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RECONFIGURABLE MANUFACTURING SYSTEM – A NEW CLASS OF MANUFACTURING SYSTEM

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Abstract

Today's manufacturing environment is highly uncertain, and it is continuously changing. It is characterized by shorter life cycles of products and technologies, shorter delivery times, an increased level of customization at the price of a standard product, increased product variety, quality as well as demand variability and intense global competition. Academicians, as well as practitioners, agree that uncertainty will continue to grow in the twenty-first century. To deal with the uncertainties in demand variation and production capacity a manufacturing system is required which can be easily reconfigured when there is a need at low cost. A reconfigurable manufacturing system is such a type of system.

In the present work, the concept of the reconfigurable manufacturing system has been discussed and reviewed. It has been compared with dedicated systems and flexible manufacturing systems. Part family formation and barriers of reconfiguration also have been discussed. This work is an attempt to contribute to the conceptual systematization of the reconfigurable manufacturing system and reconfigurability by synthesizing the vast literature available after a systematic review.

Keywords

Reconfigurable manufacturing system, reconfigurability, flexible manufacturing system, flexibility, reconfigurable machine tool.

Introduction

A manufacturing system is used to produce finished products from raw materials. It consists of machines, material handling systems, materials, information. Since manufacturing systems have many features and, characteristics, these can be divided in many ways. Earlier, manufacturing systems were divided into two parts based on the flexibility to deal with uncertainties named dedicated manufacturing systems (DMSs) and flexible manufacturing systems (FMSs).

Dedicated manufacturing systems have the least flexibility. These systems have dedicated or special purpose machines which are arranged in an optimum operations sequence. These machines and systems have a fixed structure and if needed to change they require a lot of time. Since these systems have special purpose machines and many times these machines use multi-point cutting tools, therefore the productivity of these systems is highest. These systems also have the least cost and simple design [1].

A flexible manufacturing system, as its name means has very high flexibility. As defined by Groover [2] is "A flexible manufacturing system (FMS) is a highly automated GT machine cell, consisting of a group of processing stations (usually computer numerical control [CNC] machine tools), interconnected by an automated material handling and storage system, and controlled by an integrated computer system". According to Brown [3], "A flexible manufacturing system is the integration of NC machines with automatic material handling systems that can produce a large variety of medium-size products". According to Tetzlaff et al. [4], "A flexible manufacturing system can be defined as a computer-controlled production system capable of processing a variety of part types." According to Mehrabi et al. [5] "Flexible manufacturing system is a programmable machining center configuration which incorporates software to handle changes in a work order, production schedules, part programs, and tooling for several part families." From the above definitions, some points are clear. An FMS has a high level of automation, there is computerized control of machines, loading, unloading, transfer, etc. It can produce a variety of parts. Generally, it has CNC machines. Some systems which use a flexible transfer line has been said as flexible manufacturing system [3]. But nowadays FMS can't be imagined without CNC machines. Brown [3] has classified types of flexible manufacturing systems as; flexible transfer lines, flexible machining systems, flexible machining cells, and flexible transfer multi-line.

When the concept of FMS was introduced, it attracted the attention of many researchers. Many industries have started to use FMS. But a survey on FMS was conducted and it was presented by Hytler and Ulsoy during 1997 in Engineering research center for Reconfigurable manufacturing system. The details of the survey have been discussed in paper [5]. The report describes that many industries are not adapting FMS because FMS is too expensive and complex. According to the survey report, two third of the responded said that FMS is not living up to its full potential, over half reported that they purchased FMS of excess capacity and features, the problems identified with FMS were training, reliability, maintenance, software, cost, and reconfigurability. Actually, the generalization of the feature of FMS increased its complexity and cost, and very high-level automation stared problem in maintenance. Generally, FMS uses CNC machines, which have single-point cutting tools while dedicated machines have multi-point cutting tools. This decreases the productivity of FMS. Because of these limitations, reconfigurable manufacturing system has been introduced. A reconfigurable manufacturing system has flexibility, but it is customized [6–10]. However, flexible manufacturing systems are used in many industries worldwide. Even many academic institutions have a flexible manufacturing system for research purposes.

Reconfigurable manufacturing system

A reconfigurable manufacturing system is a new type of manufacturing system and it can change its capacity and functionality very easily and quickly whenever required. RMS (reconfigurable manufacturing system) has capacity and functionality exactly what is required. RMS is adjustable to the fluctuating demands in volume as well as variety and it can be easily upgraded with new process technology [6–12]. RMS has six key characteristics which are scalability, modularity, customization, integrability, convertibility, and diagnosability. The key characteristics customization, convertibility, and scalability are necessary RMS characteristics, and the other (modularity, diagnosability, and integrability) reduce the system configuration time and its ramp-up time [1, 6, 13]. RMS includes many features of dedicated as well as flexible manufacturing systems.

The concept of RMS has been proposed by Koren et al. [9]. Elmaraghy [14] compared FMS and RMS. This paper also described the opinions of the expert on FMS and RMS. The reconfigurable manufacturing system has been evolved from the dedicated manufacturing system. With the concept of using a modular machine, the concept of reconfiguration arises. But it is not limited to modular machines. Some researchers have given the concept of reconfiguration by material handling systems [15], reconfiguration by relocation [16], reconfiguration process plan [17], etc. Lee [16] has given some relocation rules. Galan el at. [18] presented a methodology for the selection of part family. Prasad et al. presented methodology for part family selection to facilitate reconfiguration in manufacturing system [10] and selection of level of reconfiguration [19]. Prasad et al. [6, 20] considered reconfigurability in the manufacturing industry. Puik et al. [21] proposed a method to compare alternatives to implement reconfigurations considering resources and lead time. Gu et al. [22] defined throughput settling time, production loss and total underproduction time. System resilience was measured, and measured values were used for designing of RMS. The designing factors used were system configuration, buffer capacity and level of redundancy. The effect of the factors on system resilience was investigated. Goyal et al. [23] proposed methods to measure machine reconfigurability and operational capability of the reconfigurable machine tool. The developed performance index along with the cost was considered for optimal machine assignment. The problem was solved by using NSGAII and TOPSIS. Koren et al. [24] presented the concept of a practical reconfigurable manufacturing system using cell gantry and spine gantry. It is like a special type of layout of flexible manufacturing system. Later reconfigurable machines were added [25]. Prasad et al. presented methodologies for scheduling in reconfigurable manufacturing system [7, 12]. Reconfigurability has been

Table 1
Comparisons of system features of dedicated system, RMS and FMS.

S.N.	Dedicated	RMS	FMS
1	System structure is fixed, and it takes a lot of time to change.	It can be changed easily	It can also be changed easily but less adjustable than RMS.
2	Machine structure is fixed. Special purpose machines are used.	Reconfigurable machines are used which can easily be adjustable.	CNC machines are less adjustable than RMTs
3	There is no scalability planning	In RMS, there is scalability planning.	In FMS, scalability planning can be done for system level but for CNC machines it is too costly.
4	In DMS, there is no flexibility.	In RMS, flexibility is customized.	In FMS, flexibility is very high.
5	In DMS, productivity is very high because of multi-point cutting tools and simultaneously operating tools.	In RMS, productivity is less than DMS and more than FMS	In FMS, productivity is the least.
6	Cost of the system is less	Cost of the system is more than DMS and less than FMS	Generalized flexibility makes it very costly.

reviewed in mining industry [26], mold and die making industry [27], Arvin Meritor industry [28], Powertrain industry [25], Continental Automotive [6, 10, 19, 20], etc.

Table 1 compares the features of DML, FMS, and RMS. Figures 1a and 1b show the difference between dedicated system, FMS and RMS. The functions of FMS are very high but it also increase the cost. The capacity of FMS is lowest and the reason for it that in FMS there are CNC machines that use the single-point cutting tool.

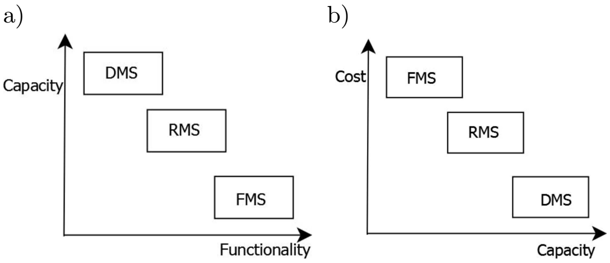

Fig. 1. Comparisons of DMS, FMS and RMS: a) functionality and capacity of DMS, FMS and RMS, b) capacity and system cost of DMS, FMS and RMS.

Some points can be given based on comparison; FMS has generalized flexibility while RMS has limited flexibility. FMS has evolved by combing CNC machines with transfer lines while RMS evolved by introducing a modular machine in dedicated transfer lines. CNC machines in FMS have single-point cutting tools which reduce the production capacity. In RMS multi-point cutting tool machines can be used. In FMS very high level of automation is required. While in RMS it is required as per need. Mostly FMS has been used in machining while the concept of RMS has been used in machining, mining, mold and die making, etc.

Comparison of flexibility and reconfigurability

Since flexibility and reconfigurability both are the important characteristics of the manufacturing system, therefore, in this section, these are compared to get a better understanding.

Flexibility

Flexibility is a very wide concept and its definitions keep on changing according to perspective. Early definitions of flexibility in the manufacturing system were based on the adaptability of the system to uncertainties [29, 30]. Many definitions have been given about flexibility. Mascarenhas defined it as “the ability of a manufacturing system to cope with changing circumstances or instability caused by the environment” [31, 32]. Cox [33] defines it as “the quickness and ease with which plants can respond to changes in market conditions”. Nagarur [34] defines it as “the ability of the system to quickly adjust to any change in relevant factors like product, process, loads and machine failure”. Upton defined it as “the ability to change or react with little penalty in time, effort, cost or performance” [35]. Jain et al. [36] reviewed manufacturing flexibility and various issues especially need, concept, measurement, dimensions, etc. Barad [37] described two modeling perspective-of flexibility; bottom up perspective and top-down perspective. Pérez also [38] reviewed manufacturing flexibility. This paper carried out an analysis of the terms (types, elements, dimensions, parameters, and others) used to refer to the aspects which integrate the manufacturing flexibility construct. The comparison was carried out between theoretical approaches.

More flexibility in a manufacturing system means that it has more ability to change itself according to the customer's needs. Since flexibility is the ability to change, therefore, thinking about what can be changed in the system, gives an understanding about flexibility. It should be noted that all the resources contribute to flexibility but it will increase the cost of the system. Various types of flexibility can be measured in the manufacturing system but all of them can't have the same priority. In a manufacturing system, flexibility is considered at different levels such as production resources, task of production function, performance of the production function, competitive performance of the company, etc. [29].

Upton [35] has discussed a framework to characterize flexibility. These include identification of dimensions, time horizon and elements of flexibility. Dimensions tell about the purpose for which flexibility is required. For example, it can be required for production rate or for variety. Time horizon tells about the time duration for which flexibility is required. Elements include range, mobility and uniformity. For example, range will describe how much variation is production volume or variety is possible. Mobility means that the system can be very easily changed within the range of flexibility. Uniformity means that the performance of the system is not affected while changes are done within range of flexibility.

Types of flexibility

Based on the literature review at least ten types of flexibilities can be identified [3, 14, 39]. These are:

1) Machine flexibility: It is related to ease of making the changes in the machines that are required for the production of a given set of products. It is related to the number of operations performed without changing the machine set-up.
2) Material handling flexibility: It is related to the number of paths available for a product due to material handling devices.
3) Operation Flexibility: It is related to the number of various process plans which can be used for the manufacturing of the product.
4) Process Flexibility: It is related to the group of product types that can be manufactured without any set-up changes.
5) Product Flexibility: It is related to the ease of making a new product into product set-up of a part family.
6) Routing Flexibility: It is related to the number of possible routes for all types of products.
7) Volume Flexibility: It is the ability to change to changes in the production volume in a relatively short time.
8) Expansion Flexibility: It is related to the capacity and capability of the manufacturing system.
9) Control Program Flexibility: It is related to control software, algorithms, and intelligent machines.
10) Production Flexibility: It is related to the number of all products that can be manufactured without any set-up change.

Reconfigurability

Various researchers have viewed reconfigurability. NSF Engineering Research Center for Reconfigurable Manufacturing Systems has defined it as "the ability to adjust the production capacity and functionality of a manufacturing system to new circumstances by rearranging or changing the system's components" [40]. Lee [16] defines it as "the ability of a manufacturing system to be reconfigured at a low cost and in a short-period of time". From Setchi et al. [41] perspective, "the essence of reconfigurability is to enable manufacturing responsiveness to a change in market conditions – that is, the ability of the production system to respond to disturbances that may be caused by social or technological changes". Wiendahl et al. [42] give another definition: "it is the operative ability of a manufacturing or assembly system to switch with minimal effort and delay to a particular family of workpieces or sub-assemblies through the addition or removal of functional elements". According to Galan et al. [18], "reconfigurability does not necessarily arise solely from the market or customers but can also emanate from within the company for the sake of relevance". Basically, it is the adding, changing and adjusting elements of the set-up of a system at low cost to adjust fluctuation in demand and variety when required. Table 2 shows the difference between flexibility and reconfigurability.

Measurement of machine flexibility and machine reconfigurability

Machine flexibility is defined as the ratio of the number of operations that can be performed in the machine without set-up change to total operations that can be performed in the machine. If machine flexibility of *pth* machine in *qth* configuration, MF_{pq} can be calculated as

$$\mathrm{MF}_{pq} = \frac{N_{pq}}{N_q}, \tag{1}$$

where $N_{p,q}$ is the number of operations that can be processed on *pth* machine in *qth* configuration; N_p is the total number of operations on *pth* machine for all the configurations.

Table 2
Comparison of flexibility and reconfigurability.

S.N.	Flexibility	Reconfigurability
1	Flexibility happens in any manufacturing system whether it is dedicated, flexible or reconfigurable manufacturing system.	Reconfigurability happens in reconfigurable manufacturing system where we can readjust the configurations very easily.
2	In flexibility, system changeover takes no time or a little time.	In reconfigurability, system changeover takes some time.
3	Flexibility deals with uncertainty and risk in almost all the possible ways.	Reconfigurability deals with expansion or contraction of capacity or functions. According to Elmaraghy [14] present definition of reconfigurability seems to similar to expansion flexibility.
4	While considering variety, high flexibility means that any variety of products can be produced without changing the system.	High reconfigurability means that a limited variety of products can be produced and then it is reconfigured for another variety of products.
5	Flexibility is considered for a part family (group of products). Part family consists of a large variety of products.	Reconfigurability is considered between two-part families i.e. part family A and part family B. Part family consists of customized variety.

A reconfigurable machine can be changed in many configurations by adding/removing/adjusting its auxiliary modules. For ease of reconfiguration, reconfiguration effort (RE) should be minimum. It can be calculated as [8]

$$\mathrm{RE} = \alpha\frac{\text{No of modules added}}{\text{Total modules}} + \beta\frac{\text{No of modules removed}}{\text{Total modules}} + \gamma\frac{\text{No of modules readjusted}}{\text{Total modules}}, \tag{2}$$

where α, β, γ are weights assigned for modules addition, removal and adjustment respectively. Generally, $\alpha > \beta > \gamma$ and $\alpha + \beta + \gamma = 1$.

Total reconfiguration effort of machine configuration pth machine in qth configuration, $\mathrm{TRE}_{p,q}$,

$$\mathrm{TRE}_{p,q} = \sum_{j=1, j\neq q}^{j_p} \mathrm{RE}_j, \tag{3}$$

where j_p is number of configurations of pth machine.

Machine reconfigurability $MR_{p,q}$ can be calculated

$$\mathrm{MR}_{p,q} = \frac{[j_p - 1]^z}{n_p^q \times \mathrm{TRE}_{p,q}}, \tag{4}$$

where n_p^q is number of machines required; z is the power index.

Example: Let there is a machine M1 which has four configurations M_1^1, M_1^2, M_1^3, M_1^4.
Number of operations that can be done of $M_1^1 = 5$
Total number of operations that can be done on M1 $= 10$
Machine flexibility of $M_1^1 = 5/10 = 0.5$
Modules of $M_1^1 = \{1,2,3\}$
Modules of $M_1^2 = \{2,3,4\}$
Modules of $M_1^3 = \{1,3,5\}$
Modules of $M_1^4 = \{3,6\}$
When M_1^1 is changed to M_1^2,
number of modules added $= \{4\} = 1$
number of modules removed $= \{1\} = 1$
number of modules adjusted $= \{2,3\} = 2$

$$\alpha = 0.5; \quad \beta = 0.4; \quad \gamma = 0.1,$$

$$\mathrm{RE}_1 = \frac{0.5\times 1}{4} + \frac{0.4\times 1}{4} + \frac{0.1\times 2}{4} = 0.275.$$

Similarly when M_1^1 is changed to M_1^3, $\mathrm{RE}_2 = 0.275$, when $M_1^1$is changed to M_1^4, $\mathrm{RE}_3 = 0.35$.
Total reconfiguration effort (TRE) of $M_1^1 = 0.275 + 0.275 + 0.35 = 0.9$
if number of machines needed $= 1$, $z = 2$
Machine reconfigurability of $M_1^1 = \frac{(4-1)^2}{1\times 0.9} = 10$

Measurement of system flexibility and system reconfigurability

Measurement of system flexibility and system reconfigurability becomes slightly complicated. For flexibility, there are ten flexibilities in the manufacturing system. Each one is measured separately, and combined effect of these flexibility can be calculated

$$y(x) = \sum_{i=1}^{n} w_i u(x_i), \tag{5}$$

where $y(x)$ is the total evaluation, w is the weight assigned to each parameter and $u(x)$ is the value of each parameter.

If MF – machine flexibility, MHF – material handling flexibility, OF – operation flexibility, PF – process flexibility, PDF – product flexibility, RF – routing flexibility, VF – volume flexibility, EF – expansion flexibility, CPF – control program flexibility, PDTF – production flexibility then, system flexibility SF can be measured as;

$$\begin{aligned}\mathrm{SF} = {} & w_1\mathrm{MF} + w_2\mathrm{MHF} + w_3\mathrm{OF} + w_4\mathrm{PF} \\ & + w_5\mathrm{PDF} + w_6\mathrm{RF} + w_7\mathrm{VF} + w_8\mathrm{EF} \\ & + w_9\mathrm{CPF} + w_{10}\mathrm{PDTF}.\end{aligned} \tag{6}$$

Weights of the flexibilies can be given by user (manager/ engineer). For this method all the flexibilities are listed and importance of these can be obtained. Delphi method can be used to get the importance. Once importance has been obtained AHP method can be used to determine the weights of the flexibilies. The weight of a flexibility will be between 0 to 1 and sum of all weights will be 1. All the flexibilities need to normalize.

For reconfigurability, key characteristics of RMS are considered. These are modularity, convertibility, scalability, diagnosability, customization, and integrability [25]. In brief, these can be defined as;

1) Modularity: It is related to small identity module which can be added/removed in the system.
2) Convertibility: It is the ease to convert the system from one configuration to another. It includes convertibility of configuration, machine and material handling system. Convertibility of system (CV) is measured as [43]

$$\mathrm{CV} = \theta_1 C_c + \theta_2 C_m + \theta_3 C_h, \tag{7}$$

where C_c is configuration convertibility, C_m is machine convertibility, C_h is material handling convertibility. θ_1, θ_2, θ_3 are the weights assigned

$$C_c = \frac{RX}{I}, \tag{8}$$

where R is no of routing connections, X is minimum number of replicated machines at a particular stage, and I is minimum increment of conversion.

3) Scalability: It is related to minimal capacity increment which is needed to add in the system to adjust its capacity. It is defined as [44];

$$\begin{aligned}\text{scalability} = 100 - {} & \text{smallest incremental} \\ & \text{capacity in percentage.}\end{aligned} \tag{9}$$

4) Diagnosability: It is related to error detection ability.
5) Customization: System is designed for a part family. Therefore, it is related to part family formation and customized flexibility.
6) Integrability: It is related to ease to which any module can be added to the system.

If MD, CV, SC, DT, CS, IT are modularity, convertibility, scalability, diagnosability, customization, and integrability respectively. Then reconfigurability of system RS can be calculated as;

$$\begin{aligned}\mathrm{RS} = {} & w_1'\mathrm{MD} + w_2'\mathrm{CV} + w_3'\mathrm{SC} + w_4'\mathrm{DT} \\ & + w_5'\mathrm{CS} + w_6'\mathrm{IT}.\end{aligned} \tag{10}$$

Weights are assigned as per requirement and parameters are needed to normalize.

The author did research work for consideration of reconfigurability in an industry. Reconfiguration effort of the system was considered by removing or adding the modules of the machines. Details of the measurement have been given in [6].

Industry 4.0 and reconfigurable manufacturing system

Industry 4.0 is the 4th industrial revolution. First industrial revolution was the mechanization using power. Second industrial revolution was use of electric energy while third industrial revolution was automation. Fourth industrial revolution aims to make a smart factory which includes advanced sensors, IoT, Cyber physical systems, artificial intelligence, cloud computing etc. [45–47].

Reconfigurable manufacturing system is mostly about the integration of the technologies that how it can be made more responsive to the changes which can occurs in the system while industry 4.0 is about making industry more smart using advance technologies. There is no contradiction between these two concepts. Both the concepts can lead the industry to a smart and responsive manufacturing system.

Reconfigurable machine tools

The concept of modular machines has been used for many years [48]. Many definitions of modularity have been presented [49]. Modular machines are also known as reconfigurable machine tools (RMTs). In RMTs, some parts (modules) easily can be added or removed. The benefits of the modular concept are; it provides the opportunity for both short-term and long-term objectives, it enables the integration of machine system, process, tools, information flow, etc., it helps the reuse of machinery [48].

Figure 2 shows an example of machine configurations. There are two machines, 15 basic modules, and 25 auxiliary modules. In any machine, basic modules are fixed but the machine can take many configurations by addition and removal of auxiliary modules. Some performance parameters related to reconfigurable machines have been given by Goyal et al. [8]. These are the operational capability and reconfigurability of the machine. Reconfigurability of machine has been discussed in previous sections while operational capability is given by the following formula;

$$\mathrm{OC}_{p,q} = [N_{p,q} - 1]^Y, \tag{11}$$

where $\mathrm{OC}_{p,q}$ is the operational capability of *pth* machine in *qth* configuration, $N_{p,q}$ is the number of operations that can be processed on *pth* machine in *qth* configuration, Y is the power index.

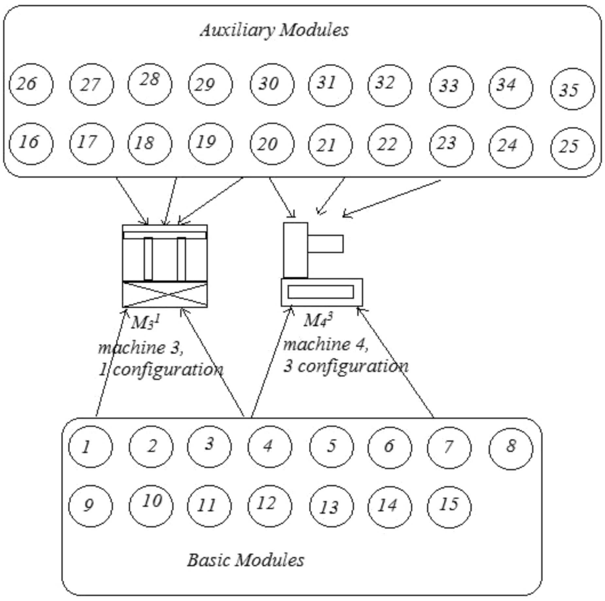

Fig. 2. Basic modules and auxiliary modules of reconfigurable machine tool.

Landers et al. [50] discussed three types of requirement related reconfigurable machine tools (RMTs); (i) manufacturing requirement, (ii) control requirement, (iii) mechanical requirement (kinematic viability, geometric accuracy, and structural stiffness). Three examples of RMTs have been discussed (i) for part change (ii) for feature change, and (iii) cycle time change. Moon [51] worked for the design of a reconfigurable machine tool. Lorenzer et al. [52] developed a software tool for RMT. McLaren et al. [53] developed a tool changer of RMT. Shneor [54] reviewed RMT subsystems.

Part family formation in reconfigurable manufacturing system

Reconfigurable manufacturing systems are designed for one or more part families therefore for a successful system there is a need to develop a methodology for part family formation. Galan et al. [18] presented an integrated method of Jaccard function (for calculation of similarity matrix), average linkage algorithm (for the formation of part family), linear programming (for the selection of part family). Part family construction was based on two types of cost; the cost of reconfiguration and the cost of under-utilization. Prasad et al. [10] presented methodology that included the calculation of similarity matrix (based on modified Jaccard coefficient), formation of the part family, and selection of the part family. ALC algorithm was used for part family formation and three criteria were considered for the selection of part family. These criteria were reconfiguration effort, under-utilization cost, and floor space cost. AHP was used to calculate the weights of criteria and reference ideal method was used for the selection of alternatives. Jaccard coefficient (S_{ij}) is be expressed as Eq. (12) [55]:

$$S_{ij} = \frac{a_1}{a_1 + a_2 + a_3}; \quad 0 < S_{ij} < 1, \tag{12}$$

where a_1 – common machines; a_2 – machines required for only product i; a_3 – machines required for only product j.

In the average linkage algorithm, two products are grouped for which the similarity coefficient is the highest. After grouping the two products, these products are treated as a single product and a new similarity index is calculated. This process is repeated until all the products are grouped. New similarity matrix can be calculated by using the following equation

$$S_{i'j'} = \frac{\sum_i \sum_j S_{ij}}{n_{i'} \times n_{j'}}, \tag{13}$$

where $n_{i'}$ – number of products in i'-th family, and $n_{j'}$ – number of products in j'-th family.

In [56], Galan et al. prepared five types of matrices; modularity matrix, commonality matrix, compatibility matrix, re-usability matrix, and product demand matrix. A weighted matrix was obtained using AHP method further average linkage algorithm was used for part family formation. Since similarity matrix is important part of part family formation, therefore many authors have worked for similarity matrix such as Askin et al. [57], Irani et al. [58], Goyal et al. [59], Prasad et al. [10], etc. Abdi et al. [60] proposed an algorithm for grouping products for RMS based on their operational similarities. Rakesh et al. [61] proposed a modified average linkage clustering algorithm.

Barriers in reconfigurable manufacturing system

Malhotra [62] discussed 14 barriers in the reconfigurable manufacturing system. These are development of the design methodology, difficult interfaces, module economy, difficult control of reconfigurable machine tool with multiple tools, integration of heterogeneous software and hardware components, reconfiguration of controller architecture, difficulty in axes location, difficult reconfiguration of control system, expensive tooling, difficult variety handling, controls of process variations, complex system, constraint satisfaction, and selection of machine modules, Table 3, Fig. 3. The barriers were identified from the literature review and expert's opinion and survey of Indian industries was conducted for reconfiguration.

Table 3
Level of barriers in reconfigurable manufacturing system.

	Barriers
Level 1	Difficult interfaces
Level 2	Expensive tooling, Difficult variety handling
Level 3	Development of the design methodology, Difficult reconfiguration of control system, constraint satisfaction
Level 4	Module economy, Reconfiguration of controller architecture, Controls of process variations, Complex system, Integration of heterogeneous software and hardware components
Level 5	Difficult control of reconfigurable machine tool with multiple tools, Difficulty in axes location
Level 6	Selection of machine modules

These barriers were divided into six levels using interpretive structural modeling, Table 3. These level shows how these barriers are related to each other and how these barriers should be implemented in a manufacturing system. Figure 3 shows the relation among these variables. ISM Methodology has been used to develop these relations. This methodology has four main steps (i) development of structural self-interactive matrix (ii) development of reachability matrix (iii) partitioning the reachability matrix, and (iv) ISM model.

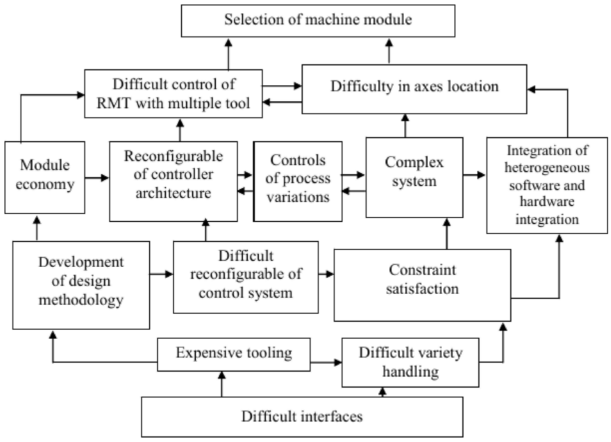

Fig. 3. Barriers in reconfigurable manufacturing system [62].

Further, driving power and dependence of these barriers have been calculated and the barriers have been grouped in 4 groups, Table 4. Driving power describes that the variable influences the other variables while dependence describes that the variable is influenced the other variables. Eight barriers (reconfiguration of controller architecture, complex system, development of design methodology, difficult reconfiguration of control system, module economy, expensive tooling, constraint satisfaction, and controls of process variations) have less driving power and dependence. Four barriers (integration of heterogeneous software and hardware components, difficult control of RMT with multiple tool, selection of machine module, and difficulty in axes location) have less driving power and more dependence. While two barriers (difficult variety handling and poor rate of difficult interfaces) have strong driving power and less dependence.

Rosio [63] identified three challenges in reconfigurable manufacturing system; knowledge in reconfigurability, structured design methodology, inclusion of reconfigurability knowledge in structured design methodology on the base case studies. This paper also describes some questionnaires for industrial study. Andersen et al. [64] discussed some prerequisites in reconfigurable manufacturing based on the work of Rosio [65, 66]. These are a life-cycle perspective on

Table 4
Driving power and dependence of barriers in reconfigurable manufacturing system.

	Less dependence	High dependence
Less driving power	reconfiguration of controller architecture, complex system, development of design methodology, difficult reconfiguration of control system, module economy, expensive tooling, constraint satisfaction, and controls of process variations	integration of heterogeneous software and hardware components, difficult control of RMT with multiple tool, selection of machine module, and difficulty in axes location
High driving power	difficult variety handling, poor rate of difficult interfaces	Nil

production systems, having long-term view on investments in production capacity, correlation between production system design and the product portfolio development, having a structured production system design process, having staff that is skilled in system design and have knowledge of reconfigurability, having a holistic perspective on production systems, and existence of product families for customized flexibility in production. Further industry cases in the Danish industry were conducted for the prerequisites in the manufacturing system.

Conclusions

This paper synthesizes the vast literature review on the reconfigurable manufacturing systems. It compares RMS with FMS. In this paper, reconfigurability and flexibility also have been compared. Further, reconfigurable machine tools, part family formation and barriers in reconfigurable manufacturing systems have been discussed. Salient points on the paper can be drawn as

1) Reconfigurable manufacturing systems are a need of the present time which can deal with uncertainties related to the capacity of the system and its functionality. It has customized flexibility.
2) It has been found that both flexibility and reconfigurability have importance. But rather than having a lot of flexibility it is better to have some flexibility and some reconfigurability. Both flexibility and reconfigurability cost money. Therefore, it becomes a research area that what should be flexibility and reconfigurability.
3) Reconfigurable machine tools are an important part of the manufacturing systems. In these machines, modular concept is used. Modules easily can be added or removed to the machines.
4) Reconfigurable manufacturing systems are designed for a part family then these are reconfigured to another part family. Therefore, a modified methodology is needed for designing of RMS.
5) Authors are doing work for the identification of barriers and their correlations. However much more industrial cases are required to get a better understanding.

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