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An adapted NSGA-2 algorithm based dynamic process plan generation for a reconfigurable manufacturing system

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Abstract With burgeoning global markets and increasing customer demand, it is imperative for companies to respond quickly and cost effectively to be present and to take the lead among the competitors. Overall, this requires a changeable structure of the organization to cater to a wide product variety. It can be attained through adoption of the concept of reconfigurable manufacturing system (RMS) that comprises of reconfigurable machines, controllers and software support systems. In this paper, we propose a new approach to generate the dynamic process plan for reconfigurable manufacturing system. Initially, the requirements of the parts/products are assessed which are then compared with the functionality offered by machines comprising manufacturing system. If the production is feasible an optimal process plan is generated, otherwise the system shows an error message showing lack of functionality. Using an adapted NSGA-2 algorithm, a multi-objective scenario is considered with the aim of reducing the manufacturing cost and time. With the help of a numerical example, the efficacy of the proposed approach is demonstrated.

Keywords Flexible manufacturing system · Reconfigurable manufacturing system · Changeability · Modularity · NSGA-2 · Process plan

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Introduction

The current age of globalization is classified by strong customer orientation of the organisation and provision of high quality goods at a very reasonable price within a short period of time. This has led to extremely competitive scenario/ situation with rapidly changing technology, shortened product life cycles and emergence of global competitors. There is a sense of urgency among the organizations/networked enterprises/supply chains to provide the desired product and/or service to the customers faster, cheaper and better than the competition. In such a turbulent environment, it is essential for organizations to revamp their statures in the market by modifying their production techniques, network structure, etc.

Figure 1 illustrates the various drivers of industrial production environment. They may lead to the slight part design modification; the introduction of new parts, the phasing out of current parts, the increase (decrease) in volume of each part, or changes in quality specifications, etc. These change enablers drive the organization to improve its technology, its network structure and its human resources in order to sustain itself in the current volatile economical and social environments.

Nowadays, customer satisfaction is a challenge for most manufacturing companies. Mass customization, a product deployment concept that combines low price with extensive variation and adaptation has emerged currently due to its potential impact upon the customer regarding the perceived value of the product. With the continuous demand for products incorporating new and complex functionalities, there has been a lot of pressure on the manufacturing organizations. Figure 2 shows the mutation of the product life cycle characteristics and the increasing divergence of the life cycle of the associated process and equipments (Wirth et al. 2004).

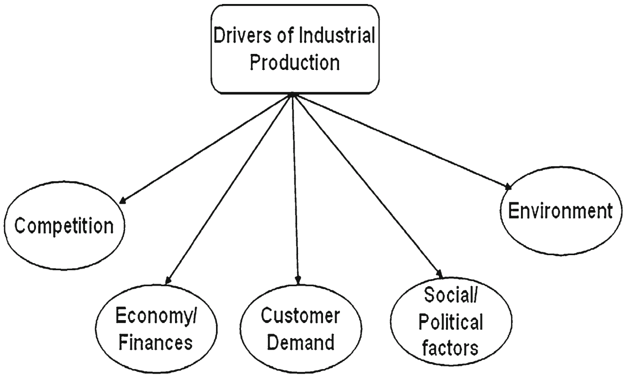


Fig. 1 Drivers of the industrial production scenario

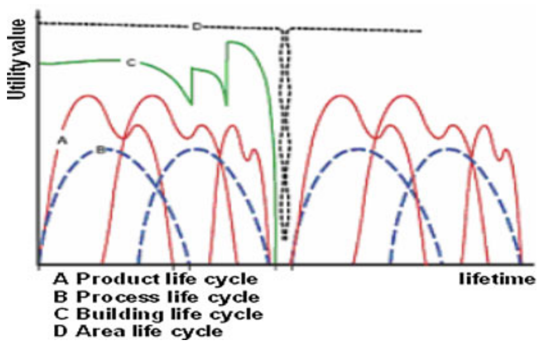


Fig. 2 Diverging life cycles of the constituent elements of a factory

It can be noticed from Fig. 2, that the product life cycle has considerably reduced in the past, this has increased the need for the organization to design more sophisticated products in large variety to cope up with the demand. The complexity has further increased by outsourcing of most of the sub-components to different countries and at different manufacturing sites. This requires a need to handle the network comprising of the manufacturing sites, the warehouses and the suppliers; the market; source of raw material in an effective way in order to maximize the benefits and improve the customer satisfaction.

In order to respond to the above challenges, there is a real need for establishing the concept of reconfigurable manufacturing system (RMS). Reconfigurability aims at achieving more competitiveness by offering enablers in terms of technology and supporting business paradigms. This paper aims to present the needs for adopting the new concept of RMS. Further an optimized reconfigurable process plan, which can adapt with the modular dynamic nature of the machines is also developed using non-dominated sorting genetic algorithm (NSGA-2).

This paper is further organized as follows. Section "Reconfigurable manufacturing systems: answer to problems observed in current systems" focuses on the manufacturing practice followed in the past, identifies the need for a change to better production techniques, describes the evolution of RMS and discusses its various requirements. Section "Reconfigurable process plan: problem description" presents the problem under consideration while Sect. "Problem formulation" illustrates its mathematical formulation. Sections "Developed methodology" and "Experiment result and analysis" discuss in detail the developed methodology and show the experimental results and analysis respectively. Section "Conclusion and future perspectives" concludes the paper with some remarks and perspectives for future works.

Reconfigurable manufacturing systems: answer to problems observed in current systems

A cost effective response to market changes requires new manufacturing approach that not only combine the high throughput of DML with flexibility of FMS, but also able to react to changes quickly and efficiently (Koren et al. 1999). RMS was proposed during the mid nineties to cater to such needs idea. RMS may be defined as the machine system which can be created by incorporating basic process modules both hardware and software that can be arranged or replaced quickly and reliably (Mehrabi et al. 2000; ElMaraghy 2006; Wiendahl et al. 2007; ElMaraghy 2009).

Furthermore, the RMSs are designed for a specific range of production requirement as opposed to a single set or the wide range of the product requirements. However, the production system can be reconfigured if the product requirement changes by adding, removing, or modifying specific process capabilities, controls, and software or machine structure. It can also accommodate any change in the technology thus prove to be efficient and cost effective in long run unlike its predecessors—DMS and FMS.

Characteristics of reconfigurable systems

Reconfigurable systems must be designed at the outset to be amended by using hardware and software modules that can be integrated quickly and reliably. In order to pursue the goal of establishing a changeable environment the RMS should possess a set of key features such as:

- *Modularity*: The hardware and software component should be designed in a modular form with standardized units or dimensions allowing flexibility and variety for use.
- *Integrability*: The hardware and software modules should be designed with interfaces for both effective integration with other system components and future introduction of new technology.
- *Convertability*: The system should allow quick changeover between different set of product requirement i.e.

different variety of existing product and quick adaptability for the future products.

- *Diagnosability*: The identification of the correct set of process parameters in order to improve the efficiency, which is a key step to reduce the ramp up time in RMS.

Comparisons of manufacturing systems

In order to overcome the limitations of the FMS and the DMS, reconfigurable systems were adopted. The RMS is designed to cope with situations where modularity of both productivity and functionality of the system are of vital importance to react to the changes. The system and machines are designed for adjustable structure that enables system scalability in response to the market demands and its adaptability to new products. The RMS can be differentiated from the FMS and DMS on the basis of three coordinates capacity, functionality and cost. As the structure is modular thus RMS possesses adjustable capacity and functionality and since it is focused around the part, makes it cost effective. Figures 3 and 4 give the comparison of RMS, DMS and FMS with respect to cost and performance.

Figure 3 shows the robustness of the RMS system with respect to the change in the capacity. There is significant rise in the FMS system cost with increase in the capacity, which proves to be disadvantageous. In the case of DMSs the variability of capacity can be handled up to a certain level after which significant investment is needed to setup new production lines in order to satisfy the increasing demand.

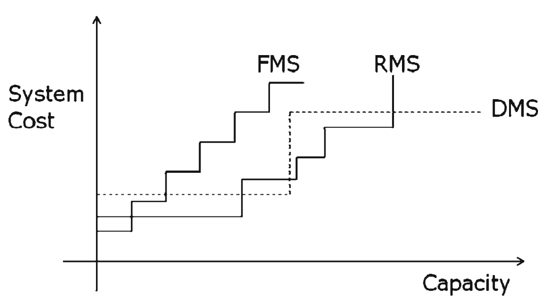


Fig. 3 System cost with vs change in capacity

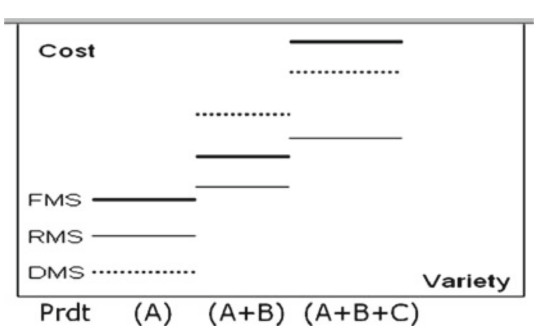


Fig. 4 System cost versus change in variety

From Fig. 4 it can be seen that for a single product, DMS proves to be more cost effective and robust because the machines and controllers are focused around the parts. Due to increase in product variety DMS cost goes up as infrastructure needs to be changed (because it cannot accommodate increased product variety). Product $(A + B)$ comes within the scope of the FMS architecture thus it gives a cost effective performance, but when product C needs to be introduced it goes beyond the scope of FMS and the it is very expensive to change the structure of FMS system. Hence it can be noticed that in the current scenario where the variety changes quickly it is most efficient to adopt an RMS environment.

Requirements for reconfigurable manufacturing systems

Reconfigurable manufacturing systems require design changes to be made at both physical and logical levels. Some of these requirements are described are shown in Fig. 5 and are described below:

Reconfigurable machine tool (RMT)

RMTs are seen as the keen enablers of the reconfigurable manufacturing systems. An RMT is designed in order to customize the desired product or the product mix in the required quantities. The term machine tool includes any machine that is utilized at any stage during the manufacturing of products. The basic aim of a RMT is to cope with various changes in the product or parts to be manufactured. Thus RMT must possess the capability to be quickly converted in both hardware and software to satisfy the requirements of new machine demands.

Hardware requirement: A machine tool should possess a set of specified motions and satisfy part tolerance demands in order to satisfy the operation demands of a particular product. In practice, an RMT is designed to perform a set of requirements (e.g. mechanical operation) of the product. Since these requirements will change, the RMT may require more or less motion axes to perform the functions.

Design of the RMT should be mechanically modular in order to accommodate the changes in a cost effective manner. Consequently, the RMT should fulfill the requirements concerning kinematics viability, structural stiffness and geometrical accuracy (Landers et al. 2006, 2001).

Software requirement: In the case of RMS, the controller structure to operate on the RMT should be reconfigurable in nature. This can be achieved by adopting an open architecture framework for the controllers. Hence, the controller should possess following key characteristics: extendibility, scalability, interoperability and portability (Pritschow et al. 2001).

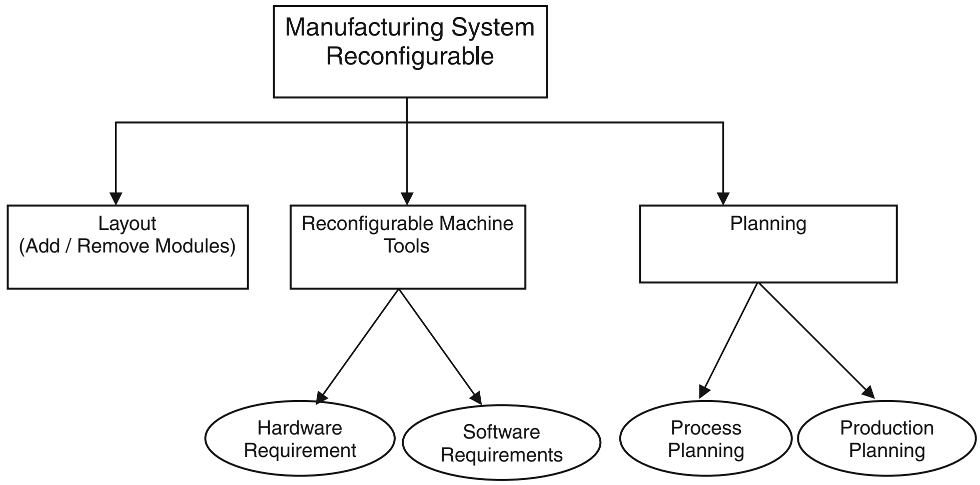


Fig. 5 Hierarchical structure of the reconfigurable manufacturing systems

Reconfigurable process plan (RPP)

Reconfigurable process plan approach represents an important enabler of changeability for evolving products and manufacturing systems. In practice, the generation of new process plans involves different assignment of machines depending on their capabilities, and with the changes in technology, process plan has to be modified accordingly (Fig. 6). The planning has to be carried out at the macro level and the micro level.

Macro-process planning: It is concerned with selecting the best sequence of multiple different processing steps and set-ups as well as the machines to perform the different operations required to manufacture a particular part of the product.

Micro-process planning: In this case, each individual operation is optimized to determine the best process parameters.

The RPP approach is more advantageous than the current method of the dynamic, adoptive and non-linear process planning that uses either the pre planning or re-planning methodologies. In the case of pre planning methodology the optimized process plans are designed before itself in anticipation of the variation that may occur in future. But this kind of approach is risky as it is not possible predict the exact market trends. Whereas re-planning involves creating a new plan from inception whenever there is change in demand or the technology. Thus this kind of approach does not take the benefit of the currently available plans making it cost inefficient.

Problems with the implementation of RMS

The problems with implementation of RMS are multifold due to the complex nature of the technology involved in it. In this section, we have discussed some of the problems related to RMS, which may be encountered, and the research gaps where the current focus needs to be directed.

Non availability of the RMT

Despite of the great advantages offered by the RMS it is important to state that currently it is not possible to implement it. This is due to the non- availability of the reconfigurable manufacturing tool because of the lack of technology in designing the modular tool. Some of the main problems are noted below:

- *Gap 1 (Design methodology for RMT)* : It is very difficult to design a mathematical framework for synthesis of the reconfigurable manufacturing tool and its validation is a major challenge (Kota 1999).
- *Gap 2 (Interfaces)*: The interfaces should be standardized and accurately machined to guarantee structural stiffness and geometrical precision.
- *Gap3 (Module Autonomy)*: The wiring and piping of the modules with the external energy source is a nuisance and can prove to be an obstacle in case of the reconfiguration.

The current state of art is such that the reconfigurable machine tools are not yet broadly available (Hardt et al. 1997; AMT 1996), as they are into various stages of development. The researchers have emphasized on the use of the *re-deployable machine tools* (ElMaraghy 2006). They should be removable and replaceable in a single shift, when major services are performed offline and thus can help to reap anticipated benefits of reconfigurable manufacturing systems.

Implementation of new technologies

The following section describes the problems, which may occur when a company adopts a new production system. The first sub-section discusses this matter further and identifies the risks with the change of the technology at the shop floor

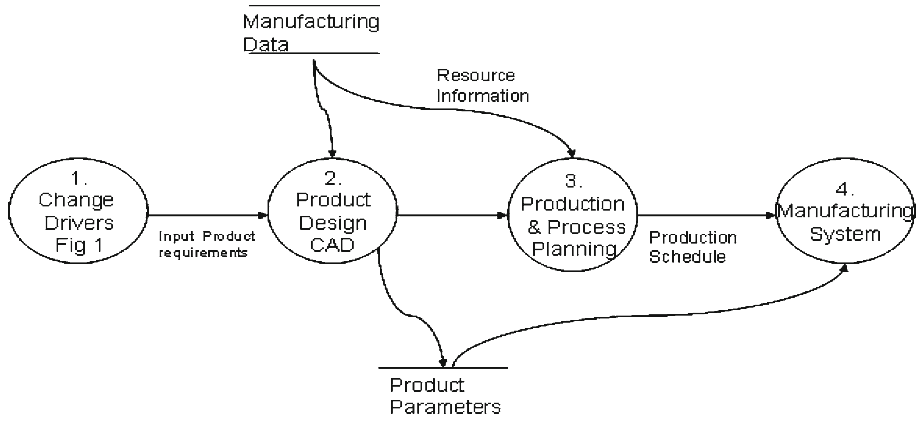


Fig. 6 Data flow diagram (DFD) information transfer in the case of a production system

whereas quality related issues are discussed in the subsequent section.

Risks associated with changing the organizational structure: The change of the technology in the organization involves a lot of efforts in order to maximize the benefits, which can be drawn from it. The major step in this regard is training the workers to use the new technology-machines, tools etc., efficiently so that the technology can be put to use in the production environment. Unfortunately it has been identified that adoption of complex technology generally is not able to maximize the profits as expected.

This failure may be due to the lack of knowledge about the use of new technology and problems with its implementation. Thus in the case of using RMS a proper framework should be designed so that this kind of situation does not arises.

Risks associated with lack of quality: In this run to satisfy the customer demand cost effectively and quickly the quality cannot be compensated. Therefore, in the case of RMS where there is high frequency of changes in manufacturing system, the product features ramp up time reduction should be the critical objective.

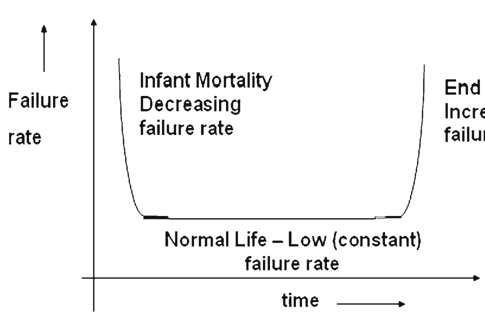


Fig. 7 The bathtub curve showing failure rate against time

As illustrated by Fig. 7, the bathtub shows the failure rate of the product after its introduction in the market. In order to prevent this, appropriate specifications, adequate design tolerance can help and should always be used. However even the best design intent can fail to cover all possible interactions of components/parts in the operation.

Thus future has to be directed in this area in order to develop the methodology and fundamental theory for ramp up time reduction for reconfigurable machining systems. Some of the key research areas are:

- Development of systematic approaches and fundamental principles to identify root causes of component failure and quality and process variation.
- Design of robust components that can operate reliably and safely under different operating condition.

In order to identify the defects it is very important to install precise measuring instruments, which can identify the product quality problem by keeping track of the tolerances.

The supply chain management (SCM) related issues

In order to satisfy the customer demands, the supply chain/ organization has to be more and more reactive. Due to the exploding number of the product models and increasing of the outsourcing there has to be manufacturing at different geographical locations. Thus, the supply chain structure has to be carefully designed to completely take the advantage of the reconfigurable manufacturing systems, the main idea of which is to prevent the delay of product transfer to the customer.

Figure 8 illustrates the centralized model of the supply chain, where the information of the customer is available at all its stages. Thus in a reconfigurable environment when there is change in the demand or new product variety is required,

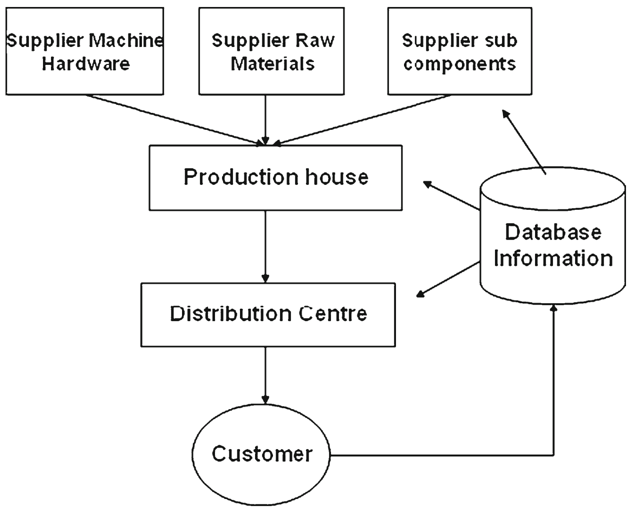


Fig. 8 Centralized model of the supply chain

the supplier of raw material, sub-components and machine modules will be informed so that they can be prepared.

The responsiveness can only be achieved if the suppliers of subcomponents also follow the same production policy that is reconfigurable manufacturing because any delay in the supply of the subcomponents will lead to halt in further production activity. Consequently, even the type of production methodology (DMS, FMS, RMS) should also be considered as an important criterion while selecting a supplier, as it will determine their extent of responsiveness.

Reconfigurable process plan: problem description

In this paper, a process plan is designed in order to schedule different parts of a particular product on the available machines. The reconfigurable manufacturing environment is one where a particular machine can exist in different configuration with varied functionality. There are various modules available with each machine providing different degrees of freedom that is motion along x, y, and z axis. Thus the functionality of the machine can be changed depending upon the capacity and the design requirement of the product. The process plan presented in this paper is developed to accommodate these changes unlike previous researches in this field, which have developed the plans for a fixed capacity and design conditions or in some cases flexible but with known variation.

Table 1 Structure of an optimal process plan

Part	P1	P2	P1	P3	P2	P1	P3
Operation	OP1	OP1	OP3	OP1	OP2	OP2	OP2
Machine	M1	M1	M2	M1	M2	M3	M2
Configuration	C1	C1	C3	C1	C2	C1	C2
Tool	T1	T2	T1	T2	T3	T2	T4
TAD	$-x$	$-x$	$+x$	$+y$	$-z$	$-z$	$-x$

Assignment of operations on machines

It can be carried out in three steps:

1. Identify the tool approach direction (TAD) and the type of tool required to carry out the particular operation.
2. Identify among the available machines and the various configuration, the set of machines, which can perform that particular operation. This is done by identifying the TAD offered by the machine and the tools available with it.
3. Assign the machines and the appropriate configuration to the particular operation of the part. A sample process plan is also shown in Table 1.

There are six different TAD ($\pm x$, $\pm y$, and $\pm z$), which an operation may require. Different type of tools may be required for different operation like the drilling tool, milling tool, shaping tool etc. If no machine with its existing configuration can provide the functionality required for the operation then in that case modules can be added or removed to increase the functionality or the capacity of the machines unlike the traditional manufacturing systems.

Operation precedence graph

The precedence relationship between the operations is due to the geometrical and the technological consideration to produce every feature of the product accurately. When the process plan is designed care must be taken that these relationship are satisfied in order to make sure that the plan is feasible in practice. There may be various types of constraints like fixture requirement, datum requirement and good manufacturing practice, which may determine the precedence relationship between the operations. A sample part with twelve operations and the corresponding operation precedence graph is shown in Fig. 9.

Other constraints of the system

Each machine has certain set of tools available with it. A machine can perform only those operation for which it possess the functionality in the form of tools and the various configuration in which it can exist. The different configurations offer different tool approach directions. While designing a process plan care should be taken that a particular operation of a job is assigned only once to the machine and while calculating the total processing time for the current scheduling check should be made whether the machines and job

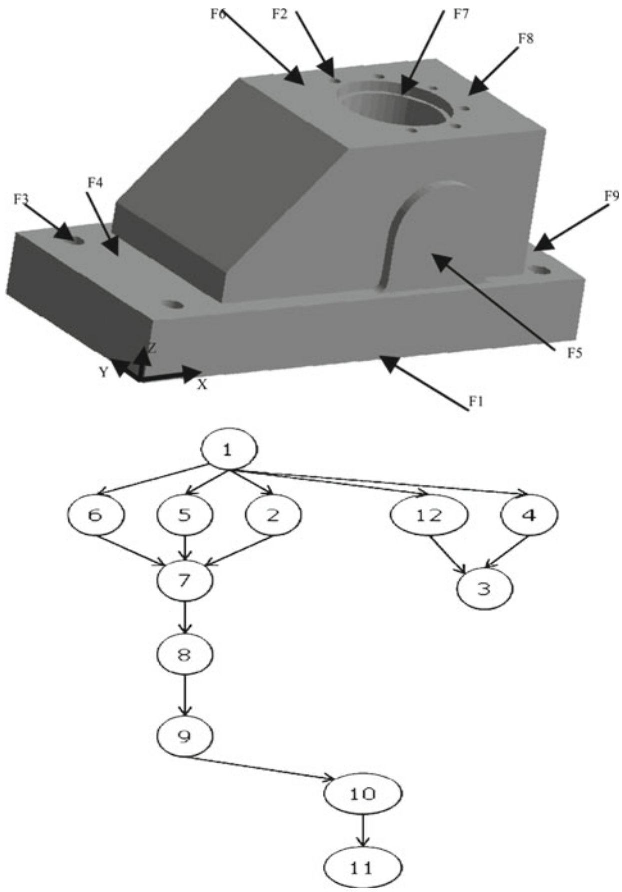


Fig. 9 Sample part structure and corresponding operation precedence graph

are free when they are assigned a task. Table 1 shows an example of the process plan containing the information about machine, configuration tool, TAD, part and the operation.

Problem formulation

In this paper, a typical scheduling problem on RMS has been considered. There is a set of jobs to be completed on a certain number of machines. The machines are reconfigurable in nature and offers varied functionalities in its different configurations, which can be modified depending on the requirements. Thus, in the reconfigurable manufacturing scheduling, there are two problems. The first one is the assignment of each operation to a machine and the second one is the scheduling of this set of operations in order to minimize the completion time and cost of the entire job schedule. Further complexities arise due to the changeable nature of the machines.

The case of process planning in reconfigurable manufacturing is considered here. A case of single product comprising of n parts is taken. It is considered that all the parts are

Nomenclature

N:	Number of parts of the product
$P_1, P_2, \ldots, P_n$:	Parts of the product considered
m:	Number of machines available
$M_1, M_2, \ldots, M_m$:	Machines available
K_i:	Number of configuration available for a particular machine
$C_1^i, C_2^i, \ldots, C_{Ki}^i$:	Configurations of the machine
NOP_1, NOP_2, $\ldots NOP_n$:	Number of operations for a particular part
TNOP:	Total number of operations of all the jobs

Inputs

MConf[]:	Matrix showing the available configuration
MTavl[]:	Matrix showing the tools available with the machine
$CTAD_i[1\ldots C_{Ki}^i][6]$:	Matrix representing the toll approach directions offered by the machine
$OPTAD_i[NOP_i][6]$:	Matrix representing the tool approach direction required for a particular operation
$OPT_i[NOP_i]$:	Matrix representing the tool required for the particular operation
$OPP[NOP_i][NOP_i]$:	Operation precedence matrix for a particular part

Cost information input

CM (1….m):	Cost of using a particular machine
$CT(t)$:	Cost of using a particular tool
$CCCost_i[K_i][K_i]$:	Configuration change cost for the machine
$TCost[m][m]$:	Transportation cost
$tCCost_i[][]$:	Tool change cost for a particular machine

Time information input

$CCTime_i[K_i][K_i]$:	Configuration change time for the machine
$tCtime_i[][]$:	Tool change time for a particular machine
$Ttime[m][m]$:	Transportation time required from one machine to the another
$Prtime[m][N][K_i]$:	The processing time for a particular operation, depends on the machine the configuration and the direction of movement

independent of each other. Each part P_i has NOP_i number of operations to be performed and also given is the precedence graph for the operation, which must be, followed i.e. an operation can be performed only when all its preceding operations are performed.

Each machine *Mi* has certain number of configuration which certain degrees of freedom available that is translatory and rotatory motion along the x, y, and z direction. These motions are required to process the jobs as each operation to be done on the job will have tool and tool approach direction requirement, which should be satisfied by the configuration of the machine.

Objective function

The objective function is minimizing the total cost and the total time, which is incurred in the manufacturing.

Z_1: Total Cost
Z_1: Total Time

Obj. 1: Min Z_1
Obj. 2: Min Z_2

From the considered objective function it can be implied that this is the case of the multi-objective optimization. A series of factor comprising the total cost and total time are discussed below:

Total cost

In the manufacturing system there is cost incurred in various activities from processing of the job to the changeover of machine, tool or configuration required during the production. Thus total cost is divided into five major factors, which are discussed in detail below:

- *Machine usage cost* (*MUC*): It is a cost of using a particular machine for carrying out an operation on the job. It depends on the processing time of the job, type of operation, which is performed, and also on the nature of the job.

$$MUC = \sum_{i=0}^{TNOP-1} CM(M(i)) \times \Pr time[M(i)][J(i)][C(i)] \tag{1}$$

- *Machine change cost* (*MCC*): This is the cost incurred when the adjacent operation of a particular part require different machines.

$$\begin{aligned} MCC = &\sum_{i=1}^{TNOP} \phi(M(i); M(pos)) \times \\ &MCC(M(i); M(pos)) \end{aligned} \tag{2}$$

$$\begin{aligned} Pos = &\text{ Min } (jk) \text{ where} \\ &i < jk < TNOP \forall J(i) = J(jk) k \in (1, TNOP) \\ \phi(x, y) &= 0; \text{ when } x = y \\ &= 1; \text{ when } x \neq y \end{aligned}$$

- *Configuration change cost* (*CCC*): It is the cost incurred in changing the configuration of the particular machine. The cost incurred is machine dependent and on the previous configuration in which machine was operating.

$$\begin{aligned} CCC = &\sum_{i=1}^{TNOP} \phi(C(i); C(pos)) \\ &\times CCC(C(i); C(pos)) \\ Pos = &\text{ Min } (jk) \text{ where } i < jk < TNOP \forall M(i) \\ &= M(jk) k \in (1, TNOP) \end{aligned} \tag{3}$$

- *Tool usage cost* (*TUC*): It is the cost of using a particular tool. It depends on the type of the tool used, the processing time and the type of job.

$$TUC = \sum_{i=0}^{TNOP-1} CT(T(i)) \times \Pr time[M(i)][J(i)][C(i)] \tag{4}$$

- *Tool change cost* (*TCC*): It is the cost incurred in changing the tool as different operation may require different kind of tool. This cost varies from one machine to another.

$$\begin{aligned} TCC = &\sum_{i=1}^{TNOP} \phi(T(i); T(pos)) \\ &\times TCC(T(i); T(pos)) \end{aligned} \tag{5}$$

$$\begin{aligned} Pos = &\text{ Min } (jk) \text{ where } i < jk < TNOP \forall M(i) \\ &= M(jk) k \in (1, TNOP) \end{aligned}$$

Total time

Since the aim of the RMS is to be cost effective and responsive thus it is very important to consider the total time of the production in order to generate an optimal process plan. The total time will give the information about the time required for the last unit in the process plan to be manufactured.

- *Processing time of a particular operation:* It is the time required for the machine to process the job for particular operation. It depends on the machine, its configuration, job and the type of the operation to be performed. The information about the processing time may be obtained from the past data or by conducting pilot runs.
- *Tool changeover time:* It is the time required for a machine to change its tool depending on the type of operation to be performed on it.
- *Transportation time:* It is the time required for the transportation of the jobs from one machine to another. It is calculated in the case where a particular job has subsequent job performed on different machine.

- *Setup change time (Configuration change time):* It is the time required to change the configuration of the machine. It is accomplished by adding or removing the modules of the machine to change its functionality. The time involved in this activity depends on the machine and the previous configuration on which machine was operating.
  So, our objective function will be stated as below:

$$\mathrm{Min}\{\mathrm{Max}\ \{C_{\mathrm{i}}\}\} \tag{6}$$

where,

$$C_{\mathrm{i}} = (C_{\mathrm{i},Xj,k} | X_j \text{ is the last operation to be processed for a particular job in the generated process plan}) \tag{7}$$

$$C_{i,j,k} = S_{i,j,k} + \mathrm{Pr}\, time_{i,j,k} \tag{8}$$

$$S_{i,j,k} = Max(C_{i,j-1,k'} + Ttime_{i,k',k}, C_{i',j',k} + tCTime_{k,t1,t2} + CCtime_{k,c1,c2}); \quad \text{where } T_{j,k,k'} = 0 \quad \text{if } k = k' \tag{9}$$

- $S_{i,j,k}$ is the starting time of $operation j$ of part i on *machine k* which is calculated as the minimum time at which the particular machine can start its execution.
- $C_{i,j,k}$ is the completion time of *operation j* of part i on *machine k*.

Constraints

The constraints present in the system are discussed below:

- *Machine configuration capabilities:* Machine should be capable of performing the operation of the job assigned to it.

$$CTAD_{Mj}[C_j][TAD_j] = 1 \quad \forall\ j \in TNOP \tag{10}$$

- *Precedence constraints for operations:* All operation should satisfy the precedence cluster, which is assigned to them.

$$OPP(op_{i,x}, op_{i,y}){=}0\ \forall\ x > y; \text{ where } x, y \in TNOP \tag{11}$$

$op_{i,x}$ = operation corresponding to ith job and xth position

- *Operation assigned only once:*

$$op_{i,x} \neq op_{i,y}; \quad \forall x \neq y \quad \text{where } x, y \in TNOP \tag{12}$$

- *Tool capabilities:* The tool assigned to the operation should be capable of doing that job.

$$T_{\mathrm{j}} = OPT_{\mathrm{Jj}}[op_{\mathrm{j}}] \quad \forall j \in TNOP \tag{13}$$

T_{j} : Tool at jth position

$J\mathrm{j}$: Job at jth position

- *Machine and job should be free*

Developed methodology

The $M \times N$ (M machines and N jobs) scheduling problems fall under the domain of so-called NP-hard problems. Some of the scheduling problems are of the nature of multi-objective optimization problems and are exceedingly tough to solve using popular optimization techniques like integer programming and branch-bound techniques. Besides these, several approximation techniques like priority dispatch rules; bottleneck heuristics, etc have also been proposed to solve the classic Job Shop Scheduling Problems (JSP). Most traditional approaches to solving scheduling problems use simulation models, analytical models, heuristic approaches or a combination of these methods. In recent years, with the advent of better heuristic methods like GAs, simulated annealing, and other evolutionary algorithms inspired from naturally occurring phenomena, it has become possible to tackle these problems in a totally new way.

GA outperforms the standard algorithms, i.e., Simulated Annealing and Tabu Search in the context of problems related to FMS. The various renditions of GA differ primarily in the encoding methods. In this case a Multi Objective Genetic Algorithm has been used to generate a dynamic process plan for Reconfigurable Manufacturing System. Section "Algorithm adopted" further discusses the algorithm adopted and the MOGA used for this problem is described in detail in Sect. "Non dominated sorting genetic algorithm 2".

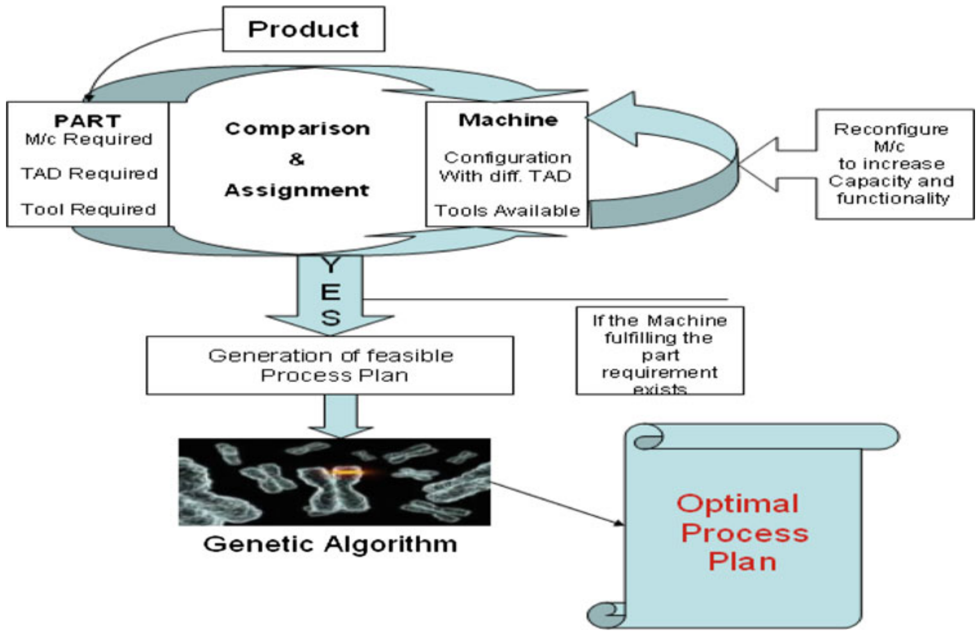
Algorithm adopted

A GA based approach is used to solve this dynamic scheduling problem. The algorithm adopted is described in detail below:

Step 1: Input the required information regarding the product and the machine.

Step 2: Number of parts, number of operation of each part, operation precedence graph, tools and tool approach direction required for each operation. Configuration available, Tools, TAD provided by each configuration.

Fig. 10 The steps followed in the proposed algorithm to generate an optimal process plan



Step 3: Compare the part requirement of a product with the functionality offered by the machines and find whether it is feasible to produce a particular part.

Step 4: If the functionality is not sufficient to manufacture the parts, identify the shortcomings and try to modify it by introducing more configuration or tools as required.

Step 5: If the functionality is sufficient to carry out the production of all the parts then for each operation of all the parts identify the machines and configurations, which are capable of manufacturing it.

Step 6: Generate a set of random feasible chromosome representing the process plans by the method described in section.

Step 7: Find the total cost and the total time values for the generated chromosome. The time and cost are the objective factors for deciding the optimality of the process plan.

Step 8: Apply the multi-objective genetic algorithm (MOGA) to obtain the optimal process plan. The MOGA used in the current algorithm is non-dominated sorting genetic algorithm, which is further discussed in the following.

The steps required for generating the optimal process plan is further illustrated by Fig. 10. Here the reconfigurable nature if the machine is also highlighted as the capacity and the functionality of the machine can be modified depending on the requirement.

Non Dominated Sorting Genetic Algorithm-2 (NSGA-2)

Introduced first in 1975 by Holland (1975), GAs have been used since then as a powerful meta heuristic global optimization method that can solve the NP complete problems. As the problem described above deals with more than one objective thus we have used a Multi Objective Genetic Algorithm (MOGA) in this case. The MOGA used in the current study is the so-called Non-dominated Sorting Genetic Algorithm 2 (NSGA-2) (Deb et al. 2002). The NSGA-2 is considered one of the champions in multi-objective optimization using GA (Fig. 11). The main advantages of the developed NSGA approach over the other MOGA variants are:

- Reduced computational complexity from $O(mN^3)$ to $O(mN^2)$ where m is the number of the objectives and N is the population size.
- The NSGA2 uses the non-dominated sorting approach, which ranks the solution of a population by layers of non-dominated solution.
- A crowded comparison operator is used in solution selection for diversity preservation.
- An elitism selection procedure that combines parent and offspring for the next population top solutions ranked first by the non-dominated sorting approach and then the crowded comparison approach.

The chromosome considered in this case is generated using the continuous domain variables. This kind of string structure makes it possible to generate feasible chromosomes

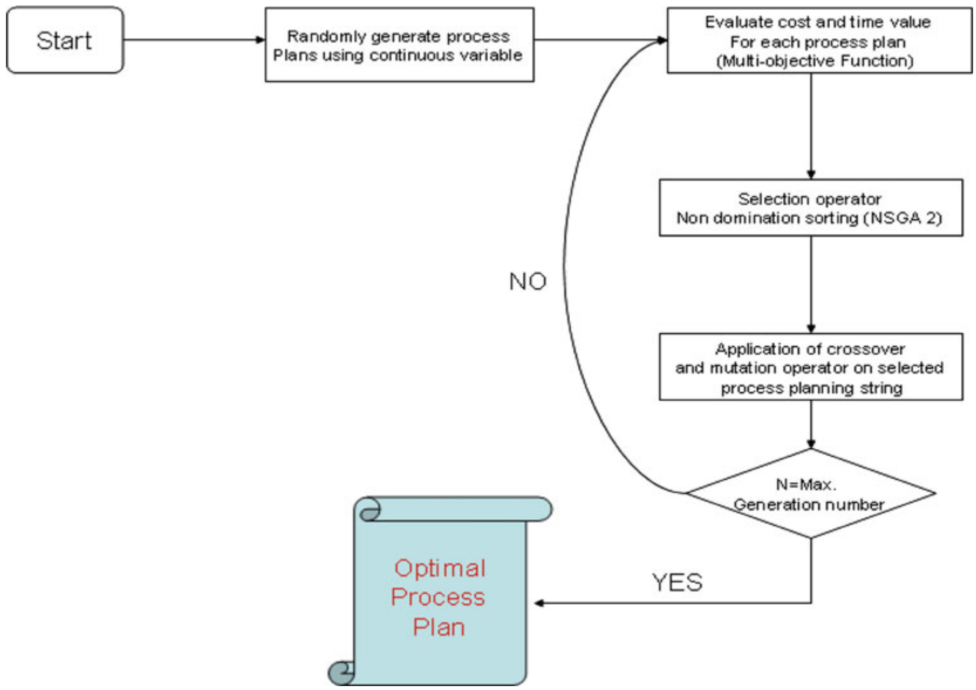


Fig. 11 Flow chart showing steps to be followed for NSGA-2

unlike the previous approaches. An example of such chromosome is shown in Table 2.

The encoded string contains six groups of variables part, operation, machine, configuration, tool, TAD and this string is further decoded to find the process plan and calculate the corresponding objective function values. The crossover and mutation operation are carried out in the encoded form. In this case the single point crossover is considered for the chromosome considered above. The decoding procedure has been illustrated in Table 3.

Table 2 Process plan containing randomly generated value between 0 and 1 in each cell

Part	.34	.45	.34	.344	.65	.76	.45
Operation	.54	.56	.32	.12	.78	.90	.08
Machine	.17	.22	.23	.54	.67	.86	.37
Configuration	.71	.56	.78	.32	.85	.32	.52
Tool	.5	.93	.59	.34	.77	.43	.12
TAD	.64	.90	.22	.48	.43	.21	.06

Genetic operations

Crossover and mutation are two basic genetic operators for searching new solutions starting from the current population. A single point crossover technique is been adopted in this particular case to generate new and improved solutions. A unique mutation method is used, i.e. the value present in the particular cell is replaced by another randomly generated number. This improves the search space explored by the algorithm. The crossover and the mutation operator are performed with a given crossover and mutation probability.

Before the crossover and mutation operations, individuals (chromosomes) are selected from the current generation to be parents. The individuals are selected based on the fitness, a value that reflects the quality of an individual. The larger the fitness value of an individual, the higher its chance of survival and reproduction. For a Pareto-based MOGA, a ranking procedure is necessary to determine the fitness. The rank of an individual is generally determined by its Pareto dominance in present population.

A Pareto-set filtering procedure is introduced to record the so-called Pareto-front solutions that are Pareto optimal among all solutions ever encountered by the GA. At each generation, after the ranking of the current generation, all nondominated individuals in the current generation are copied and put into an independent Pareto set. When new solutions are added into the set, a new round of dominance check (filtering process) is performed. Thus dominated ones are discarded and real nondominated points are reserved.

Experiment result and analysis

This section presents the optimal process plan, generated using the NSGA-2 minimizing the cost and time of manufacturing. The programming was done on an x86 family

Table 3 Decoding procedure for the chromosome comprising of random numbers to generate a feasible process plan

Variable to be decoded	Method
Part	Obtain all the part which can be placed in the particular cell, it depends on the number of operation left in that part (the part with more operation left is given more preference) e.g. part 1—four operations left, part 2—two operations so it will be 111122 and total number is six which is multiplied by the 0–1 value generated and rounded off to nearest integer
Operation	For the job selected analyze the operation precedence graph and obtain the total number of operations that can be placed in the particular cell and multiply it with the 0–1 value and by approximating it to the nearest integer obtain the operation
Machine used	0–1 value is multiplied by the corresponding number of machine which can manufacture the operation of the particular job. The value obtained is rounded of to nearest integer to obtain the machine used
Configuration used	For the machine selected, obtain the number of configuration, which can process the given job and multiply it by 0–1 value and round it off to nearest integer to obtain the configuration

Table 4 Operation precedence relationship matrix

	OP1	OP2	OP3		
Part 1: three operations					
OP1	0	0	0		
OP2	0	0	1		
OP3	1	0	0		
	OP1	OP2	OP3	OP4	OP5
Part 2: five operations					
OP1	0	0	0	0	0
OP2	1	0	0	0	0
OP3	1	0	0	0	0
OP4	1	0	1	0	0
OP5	1	0	1	0	0
	OP1	OP2	OP3	OP4	
Part 3: four operations					
OP1	0	0	0	0	
OP2	1	0	0	0	
OP3	1	0	0	0	
OP4	1	1	1	0	

Table 5 Tools required for the various parts to be manufactured

Part 1	1	2	1		
Part 2	3	5	4	1	1
Part 3	3	4	4	2	

1.6 GHz Intel processor having 1 GB RAM, using JAVA as a programming tool.

The various genetic operators and their criteria are defined as follows:

- Initial population generated randomly
- Population Size (*pop*) = 200
- Crossover criteria (C_p) = 0.75
- Mutation criteria (M_p) = 0.35
- Maximum number of generations (*Gen*) = 15000

The input data here consists of operation precedence relationship matrix for each part to be manufactured, tools required and the tool approach direction for each operation. Since reconfigurable environment is considered with modular structure thus machines may exists in different configuration. Machine input specification includes approach directions provided by different configurations and the tools available with the machines.

It is assumed that each job consists of three parts. Part 1 consists of three operations, part 2 consists of five operations and part 3 requires four operations to be performed. Table 4 gives the operation precedence matrix for each part. The tools and tool approach direction required for the processing for each chart is mentioned in Tables 5 and 6.

There are three available machines in the shop floor. Each machine is reconfigurable in nature, machine 1 currently can exist in three different configurations, machine 2 in four different configurations and machine 3 possess two different configurations providing different tool approach directions as shown in Table 7. The tools available with the machine are also shown in Table 7. In this case, a machine existed for each part so there is no error message generated.

If there was lack in functionality of the machine, an error message would have appeared showing the part which could not be produced and the lack of functionality which led to that. Table 8 shows the Total time and the Total cost values for each non-dominated solution. A particular solution can be selected depending on the managerial policy of the company. The company may either select a process plan requiring lower cost and more time (Table 9) in case of reduction of manufacturing cost or it may adopt the one with higher cost and lesser time (Table 10) when the product has to be launched early in the market.

Figure 12 shows the plot of the *Total Cost* vs *Total time* obtained. This further helps in analyzing the decision about selection of the process plan, which may help in generating

Table 6 Tools approach direction required by different parts

	+X	−X	+Y	−Y	+Z	−Z
Part 1: TADs required						
OP1	1	1	0	0	0	0
OP2	0	0	0	0	1	1
OP3	1	0	0	0	0	0
Part 2: TADs required						
OP1	0	1	0	0	0	0
OP2	0	0	0	0	1	1
OP3	0	1	0	0	0	1
OP4	0	0	0	0	1	0
OP5	0	0	1	1	0	0
Part 3: TADs required						
OP1	0	0	1	0	0	0
OP2	0	1	0	0	0	0
OP3	0	0	0	1	0	0
OP4	1	0	1	0	0	0

Table 7 TADs provided by different machine configurations

	+X	−X	+Y	−Y	+Z	−Z
Machine 1						
C1	1	1	1	0	0	0
C2	1	0	1	0	1	0
C3	1	1	0	1	0	1
Machine 2						
C1	1	0	0	0	1	1
C2	0	1	1	1	0	0
C3	0	1	0	1	0	1
C4	0	0	1	1	1	1
Machine 3						
C1	0	0	0	0	1	1
C2	1	1	0	0	0	0
Tools available with machine						
Machine 1	1	4	2			
Machine 2	2	3	1	6		
Machine 3	1	7	5			

Table 8 Total time and cost values of optimal process plan

Total cost ($)	Total time (s)
3306.0	43190.0
3358.0	30600.0
5182.0	22367.0
5350.0	17979.0
4830.0	27808.0
4143.0	28766.0

maximum profit for the company both in terms of the reduced cost and time to the market.

Conclusion and future perspectives

The concept of reconfiguration has sparked interest in the academic and industrial communities. It has encouraged active research into supportive areas that are proving very

Table 9 Optimal process plan 1 (cost: 3306, time: 43190)

Part	P2	P3	P1	P2	P1	P3	P2	P2	P3	P1	P3	P2
Operation	OP1	OP1	OP1	OP2	OP3	OP2	OP3	OP5	OP3	OP2	OP4	OP4
Machine	M2	M2	M1	M3	M1	M1	M1	M2	M1	M2	M1	M3
Configuration	C3	C4	C3	C1	C3	C3	C3	C2	C3	C4	C1	C1
Tool	3	3	1	5	1	4	4	1	4	2	2	1

Table 10 Optimal process plan 2 (cost: 5350, time: 17979)

Part	P1	P3	P1	P2	P3	P2	P3	P2	P2	P1	P2	P3
Operation	OP1	OP1	OP3	OP1	OP3	OP2	OP2	OP3	OP5	OP2	OP4	OP4
Machine	M1	M2	M1	M2	M1	M2	M1	M1	M2	M2	M3	M1
Configuration	C1	C3	C1	C3	C3	C4	C3	C3	C2	C1	C1	C1
Tool	1	3	1	3	4	5	4	4	1	2	1	2

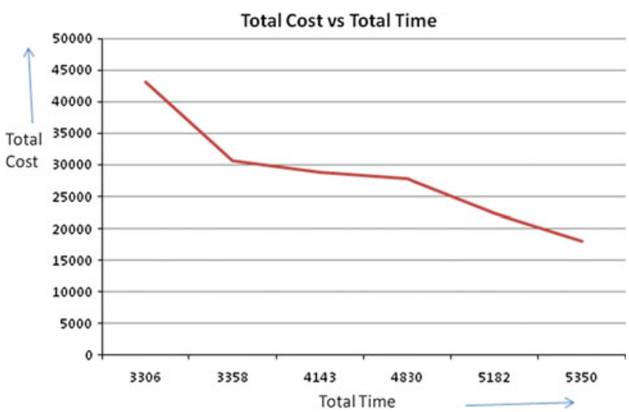


Fig. 12 Graph between total time and total cost

beneficial to existing manufacturing systems. The technology required for the RMS system needs to be developed in order to implement it in production and derive benefits. A study by the national research council (NRC 1998) has identified reconfigurable manufacturing as the highest priority for the future research in manufacturing challenges for the year 2020.

Understanding the need for a change, this paper initially focused on the problems with the existing manufacturing systems and the shortcomings, which it faces in the current market scenario. The key features of the Reconfigurable Manufacturing System were also listed in subsequent sections and the benefits of RMS over other manufacturing systems were identified. Also the paper highlighted the problems in the implementation of the new technology and listed out areas where focus has to be directed.

The problem of designing an optimal process plan for reconfigurable manufacturing environment was considered. The NSGA-2 algorithm was adopted and a set of non-dominated solutions considering time and cost of production as decision variables were generated. These solutions were further plotted on a Pareto front, which will further assist the management in making the decision regarding the configuration of the machines to be used for carrying out the production.

Future research can be targeted around better heuristic procedures and parallel computing to solve various seemingly difficult combinatorial problems encountered in RMS. The developed model can be further extended by incorporating various other constraints like machine failure. Data mining rule based approach may be used with NSGA-2 to reduce the computation time which may help to achieve maximum benefits of RMS.

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