therefore SRS = \frac{3}{6}\left(\frac{5}{9}\right) + \frac{2}{6}\left(\frac{13}{27}\right) + \frac{1}{6}\left(\frac{4}{9}\right) = \frac{83}{162} = 0.5123.$$

- Machine-level reconfiguration smoothness (MRS) [Eqs. (5.9)–(5.11)]:

$$MRS_d = \frac{2}{3}\left(\frac{1+2(1)}{(3+1)+2(1+1)}\right) + \frac{1}{3}\left(\frac{0}{(3+1)+2(1+1)}\right) = \frac{1}{4}, \quad MRS_o = 0$$

$$\therefore MRS = \frac{2}{3}\left(\frac{1}{4}\right) + \frac{1}{3}(0) = \frac{1}{6} = 0.1667.$$

- Overall reconfiguration smoothness (RS) [Eq. (5.1)]:

$$RS = \frac{1}{6}\left(\frac{107}{324}\right) + \frac{3}{6}\left(\frac{83}{162}\right) + \frac{2}{6}\left(\frac{1}{6}\right) = 0.3668$$

The different components of the RS metric according to the second reconfiguration alternative can be evaluated and compared to the previous evaluations to validate the merits of using the reconfiguration planning rules.

RS evaluation of (C_1–C_2) for the second reconfiguration alternative:

- Market-level reconfiguration smoothness (TRS) [Eqs. (5.2)–(5.4)]:

$$RS = \frac{1}{6}\left(\frac{107}{324}\right) + \frac{3}{6}\left(\frac{83}{162}\right) + \frac{2}{6}\left(\frac{1}{6}\right) = 0.3668$$

- System-level reconfiguration smoothness (SRS) [Eqs. (5.5)–(5.8)]:

$$SRS_s = \frac{2}{3}\left(\frac{1+1}{3}\right) + \frac{1}{3}\left(\frac{0+1}{3}\right) = \frac{5}{9},$$

$$SRS_m = \frac{2}{3}\left(\frac{4+2}{9}\right) + \frac{1}{3}\left(\frac{2+2}{9}\right) = \frac{16}{27},$$

$$SRS_f = \frac{2}{3}\left(\frac{(6-4)+(6-0)}{6+6}\right) + \frac{1}{3}\left(\frac{0}{6+6}\right) = \frac{4}{9}$$

$$SRS = \frac{3}{6}\left(\frac{5}{9}\right) + \frac{2}{6}\left(\frac{16}{27}\right) + \frac{1}{6}\left(\frac{4}{9}\right) = \frac{89}{162} = 0.5494.$$

- Machine-level reconfiguration smoothness (MRS) [Eqs. (5.9)–(5.11)]:

$$MRS_d = \frac{2}{3}\left(\frac{1+2(1)}{(3+1)+2(1+1)}\right) + \frac{1}{3}\left(\frac{0}{(3+1)+2(1+1)}\right) = \frac{1}{4}, \quad MRS_o = 0 MRS = \frac{2}{3}\left(\frac{1}{4}\right) + \frac{1}{3}(0) = \frac{1}{6} = 0.1667.$$

- Overall reconfiguration smoothness (RS) [Eq. (5.1)]:

$$RS = \frac{1}{6}\left(\frac{107}{324}\right) + \frac{3}{6}\left(\frac{89}{162}\right) + \frac{2}{6}\left(\frac{1}{6}\right) = 0.3853.$$

The results of evaluating the RS metric for both alternatives show the superiority of the first reconfiguration alternative. Although, both alternatives gave the same values for the TRS and MRS components, as expected, the values of the SRS component caused the distinction between both alternatives since the first alternative leads to fewer machine relocations. This illustrates the merits of the developed reconfiguration planning rules that arrived at the same decision of choosing the first alternative.

6 Stochastic reconfiguration smoothness

The probability theory is utilized, when there is more than one possibility (scenario) for the next configuration (see Sub-Section 3.2), in order to evaluate the expected value of reconfiguration smoothness (RS) between the two consecutive periods for the specific configurations selected for each demand scenario (DS). Figure 7 gives an example of evaluating the RS stochastically where C_{ij} represents the configuration selected for demand scenario DS_{ij}. C_{ij} will be in the form presented previously in Fig. 4.

7 Case study

7.1 Example part

In order to demonstrate the use of the developed metric and perform sensitivity analysis, a case study is presented using an example part (CAM-I[1], 1986 test part ANC-101) that is widely used in the literature [32–37]. Figure 8 shows part ANC-101 and its features. Table 4 (Appendix A) provides the different features' description, the operations required to produce these features and their IDs, the tool access direction (TAD) candidates and the tool candidates for each operation.

Figure 9 shows the operations precedence graph according to the data in Table 4 (Appendix A). As shown in Fig. 9, there are some operations that have to be performed together (clustered) on the same machines due to either logical constraints (L) or datum tolerance constraints (D). Figure 10 demonstrates the precedence relationship between different operation clusters (OCs), which are listed in Table 1.

A basic part (ANC-90) was developed as a variant of the example part (ANC-101). This part is similar to the part ANC-101 but with five fewer features. Figure 11 shows part ANC-90 and its accompanying features. Figure 12 shows the operations precedence graph of part ANC-90

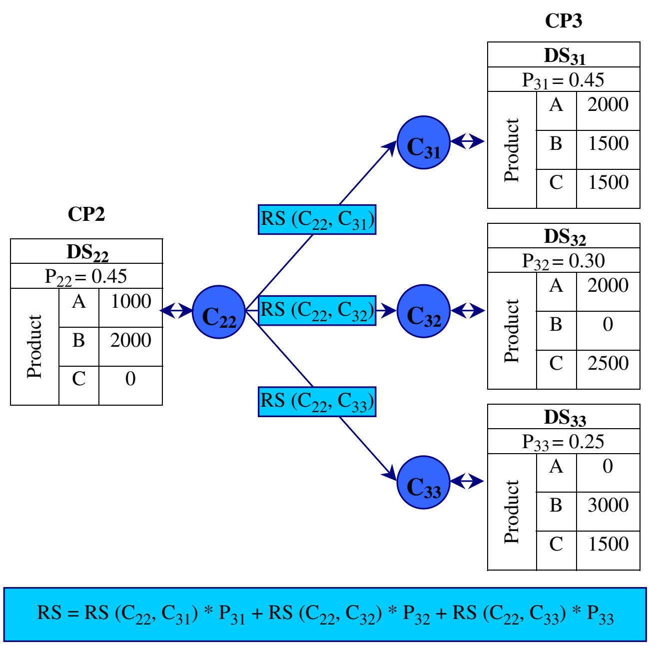

Fig. 7 An example of stochastic evaluation of reconfiguration smoothness (RS)

[1] CAM-I: Computer Aided Manufacturing-International

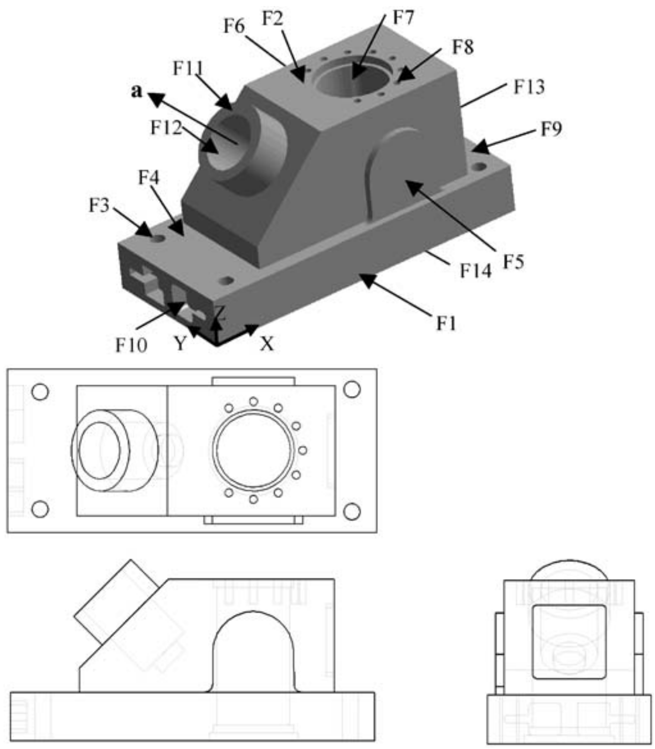

Fig. 8 Part ANC-101 and its features (CAM-I, 1986 test part)

according to the data in Table 5 (Appendix A). Figure 13 represents the operation clusters precedence graph for which all the OCs are listed in Table 2.

Table 3 includes a listing of the available/obtainable resources in terms of reconfigurable machines (Ms) in

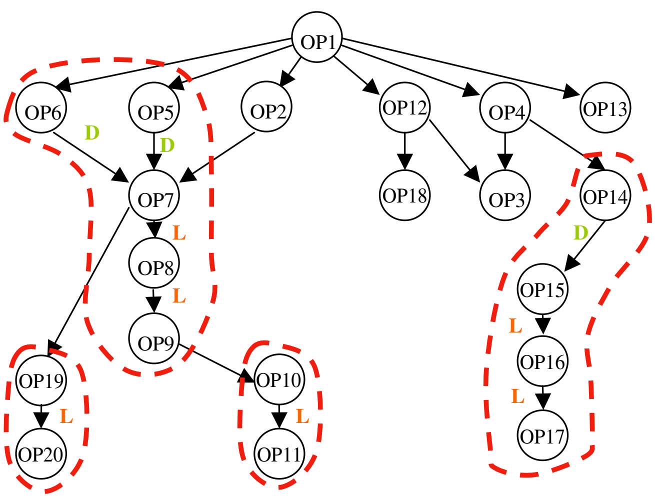

Fig. 9 Operations precedence graph for part ANC-101

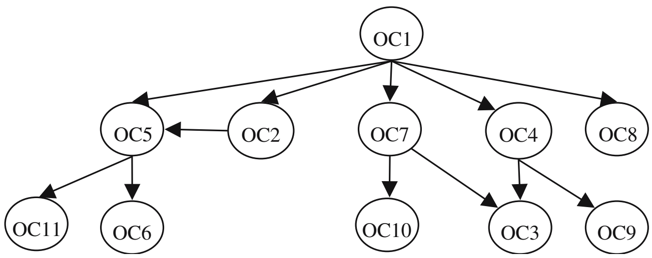

Fig. 10 Operation clusters precedence graph for part ANC-101

addition to the sets of feasible machine configurations (MCs) for each of these Ms accompanied by the number of removable modules for each M-MC combination.

Table 6 (Appendix A) provides the time required for performing different operation clusters setups (OSs) using different feasible M-MC combinations and the production rates information accordingly. Note that the production rate for the machines with multi-spindle configurations is a multiple of that of the same machine with a single-spindle configuration although they have the same standard time.

7.2 Case description

Now, all the processing information for both parts (ANC-90 & ANC-101), the information about the available/obtainable resources, and the production rates of using these resources to produce the different operation clusters setups for the two parts are well defined.

Consider the case of having a first configuration period (CP1) where part ANC-90 (part A) is to be produced with a rate of 120 parts/hour followed by a second configuration period (CP2) where part ANC-101 (part B) is to be produced with a rate of 180 parts/hour. Figure 14 demonstrates two possible reconfiguration scenarios from a first configuration (C_1) capable of satisfying the demand requirements of CP1 (part A at 120 parts/hour) to two possible candidates for a second configuration (C_{21} & C_{22}) that are capable of satisfying the requirements of CP2 (part B at 180 parts/hour). The developed RS metric will be evaluated for the two reconfiguration scenarios in order to choose the best in terms of reconfiguration smoothness.

Table 1 Operation clusters definitions for part ANC-101

Operation cluster	Operations
OC1	[OP1]
OC2	[OP2]
OC3	[OP3]
OC4	[OP4]
OC5	[OP5, OP6, OP7, OP8, OP9]
OC6	[OP10, OP11]
OC7	[OP12]
OC8	[OP13]
OC9	[OP14, OP15, OP16, OP17]
OC10	[OP18]
OC11	[OP19, OP20]

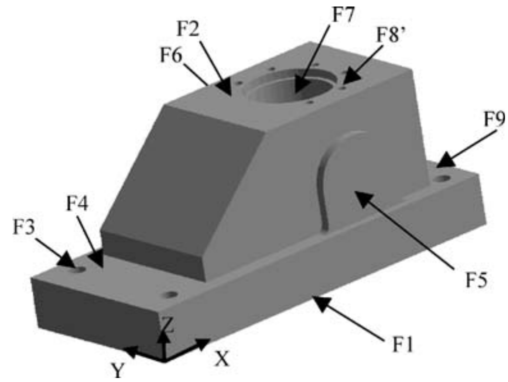

Fig. 11 Part ANC-90 and its features

The reconfiguration planning rules were, first, implemented to decide the reconfiguration steps from C_1 to each of the two configurations C_{21} and C_{22}. Starting with the original configuration (C_1), the first rule aims at maximizing the number of stage types that keep their locations. In both reconfiguration scenarios, all four stage types of configuration (C_1) can keep their locations so there is no need to proceed to the following rules. Therefore, the locations of the stages forming both configurations C_{21} and C_{22} will be as indicated in Fig. 14. That means that there will be no stage or machine relocation in the reconfiguration process for both scenarios.

7.3 Reconfiguration smoothness evaluation results

Now, the reconfiguration smoothness metric can be evaluated between configuration C_1 and each of configurations C_{21} and C_{22}. Values for the different metric weights were chosen according to the suggested recommendations.

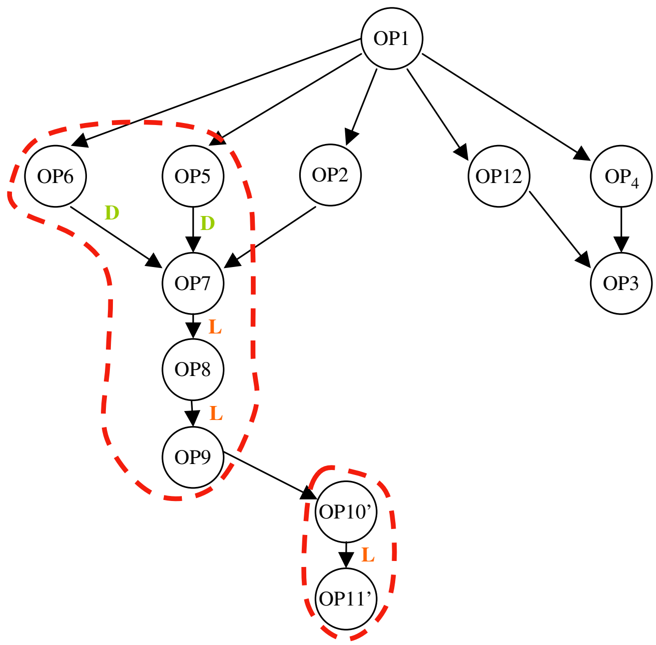

Fig. 12 Operations precedence graph for part ANC-90

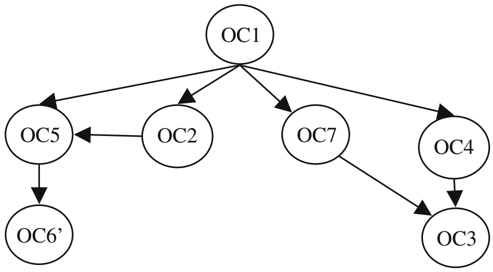

Fig. 13 Operation clusters precedence graph for part ANC-90

Details of the RS evaluations are provided in Appendix B. A summary of the results is as follows:

RS evaluation for the first reconfiguration scenario (C_1–C_{21}):

- Market-level reconfiguration smoothness (TRS)= 0.2515.
- System-level reconfiguration smoothness (SRS)= 0.2963.
- Machine-level reconfiguration smoothness (MRS)= 0.1413.
- Overall reconfiguration smoothness (RS)=0.2371.

Table 2 Operation clusters definitions for part ANC-90

Operation cluster	Operations
OC1	[OP1]
OC2	[OP2]
OC3	[OP3]
OC4	[OP4]
OC5	[OP5, OP6, OP7, OP8, OP9]
OC6'	[OP10′, OP11′]
OC7	[OP12]

RS evaluation for the second reconfiguration scenario (C_1–C_{22}):

- Market-level reconfiguration smoothness (TRS)= 0.2830.
- System-level reconfiguration smoothness (SRS)= 0.3186.
- Machine-level reconfiguration smoothness (MRS)= 0.1413.
- Overall reconfiguration smoothness (RS)=0.2535.

It is clear, from the RS results shown above, that the first reconfiguration scenario is smoother than the second one. For both scenarios, the machine-level reconfiguration was the smoothest (MRS has the least value) because the number of machine reconfiguration activities for machines remaining in the system was limited. In addition, the change in operation cluster assignments, for the machines that kept their configurations, was small. The market-level reconfiguration was less smooth because there is a need for many new machines to be added to the system, which will lead to a large number of market-level activities (examples of these activities are mentioned in Sub-Section 5.1). However, the market-level activities involved with the machine modules are limited. The system-level reconfiguration smoothness was the worst in both scenarios because of the fact that there are changes with regards to addition of stages, addition of new machines and addition of more flow paths between different stages. Therefore all the components involved in the SRS were influential on the final value of the SRS, which was the highest between the three levels.

Both scenarios were identical on the machine-level reconfiguration due to identical reconfiguration processes being involved for the machines remaining in the system. However, on both the market-level and the system-level, reconfiguration smoothness values for the first scenario were better than the second one due to the fact that the

Table 3 Available/obtainable resources description

Machine (M)		Machine configuration (MC)		Number of removable modules
Code	Description	Code	Description	
M1	Reconfigurable horizontal milling machine	$MC1_1$	3-axis with 1 spindle	3
		$MC1_2$	3-axis with 2 spindles	4
		$MC1_3$	3-axis with 3 spindles	5
		$MC1_4$	3-axis with 4 spindles	6
		$MC1_5$	4-axis with 1 spindle	4
M2	Reconfigurable drilling press	$MC2_1$	1 spindle	1
		$MC2_2$	2 spindles	2
		$MC2_3$	3 spindles	3
		$MC2_4$	4 spindles	4
M3	Reconfigurable boring machine	$MC3_1$	1 spindle	1

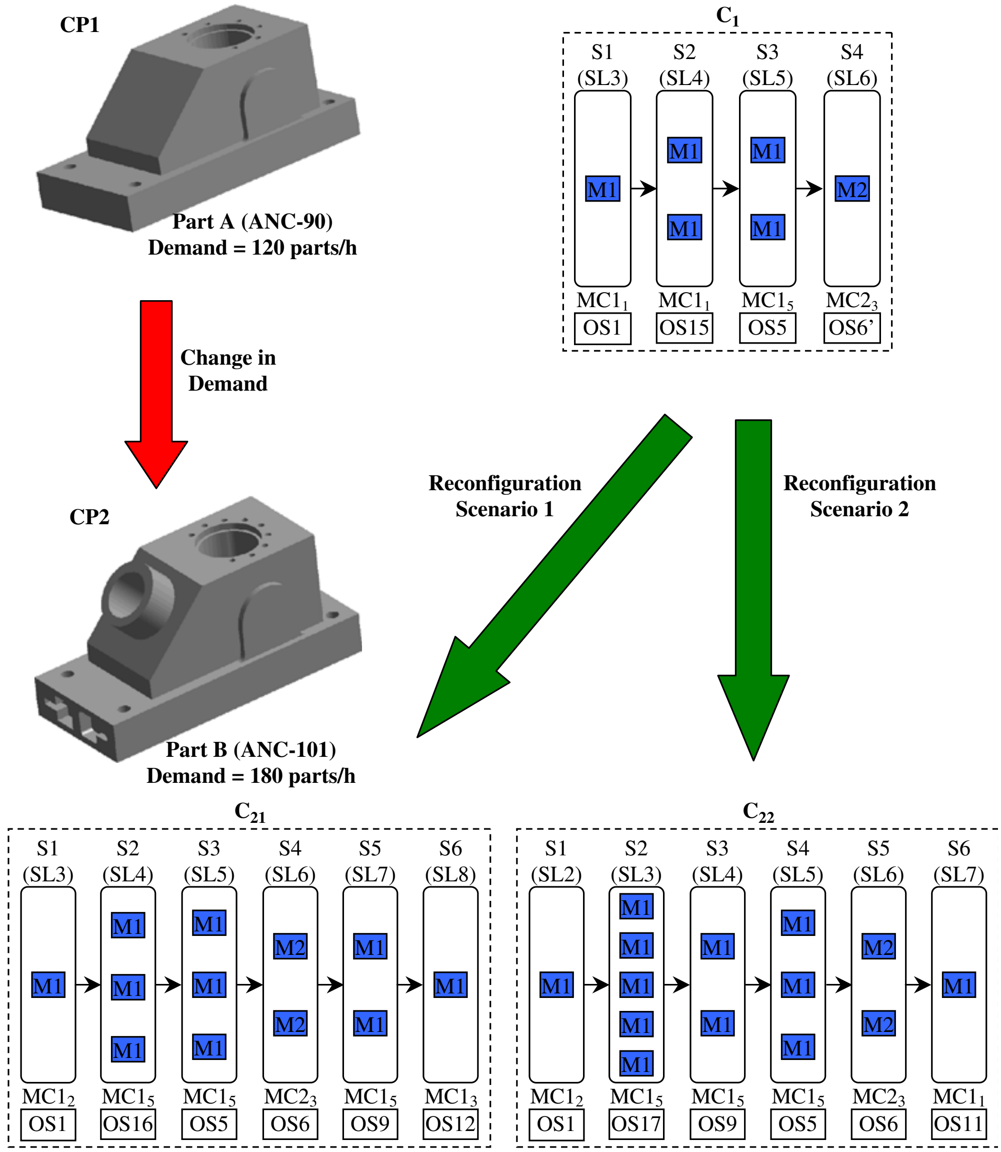

Fig. 14 Two possible reconfiguration scenarios for the case study

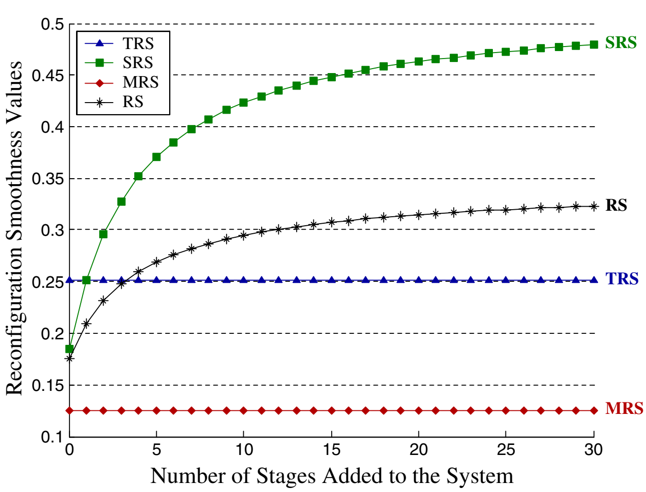

Fig. 15 The effect of adding stages to the system on RS values

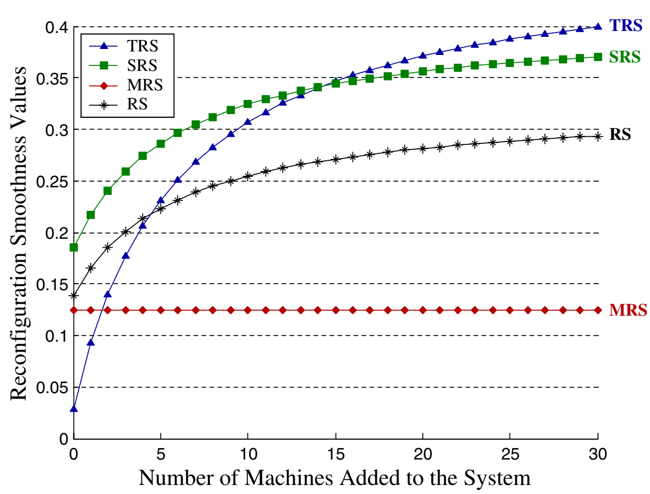

Fig. 16 The effect of adding machines to the system on RS values

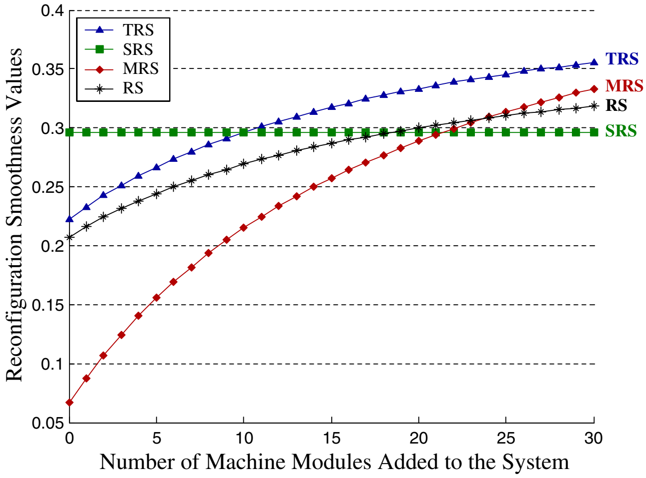

Fig. 17 The effect of adding machine modules to the system on RS values

number of machines being added to the system was less in the first scenario.

In conclusion, the recommendations will be to proceed with the first reconfiguration scenario (C_1–C_{21}) rather than the second one (C_1–C_{22}), which will be more costly in time, effort and money. This means that, if the configuration selection decision at this stage is based only on reconfiguration smoothness, then configuration C_{21} will be selected for the second configuration period.

7.4 Sensitivity analysis

The first reconfiguration scenario was used to perform sensitivity analysis in order to demonstrate the effect of changing the metric parameters on the different reconfiguration smoothness values; TRS, SRS, MRS and the total RS value. Figures 15, 16, 17 show the effect of changing the number of stages, the number of machines and the number of machine modules added to the system on these RS values respectively.

Figure 15 shows that the SRS is the only component that is sensitive to the change in the number of stages added to the system, which is expected since this type of change only affects the physical reconfiguration activities at the system level. Therefore, the more weight assigned to the SRS in the RS metric (the higher the value of α), the more sensitive the overall RS value will be to the change in the number of stages.

Figure 16 shows that the TRS value is the most sensitive to the number of machines being added because this number is the major driver for most of the market-level activities associated with a reconfiguration process. The MRS, on the other hand, is insensitive to this number, as it has no effect on the reconfiguration activities performed at the machine-level.

Figure 17 shows that the MRS value is the most sensitive to the number of machine modules added to the system due to the fact that this number reflects the effort and time of machine-level reconfiguration. The SRS, on the other hand, is insensitive to this number as the system level is concerned with higher-level activities of reconfiguration.

The sensitivity of the various RS components (TRS, SRS, MRS, or RS) to the addition of system modules (stages, machines, or machine modules) decreases as the number of added modules increases as shown in Figs. 15, 16, 17. This is due to the fact that the developed metric is based on evaluations that are relative to the total number of modules available in the system. This further illustrates the merits of the developed metric as it takes into consideration the scale of change involved in the reconfiguration process.

8 Conclusions and future work

It is essential to consider the influence of manufacturing systems configuration selection on the smoothness of the subsequent reconfiguration process. This paper introduced the term "*reconfiguration smoothness*" and presented a metric to evaluate it. This metric reflects the activities associated with different levels of reconfiguration; market-level, system-level, and machine-level. The developed metric considers the influence of individual reconfiguration activities at more than one reconfiguration level, each from its perspective. For example, the addition/removal of machines affects both the market-level (TRS) and the system-level (SRS) and the addition/removal of machine modules affects both the market-level (TRS) and the machine-level (MRS).

Rules were developed to guide the decisions concerning the execution of the reconfiguration process, which was called "*reconfiguration planning*". The concept of stochastic evaluation of the reconfiguration smoothness was introduced by considering the different anticipations for future demand. A case study was presented to demonstrate the use of the reconfiguration planning rules and the developed RS metric. Sensitivity analysis was performed to show the effect of changing different metric parameters on its value and accordingly on the configuration selection decisions.

The proposed RS metric provides a quantitative assessment for characteristics of manufacturing systems that make certain feasible candidate configurations inherently better than others in terms of smoothness of reconfiguration from a current configuration as illustrated by the case study. These RS evaluations can be provided to the higher-level management to support their decision-making regarding the configuration selection

The proposed method and metric consider only the next production planning period. An approach capable of evaluating the reconfiguration smoothness over all future configuration periods, taking into consideration the stochastic nature of the anticipated configurations corresponding to future demand scenarios, represents a natural extension of the proposed methodology.

Appendix A: Example part processing information

Table 4 Operations data for part ANC-101

Feature	Description	Operation	Op. ID	TAD candidates	Tool candidates
F1	Planar surface	Milling	OP1	+Z	C6, C7, C8
F2	Planar surface	Milling	OP2	−Z	C6, C7, C8
F3	Four holes arranged as a replicated feature	Drilling	OP3	+Z, −Z	C2
F4	A step	Milling	OP4	+X, −Z	C6, C7
F5	A protrusion (rib)	Milling	OP5	+Y, −Z	C7, C8
F6	A protrusion	Milling	OP6	−Y, −Z	C7, C8
F7	A compound hole	Drilling	OP7	−Z	C2, C3, C4
		Reaming	OP8		C9
		Boring	OP9		C10
F8	Nine holes arranged in a replicated feature	Drilling	OP10	−Z	C1
		Tapping	OP11		C5
F9	A step	Milling	OP12	−X, −Z	C6, C7
F10	Two pockets arranged as a replicated feature	Milling	OP13	+X	C6, C7. C8
F11	A boss	Milling	OP14	−a	C7, C8
F12	A compound hole	Drilling	OP15	−a	C2, C3, C4
		Reaming	OP16		C9
		Boring	OP17		C10
F13	A pocket	Milling	OP18	−X	C7, C8
F14	A compound hole	Reaming	OP19	+Z	C9
		Boring	OP20		C10

Table 5 Operations data for part ANC-90

Feature	Description	Operation	Op. ID	TAD candidates	Tool candidates
F1	Planar surface	Milling	OP1	+Z	C6, C7, C8
F2	Planar surface	Milling	OP2	−Z	C6, C7, C8
F3	Four holes arranged as a replicated feature	Drilling	OP3	+Z, −Z	C2
F4	A step	Milling	OP4	+X, −Z	C6, C7
F5	A protrusion (rib)	Milling	OP5	+Y, −Z	C7, C8
F6	A protrusion	Milling	OP6	−Y, −Z	C7, C8
F7	A compound hole	Drilling	OP7	−Z	C2, C3, C4
		Reaming	OP8		C9
		Boring	OP9		C10
F8′	Six holes arranged in a replicated feature	Drilling	OP10′	−Z	C1
		Tapping	OP11′		C5
F9	A step	Milling	OP12	−X, −Z	C6, C7

Table 6 Time and production rate information for different M-MC-OS combinations

Operation clusters setup (OS)		Standard time in seconds (Production rate in parts/hour)								
		M1					M2			
Code	Operation clusters (OCs)	$MC1_1$	$MC1_2$	$MC1_3$	$MC1_4$	$MC1_5$	$MC2_1$	$MC2_2$	$MC2_3$	$MC2_4$
OS1	[OC1]	30 (120)	30 (240)	30 (360)	30 (480)	30 (120)	X	X	X	X
OS2	[OC2]	20 (180)	20 (360)	20 (540)	20 (720)	20 (180)	X	X	X	X
OS3	[OC3]	30 (120)	30 (240)	30 (360)	30 (480)	30 (120)	30 (120)	30 (240)	30 (360)	30 (480)
OS4	[OC4]	20 (180)	20 (360)	20 (540)	20 (720)	20 (180)	X	X	X	X
OS5	[OC5]	X	X	X	X	60 (60)	X	X	X	X
OS6	[OC6]	120 (30)	120 (60)	120 (90)	120 (120)	120 (30)	120 (30)	120 (60)	120 (90)	120 (120)
OS6′	[OC6′]	90 (40)	90 (80)	90 (120)	90 (160)	90 (40)	90 (40)	90 (80)	90 (120)	90 (160)
OS7	[OC7]	18 (200)	18 (400)	18 (600)	18 (800)	18 (200)	X	X	X	X
OS8	[OC8]	X	X	X	X	20 (180)	X	X	X	X
OS9	[OC9]	X	X	X	X	40 (90)	X	X	X	X
OS10	[OC10]	X	X	X	X	18 (200)	X	X	X	X
OS11	[OC11]	24 (150)	24 (300)	24 (450)	24 (600)	24 (150)	X	X	X	X
OS12	[OC3, OC11]	60 (60)	60 (120)	60 (180)	60 (240)	60 (60)	X	X	X	X
OS13	[OC8, OC10]	30 (120)	30 (240)	30 (360)	30 (480)	30 (120)	X	X	X	X
OS14	[OC2, OC4, OC7]	40 (90)	40 (180)	40 (270)	40 (360)	40 (90)	X	X	X	X
OS15	[OC2, OC3, OC4, OC7]	60 (60)	60 (120)	60 (180)	60 (240)	60 (60)	X	X	X	X
OS16	[OC2, OC4, OC7, OC8, OC10]	X	X	X	X	60 (60)	X	X	X	X
OS17	[OC2, OC3, OC4, OC7, OC8, OC10]	X	X	X	X	90 (40)	X	X	X	X

Appendix B: RS detailed evaluations for the case study

RS evaluation for the first reconfiguration scenario (C_1–C_{21}):

- Market-level reconfiguration smoothness (TRS) [Eqs. (5.2)–(5.4)]:

$$TRS_m = \frac{2}{3}\left(\frac{6}{12}\right) + \frac{1}{3}\left(\frac{0}{12}\right) = \frac{1}{3},$$

$$TRS_d = \frac{2}{3}\left(\frac{1+2(1)+2(0)+0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) + \frac{1}{3}\left(\frac{0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) = \frac{2}{23}$$

$$\therefore TRS = \frac{2}{3}\left(\frac{1}{3}\right) + \frac{1}{3}\left(\frac{2}{23}\right) = \frac{52}{207} = 0.2512.$$

- System-level reconfiguration smoothness (SRS) [Eqs. (5.5)–(5.8)]:

$$SRS_s = \frac{2}{3}\left(\frac{2+0}{6}\right) + \frac{1}{3}\left(\frac{0+0}{6}\right) = \frac{2}{9},$$

$$SRS_m = \frac{2}{3}\left(\frac{6+0}{12}\right) + \frac{1}{3}\left(\frac{0+0}{12}\right) = \frac{1}{3},$$

$$SRS_f = \frac{2}{3}\left(\frac{(3-2)+(9-4)+(6-2)+(4-0)+(2-0)}{3+9+6+4+2}\right) + \frac{1}{3}\left(\frac{0+0+0}{3+9+6+4+2}\right) = \frac{4}{9}$$

$$\therefore SRS = \frac{3}{6}\left(\frac{2}{9}\right) + \frac{2}{6}\left(\frac{1}{3}\right) + \frac{1}{6}\left(\frac{4}{9}\right) = \frac{8}{27} = 0.2963.$$

- Machine-level reconfiguration smoothness (MRS) [Eqs. (5.9)–(5.11)]:

$$\mathrm{MRS_d} = \frac{2}{3}\left(\frac{1+2(1)+2(0)+0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) + \frac{1}{3}\left(\frac{0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) = \frac{2}{23},$$

$$\mathrm{MRS_o} = \frac{2}{3}\left(\frac{1}{2(1)+2}\right) + \frac{1}{3}\left(\frac{1}{2(1)+2}\right) = \frac{1}{4}$$

$$\therefore \mathrm{MRS} = \frac{2}{3}\left(\frac{2}{23}\right) + \frac{1}{3}\left(\frac{1}{4}\right) = \frac{13}{92} = 0.1413.$$

- Overall reconfiguration smoothness (RS) [Eq. 5.1]:

$$\therefore \mathrm{RS}(C_1 - C_{21}) = \frac{1}{6}\left(\frac{52}{207}\right) + \frac{3}{6}\left(\frac{8}{27}\right) + \frac{2}{6}\left(\frac{13}{92}\right) = 0.2371.$$

RS Evaluation for the second reconfiguration scenario (C_1–C_{22}):

- Market-level reconfiguration smoothness (TRS) [Eqs. (5.2)–(5.4)]:

$$\mathrm{TRS_m} = \frac{2}{3}\left(\frac{8}{14}\right) + \frac{1}{3}\left(\frac{0}{14}\right) = \frac{8}{21},$$

$$\mathrm{TRS_d} = \frac{2}{3}\left(\frac{1+2(1)+2(0)+0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) + \frac{1}{3}\left(\frac{0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) = \frac{2}{23}$$

$$\therefore \mathrm{TRS} = \frac{2}{3}\left(\frac{8}{21}\right) + \frac{1}{3}\left(\frac{2}{23}\right) = \frac{410}{1449} = 0.2830.$$

- System-level reconfiguration smoothness (SRS) [Eqs. (5.5)–(5.8)]:

$$\mathrm{SRS_s} = \frac{2}{3}\left(\frac{2+0}{6}\right) + \frac{1}{3}\left(\frac{0+0}{6}\right) = \frac{2}{9},$$

$$\mathrm{SRS_m} = \frac{2}{3}\left(\frac{8+0}{14}\right) + \frac{1}{3}\left(\frac{0+0}{14}\right) = \frac{8}{21},$$

$$\mathrm{SRS_f} = \frac{2}{3}\left(\frac{(5-2)+(10-4)+(6-2)+(6-0)+(2-0)}{5+10+6+6+2}\right) + \frac{1}{3}\left(\frac{0+0+0}{5+10+6+6+2}\right) = \frac{14}{29}$$

$$\therefore \mathrm{SRS} = \frac{3}{6}\left(\frac{2}{9}\right) + \frac{2}{6}\left(\frac{8}{21}\right) + \frac{1}{6}\left(\frac{14}{29}\right) = \frac{194}{609} = 0.3186.$$

- Machine-level reconfiguration smoothness (MRS) [Eqs. (5.9)–(5.11)]:

$$\mathrm{MRS_d} = \frac{2}{3}\left(\frac{1+2(1)+2(0)+0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) + \frac{1}{3}\left(\frac{0}{(3+1)+2(3+1)+2(4+0)+(3+0)}\right) = \frac{2}{23},$$

$$\mathrm{MRS_o} = \frac{2}{3}\left(\frac{1}{2(1)+2}\right) + \frac{1}{3}\left(\frac{1}{2(1)+2}\right) = \frac{1}{4}$$

$$\therefore \mathrm{MRS} = \frac{2}{3}\left(\frac{2}{23}\right) + \frac{1}{3}\left(\frac{1}{4}\right) = \frac{13}{92} = 0.1413.$$

- Overall reconfiguration smoothness (RS) [Eq. 5.1]:

$$\therefore \mathrm{RS}(C_1 - C_{22}) = \frac{1}{6}\left(\frac{410}{1449}\right) + \frac{3}{6}\left(\frac{194}{609}\right) + \frac{2}{6}\left(\frac{13}{92}\right) = 0.2535.$$

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