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Co-Evolution and algorithmic generation of machining process plans and kinematic configurations

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ABSTRACT

The field of manufacturing is one of the oldest and the most established industry of the world. It has been evolving and developing for many ages. The concept of using machines to develop the products started in the early twentieth century. At the end of the twentieth century a new manufacturing system known as RMS (reconfigurable manufacturing systems) was introduced. It completely revolutionized the manufacturing setup with reconfigurable machines which can adapt to the changes in the products while accommodating the machinability issues as well.

As the ability to adapt increased, the demands for changes in the products increased as well. Due to the rapid changes in the products these days, the process plans and the structures required to develop the products following the process plans are changing at a rapid pace as well. Traditionally, the approaches developed for the process plans and kinematic configurations of RMS either focus on the process plans and then develop the corresponding kinematic configurations or develop the kinematic configuration and then the process plan. Furthermore the issues that these approach address make them unilateral: i.e. the approaches either minimize the initial cost of production or the overall production rate while completely ignoring the overall quality of the product.

This thesis is focused on improving the previous approaches and to address certain issues regarding co-evolution. The approaches that have been improved are algorithmic in general, however, a Petri-net model for a particular system has been proposed as well. Furthermore, an algorithm for changing parts within the same part family is presented. It explores the complete solution space for a particular part group. The application of the proposed algorithm is illustrated by its implementation on automotive parts, having a set of machining features to be realized.

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Contents

List of Tables

List of Figures

List of Abbreviations

DML	Dedicated Manufacturing Lines
DMS	Dedicated Manufacturing System
FMS	Flexible Manufacturing System
RMS	Reconfigurable Manufacturing System
CAPP	Computer Aided Process Planning
RMT	Reconfigurable Machine Tool
CNC	Computer Numeric Control
CPGA	Configuration and Plan Generation Approach
MSCA	Machine Structure Configuration Approach
PPCGA	Process Plan and Configuration Generation Approach
CAD	Computer Aided Drawing
CAM	Computer Aided Manufacturing
AI	Artificial Intelligence
MEGF	Machining Enabled Geometrical Feature
OSE	Operation Sequence Entity
TAD	Tool Approach Direction
B:	Boring Operation
M:	Milling Operation
Ch:	Chamfer Operation
F:	Facing Operation
R:	Reaming Operation
PEPP:	Previously employed process plans.
PPP:	Proposed process plan.
CPP:	Counter for the difference in PPP and PEPP’s operations.
CKC:	Counter for the overall kinematic configuration difference between PPP and PEPP.

Chapter 1:
Introduction

1.1 Background

Since the start of human history, manufacturing has remained an integral part of life. Laying down the definition of manufacturing in simple and compact words, it can be understood as the conversion of raw materials into finished products. The wheel which is the first product developed by man started an unending era of development. The early twentieth century led to the automation of manufacturing. The production when left unorganized, lead to unfinished products, low production rate and other similar issues. Therefore, a need to organize this production was felt and the concept of manufacturing systems emerged. Since the dawn of automation, many different systems were introduced. These systems are divided into three main categories:

- Dedicated Manufacturing Lines
- Flexible Manufacturing Systems
- Reconfigurable Manufacturing Systems

These systems, along with suitable examples are discussed in the following sections:

1.1.1 Dedicated Manufacturing Lines

The automated machines in the early twentieth century consisted of fixed mechanisms which were designed to serve any single purpose. Examples of these include: cork fitting, bottle capping and basic assembly mechanisms. These machines constituted the manufacturing system which is known as Dedicated Manufacturing System (DMS) or Dedicated Manufacturing Lines (DML) designed specifically to serve a single dedicated purpose. Examples of the complete system include the bottle making plant or the cement plant (Figure 1).

Because the system is designed to produce a single product with few or no changes, DMS is very suitable for high production rates. Skill level requirement for the labor and the training required to operate the machines is low. The machines are perfected over the years for the same product, therefore requiring very low maintenance. Consequently, the machines have a very high initial cost. The system has a conventional rigid structure and the machines are generally interconnected by a set of production lines, hence the name dedicated manufacturing lines. The overall setup of the system is also rigid, thus the up gradation potential of the system does not hold much promise. Focus of DMS is the product or the part that it produces. This focus seriously hampers the development of any change in the part specifications. DMS in the current age is gradually becoming obsolete due to the changing customer needs and its inability to cope with this change.

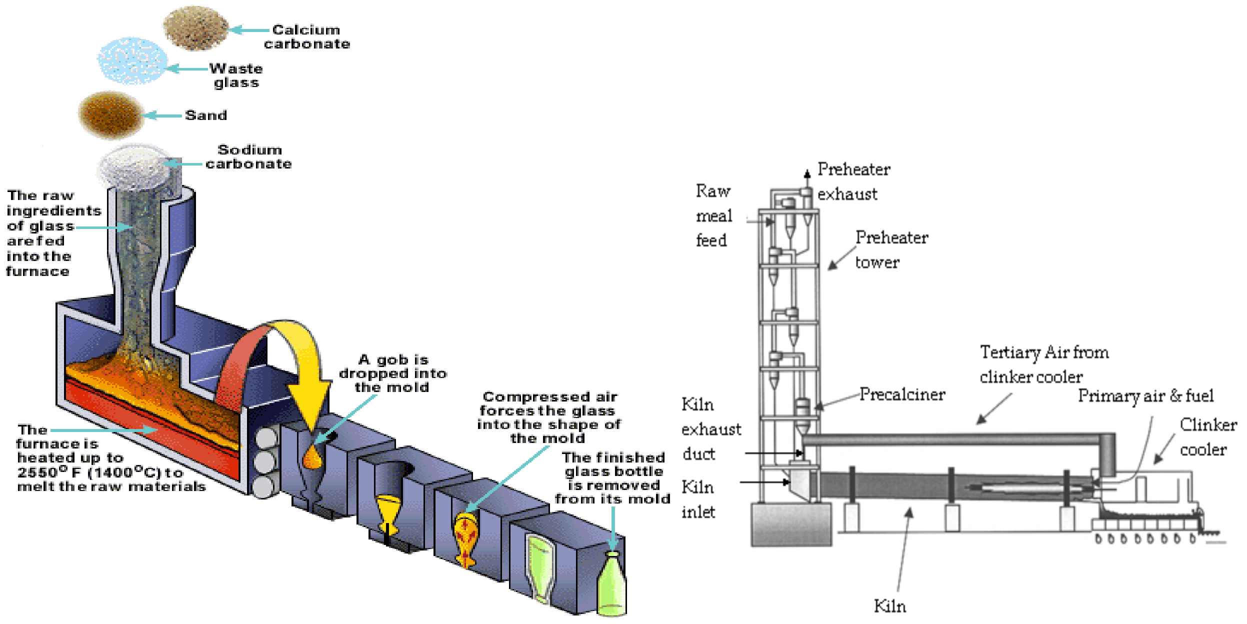

Figure 1: Examples of DML from left to right: bottle making plant [1] and cement plant [2].

1.1.2 Flexible Manufacturing Systems

In the late twentieth century, the concept of Flexible Manufacturing Systems (FMS) emerged. FMS is a very popular manufacturing system in current times. FMS is based upon cellular manufacturing. There are different manufacturing cells for each type of operation. For example; there can be: one cell for drilling operations, another for surface finish and another for milling. FMS, in this thesis, is limited to machining operations to produce metal products. In general, however, FMS has proved to be suitable for developing a high variety of products. Figure 2 shows an example of flexible manufacturing plant.

Figure 2: An example of FMS Plant [3].

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[1] http://www.wisedude.com/science_engineering/bottles.htm

[2] http://www.intechopen.com/books/alternative-fuel/alternative-fuels-in-cement-manufacturing

FMS can adapt to substantial changes in the final product. If for example, a hole has been relocated in the design of a product, only the drilling cell will require minor adjustments allowing the system to drill the hole in the new location. DMS does not have this capability. Hence, different products can easily be made by simply changing the surface finish or the locations of the operations on the surface etc. The order/ sequence of operations on the part can also be changed in FMS by changing the order of the operation cells.

1.1.3 Reconfigurable Manufacturing System

Near the end of the twentieth century, the concept of Reconfigurable Manufacturing Systems (RMS) emerged. This manufacturing system has reconfigurable machines consisting of many tool posts and a high degree of freedom, thus having the capability to develop many different products using a single platform. The main difference between RMS and FMS is that RMS has reconfigurable machines which generally have a single unit (see Figure 3) and FMS has dedicated set of fixed machine structures (manufacturing cells). Many new paradigms have been developed in manufacturing during the past decade. Further details on manufacturing systems can be found in ref. [1].

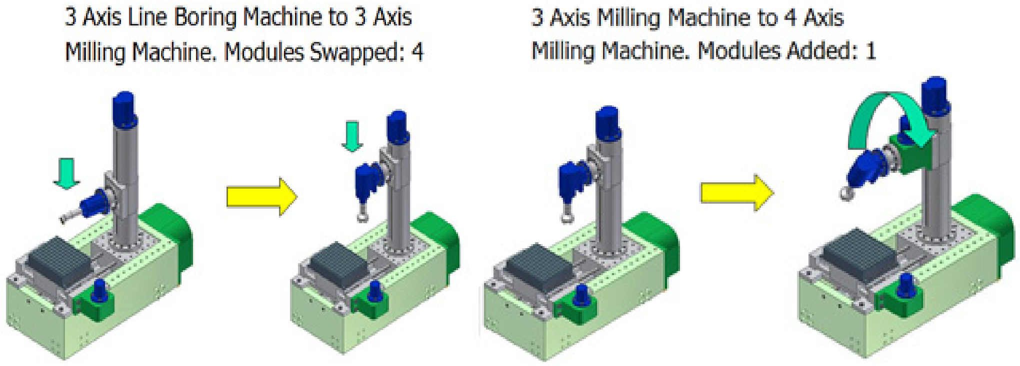

Figure 3: Reconfigurable machines having different capabilities w.r.t. modules attached [2].

RMS due to less lead time and the ability to adapt to changing market trends is an effective and successful manufacturing system of the current era where tough competition and unanticipated customer requirements is a regularity. RMS can convert its production methodology from a low volume single batch production to the high volume line production by changing the tool posts and the sequences, thus its usefulness is obvious. RMS is basically designed for automated industries, therefore two level of configuration is required, first at the overall system level and the second at the localized machine level i.e. tooling and tool positioning. Therefore, two levels of control is also a requirement in RMS, software control at the system level and a G&M code (CNC) control at the hardware or machine level. This starts

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[3] http://www.scribd.com/doc/47683872/Process-simulation-using-Delmia-2003-final

off with the algorithms developed to control the system level and once the overall system is configured, the algorithm is converted to G&M codes which control the CNC machines. A comparison of the three manufacturing systems is shown in Table 1 indicating that overall RMS is a more suitable choice as a manufacturing system.

Table 1: Comparison between DML, FMS and RMS.

Factors	**DMS**	**FMS**	**RMS**
Complexity	Low	High	Medium
Initial Cost	High	High	Medium
Skill level and Training required	Low	High	Medium
Capacity to Integrate new additions	Low	Low	High
Up gradation Potential	Low	Low	High
Structure	Rigid	Rigid	Modular
Product variety	Low	High–Very High	Medium –High
Production Volume	High	Variable	Variable
Machine Structure	Fixed	Fixed	Adjustable
System Focus	Part	Machine	Part Family
Flexibility	No	General	Customized

Whenever a new part is introduced for the production purpose in any of the three systems, there are a lot of operation sequences and manufacturing processes by which that part can be produced. The selection of these can be based upon many factors such as available machinery, production rate required or the quality (tolerance limit) of the product. Still, in general there are a lot of feasible configurations that can be applied for any said production unit. These can not only be economically feasible for the system but also be within the capabilities of the available machinery.

To develop process plans (operation sequences), one first needs to understand the manufacturing system. In conventional approach when computer aided process planning systems (CAPP) is used, the machine components are considered static and only one process plan is developed for the system (dedicated manufacturing lines). On the other hand, recently most of the research is being carried out to develop multiple process plans and a system to implement them. The CAPP for RMS which is known as reconfigurable process planning (RPP) allows much freedom in this regard. Multiple process plans can be developed and multiple machine configurations can be deducted from those process plans. This concept is illustrated in Figure 4. The conventional approaches developing a single process plan for a single part and then multiple options exist for the selection of structure for that single process plan. In case of RPP, there are multiple possibilities of process plans for a single part. Therefore, the possibilities for the structure (see section 1.1.4) are multiplied as well.

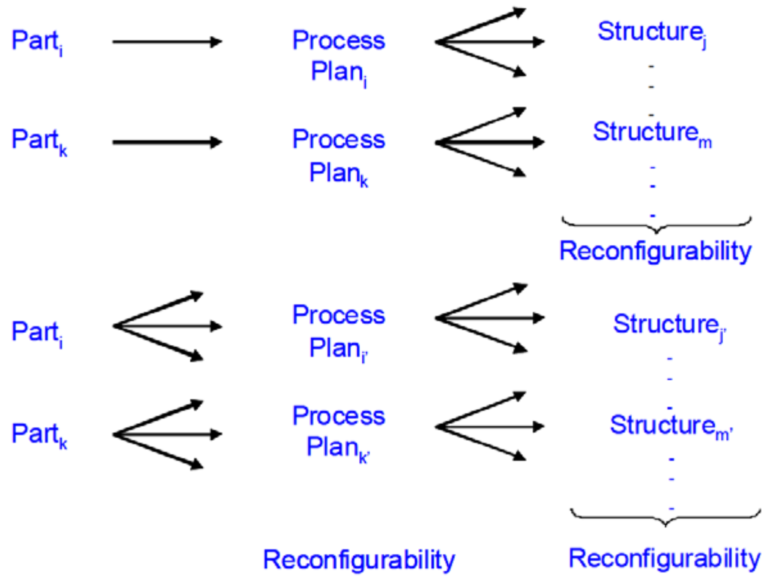


Figure 4: Enhancement of the domain of reconfigurability [3].

Process plan selection is a cumbersome task, which requires many hours of labor. Even after that, selection of one particular process plan which will take minimum time, have precise results and require relatively simple machinery is very rare. Thus, there are a number of process plans which are suitable for a single product based upon the selection criteria. For example, if the selection criterion is production rate then a particular process plan may be suitable, but, it may not be suitable if the selection criteria changes to quality and so on. The following text consists of different topics required for the development of basic understanding of manufacturing systems.

1.1.4 Machine Structures

A kinematic chain-like diagram is suitable for the representation of the machine tool structure [4]. The whole machine structure can be divided into two different segments of a chain. One starts form machine structure and ends at the work piece. The other starts form the machine structure and ends at the tool. The tool and the work piece interact to form the desired product as shown in Figure 5.

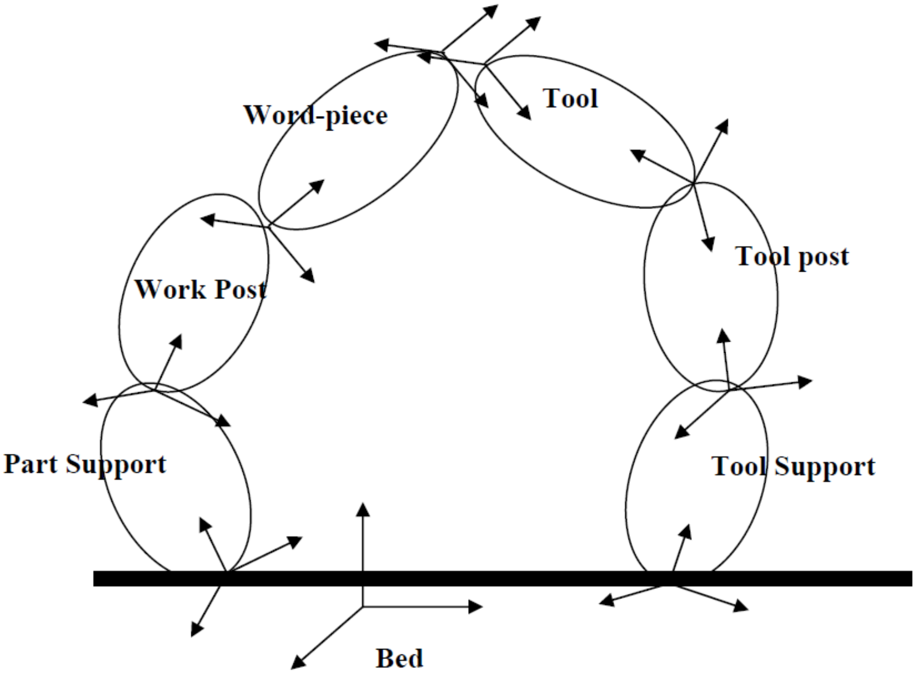


Figure 5: Chain-Like Diagram [4]

The kinematics of the machine structure of any machine has two possibilities: either the work piece travels along all the movements' axis to reach the tool or the tool moves from its default position towards the work piece to perform the specified operation. The first solution is considered redundant because generally the work piece is generally quite large and if it is made to travel along different axis of motion then the clamping and other factor cause serious issues in its manufacturing. Therefore it is more convenient to make the tool travel the specified path using several degrees of freedom to reach the work piece and perform the specified operations which is the general case in RMS. Still, some machines have the work piece move along the translational axis whereas the tool has the rotational degree(s) of freedom.

1.1.5 Machining Workspace

Machining workspace, as the name implies is the space in which the machine can perform operations (work), and outside of this space no machining operations can take place. If the configuration of axes is different, then the machining workspace of the machine is different and therefore their capabilities vary as well. If the overall axes of two different machines are same however, they will have the same machine capabilities. For example, if a machine has three translations, one rotation on the tool side and another has three translations on the work piece side, one rotation on the tool side then both of these machines will overall form same machine kinematics. Still, the approach to perform any operation may be different in both cases.

The machine with all the degrees of freedom on the tool side will have the tool moving along the axes, whereas in the second case the work piece will be moving along the translational axes and the tool rotational axes to perform any operation as per requirement. Figure 6 shows a sample 5-axis machine with all the movements at the tool side along-with its kinematic representation in Figure 7. The kinematic chain like representation of the tool in Figure 6 shows that the tool can move in the x, y, and the z directions and due to the modules attached very close to the tool, two rotation axis (around y and z axes) are possible. Therefore, the overall capability of the machine is 5 axes.

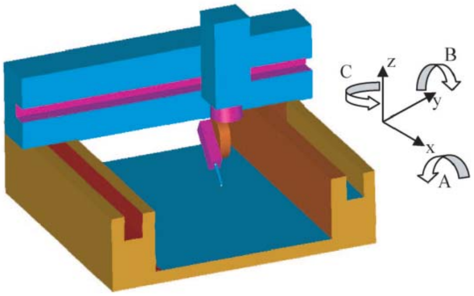


Figure 6: Five axis machine tool. [5]

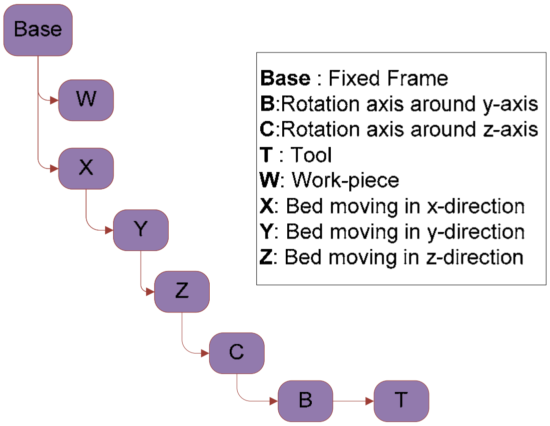


Figure 7: Kinematic-like structure for the five-axis machine tool in Figure 6.

The size is also an important consideration especially for large work pieces. If these work pieces are large enough, some portion of their body falls outside the machining workspace and is therefore; not machinable. It is imperative that the machine should have sufficient work space to accommodate the work piece.

1.1.6 Process Plans

The process of determining the sequence of operations for manufacturing a part from its design specifications is called "process planning" [6,7]. Therefore, the process plan signifies all the operations in a certain sequence to machine the work piece into the end product. For the production of any product, generally there a number of operations required. In terms of machining; they may be drilling, boring reaming, surface milling and so on. Each of these operations may be required a number of times on different surfaces of the work-piece. Figure 8 shows a sample end product along with its different desired operations. Observing this, it can be concluded that there are a number of operation sequences that can be followed and therefore multiple process plans that can be implemented to develop this product. Table 2 shows some of these sample operation sequences of the product shown in Figure 8. These operation sequences can be separated and prioritized on a number of factors such as production time, accuracy, machining structure required and so on.

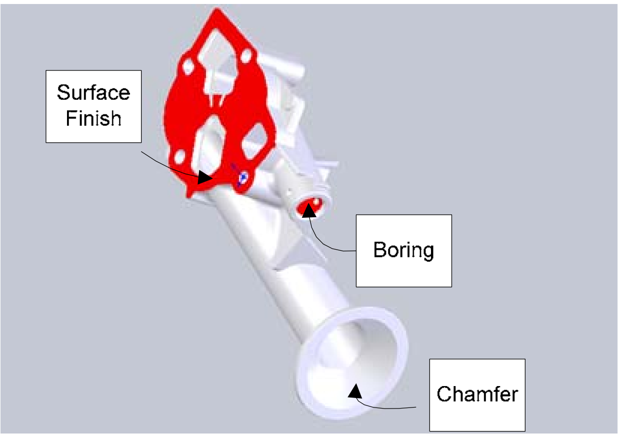


Figure 8: A sample end product [8].

Table 2: Possible operation sequences (Op. Seq.).

Sr. No.	Op. Seq. 1	Op Seq. 2	Op. Seq. 3
1.	Surface Finish	Boring	Chamfer
2.	Chamfer	Surface Finish	Boring
3.	Boring	Chamfer	Surface Finish

To generate process plans, two approaches are currently used. Firstly, variant process planning based on alternative cases and second is generative process planning (Figure 9). All parts already designed and machined in the company are categorized according to their morphology and dimensions, process plans or other intrinsic characteristics considered relevant and discriminating [9]. When a new part is designed, it is possible to find all similar cases and thus to select the corresponding plan [10]. The use of such a method requires tremendous capitalization of the know-how [11]. In addition, the durability of plans and technical solutions produces lack of flexibility as it is impossible to adjust one routing if the part to be realized differs locally from the saved reference.

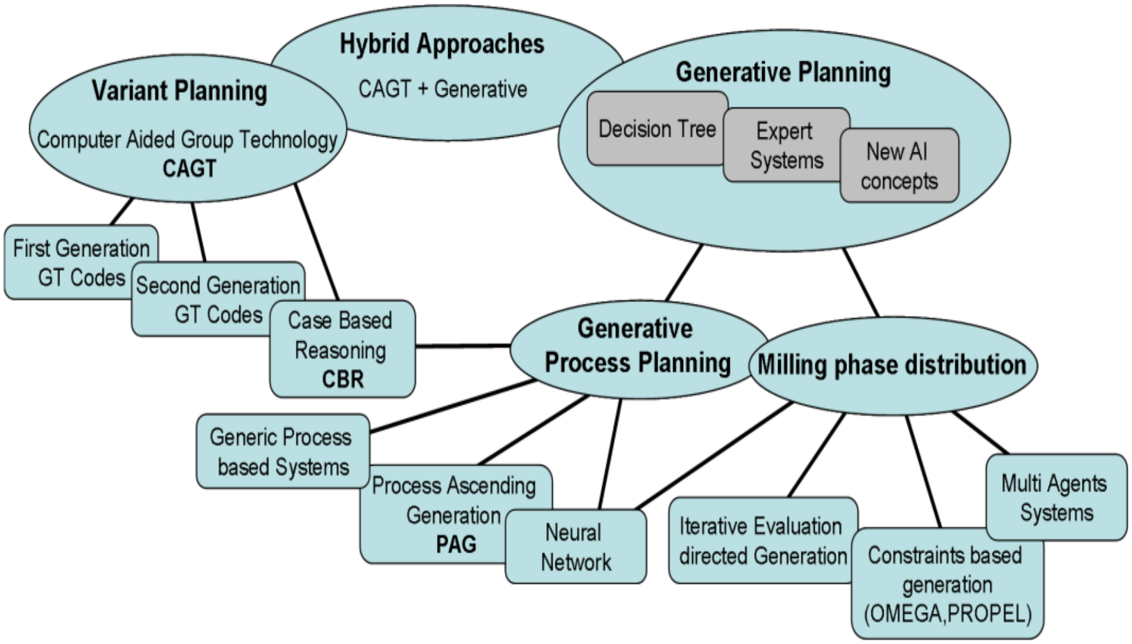


Figure 9: Applicability of the domain of reconfigurability. [9]

The second approach is the generative approach; it does not retrieve and modify an existing process plan but rather consists of generating one when a new part is designed. Furthermore, this method does not capitalize the problem and its solutions (the machined artifact and its process plan) but rather capitalizes the method and operations needed to find a solution. In generative process planning, process information of a part is used to construct a process plan which improves the manufacturing process and generates the required part programs to machine the part.

To reduce the production time, the operation sequence should be such that the overall time to produce the part is less compared to other possible operation sequences. This can be achieved by: performing operations on the same face of the work piece in a sequential manner, performing operations with the same tool requirement in continuous order, performing parallel operations and using high spindle speeds and feed rates. The process plans with less production time require more machining structures and other factors such as accuracy may be reduced. Conversely the process plans that require less structures cost more in terms of production time.

1.2 Literature Review

The machine tools which allow the concept of reconfigurability to be implemented while keeping flexibility and productivity in check are known as Reconfigurable Machine Tools (RMT's). The first of these is named SHIVA and was developed in 1992 by O. Garro and P. Martin [12, 13]. That work presents a design methodology for the development of machine tools, which was further elaborated by Tollenaere in 1998 [6], using the concept of machining feature. SHIVA consists of multiple spindles allowing it to perform multiple operations on a fixed work piece. These spindles can either be used in sequential or in simultaneous manner. Simultaneous operations can cause more vibrations as well as the issues of accessibility, especially when the machining features are very close to each other. On the other hand, sequential operations require a lot of time. Here, the concept of operation sequencing required some sort of mathematical basis which O. Garro presented with the help of temporal logic. The logic was only a basic step towards RMS and did not detail the step involved especially positioning and orientations. Many other RMT's have been developed throughout the years after the introduction of SHIVA.

A RMT design methodology was required for the standardization of RMT's and was presented by Moon and Kota in 1999-2000 [14, 15]. Before that, C. Chu et al in 1996 presented different techniques for the setup minimization for process plans based on product design [16]. This approach did not provide with the necessary knowledge for its generic implementation and therefore was not used as a basis for RMS. Y. Koren finally implemented the machine structure quality analysis and multi spindle approach [17, 18]. The analysis of these structures was carried out by Bonev [19] and ElMaraghy [20]. In 2003, N. Ismail et al tied to combine the concepts of flow line and RMS [21]. Further research was required for the implementation of this concept on industrial scale but is still a fascinating area of research. J. Dou further developed this concept in 2007-2008 [22, 23]. Keeping all this in mind, the concept of RMT goes beyond the basis of RMS. The RMT should not only be modular (customizable and adaptive to new technologies), but it should also be cost effective and have high speed capabilities. A scientific basis of RMT's was presented in this approach.

RMTs allow the development of machine configurations of RMS. In 2006, A. Yusuf and H.A. ElMaraghy developed a methodology for the optimal machine configuration selection for RMS [24]. Moving in the same direction; in 2007, A.I. Shabaka and H.A. ElMaraghy [5] developed an approach for the minimum machine configuration selection based upon product features. The approach presented by them is known as machine structure configuration approach (Section 2.2). The inputs of this approach include the part dimensions and tool approach directions for the operations that are to be performed on the work piece. The operation precedence graph developed manually is also one of the inputs. The output is the minimum machine configuration required to produce the product.

In 2010, T. Tolio et al [25] presented the concept of co-evolution in manufacturing. The co-evolution paradigm synthesizes the recent scientific and technical approaches proposed by academic and industrial communities dealing with methodologies and tools to support the coordinated evolution (co-evolution) of products, processes and production systems. In conventional approaches for a specific product either the kinematic configuration (machine Structures, rotations, modules etc.) is fixed and the process plan (operation sequence) is developed for this kinematic configuration or the process plan is specific and the kinematic configuration is developed accordingly. The concept of co-evolution focuses directly on developing both the configuration and the process plans simultaneously for the changing product. The industrial cases support the following premises:

- The co-evolution of products, processes and production systems is a relevant industrial challenge, the complexity of which will continue to grow in the future.
- The co-evolution challenge can be addressed on multi-levels specific to the industry (e.g. flexibility, reconfigurability, modularity, technology migration) and markets because of the multiple levels of configuration of RMS.
- Managing co-evolution is economically beneficial both for technology users and for providers. Industrial companies are experiencing a trend towards increased investments in their ability to drive co-evolution.[25]

The co-evolution paradigm (Figure 10) highlights the issue that all the three components of the manufacturing system i.e. the product, processes and the production systems are interrelated. Any changes in the product will cause changes in the processes as well as the production systems. Similarly, any changes in production system will cause a change in the product (change may be higher accuracy, better surface finish etc.) as well as the processes (change may result in different operation sequences).

T. Tolio et al [25] reviewed most of the research work done till 2010 and then on the basis of the concepts of co-evolution in manufacturing, arranged it on an evolution axis (Figure 11). However, it should be noted that the term, “co-evolution” was used for the first time by T. Tolio et al in 2010. Still, the authors based on that concept compiled all the research data from the previous research according to relevance to co-evolution. The research work consisted of those papers which presented approaches for RMS and FMS. In Figure 11 the changes in products, processes and production systems represent the corner lines of the prismatic shape. The evolution axis is positive in the upward direction which actually represents the level of evolution of the research work. There are four levels of the evolution axis 0, 1, 2 and 3. The papers are stacked within this prismatic shape with triangular basis. Clusters are formed within the sets of papers and are labeled A, B, C and so on. The papers present at a higher level of the evolution axis (Y = 2, 3) are much more relevant to co-evolution as compared to the papers at a lower level of the evolution axis:

- Y=0: Papers not considering co-evolution
- Y=1: Papers very slightly considering co-evolution
- Y=2: Papers mildly considering co-evolution
- Y=3: Papers strongly considering co-evolution the co-evolution problem.

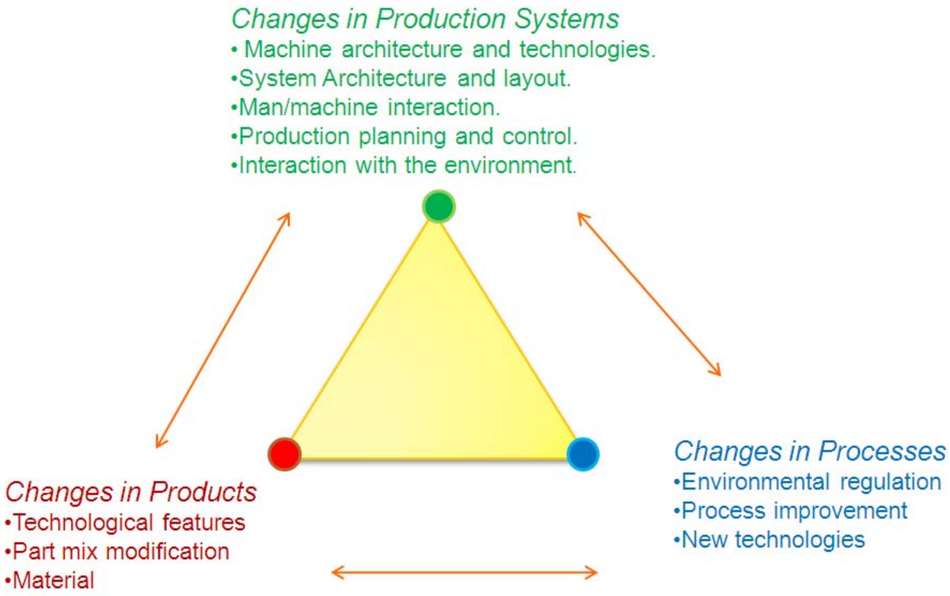


Figure 10: The co-evolution paradigm

The research work relevant to RMS present at level Y=3 is located in the 'O cluster' (Figure 11). The limitation of this review is the publication date. The research work carried out in and after March, 2010 is not a part of T. Tolio et als' work. Therefore, a thorough review of the papers presented in this period was carried out as well. The following text sheds some light on the research work in 'O cluster' and on the research after the publication of this review paper.

The ability of a production system to reconfigure itself according to the changes in its product can be heavily jeopardized if it is not supported by the evolution of the process plans. The present structure of NC codes is still mostly rigid, and the part programs require relevant changes when the production plan is modified (e.g. an operation is assigned to a different machine), or the production system is reconfigured (e.g. a flow line substitutes a job-shop), or the product evolves (e.g. removal/addition of a product feature). Therefore, methodologies are required to enable the rapid generation of process plans and their easy adaptation. The generation of reconfigurable and adaptive process plans can be supported by adopting a process plan approach that consists in relaxing constraints that are not strictly technological [26]. The resulting network of operations, compared to the traditional rigid sequence, enables to execute the operations according to various sequences and on different machines [27], quickly reconfigure process plans [28] and develop new loading and scheduling methods [29].

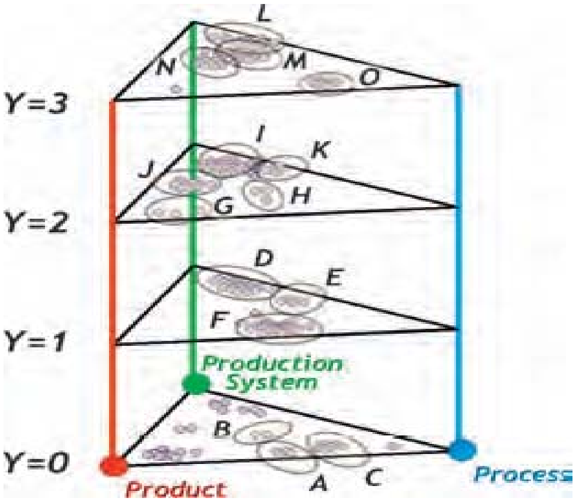


Figure 11: Papers represented in the co-evolution model and cluster analysis. [16]

A. Markus et al [30] proposed a generic constraint-based model for CAPP together with appropriate solution methods and applied to different industrial domains [31, 32]. A further approach to reconfigurable process planning has been recently developed focusing on (1) minimizing the parts handling and re-fixturing time and (2) minimizing the cost of changes in the evolved process plan referring to setups, tools, re-programming costs [33, 34]. In addition, evolving process plans have an impact on device configuration, especially in RMS [5]. He also proposed a constraint based approach for sheet metal bending allowing it to be a new avenue of research [31].

In 2010, A. Baqai [35] presented the process plan and the corresponding kinematic configuration approach. The approach focuses primarily on the development of the most suitable process plan for a given part and then the selection of the kinematic configuration based upon that process plan. Due to the primary focus on process plans, the focus shifts from the main concept of co-evolution. On the other hand, because the approach considers the machine configuration as well as the process plans, this approach after improvement can be brought closer to the concept of co-evolution.

1.3 Need

The concept co-evolution focuses on the simultaneous development of process plans and kinematic configurations. Some approaches proposed by different authors over the years have considerable relevance to co-evolution. This relevance based on Figure 11 shows that there is still room for improvement. The approaches which consider both the process plans and the kinematic configurations still focus on one of these aspects more as compared to the other. The relevant approaches along with their focus are shown in Table 3.

Table 3: Different research and its focus.

Sr. no.	**Paper Author**	**Focus Process**	**Focus Structure**
1	T. Tolio (2010)[25]	High	High
2	A. Yousef (2006) [24], El Maraghy (2007)[5]	Low	High
3	Chu et al (1996) [16], And'ras et al (2001)[32]	High	Low
4	N. Ismail et al(2003) [21], J.Dou et al(2007) [22],	High	Low
5	Andras et al(2006) [34]	High	Low
7	J. Dou et al(2008)[23], Y. Koren et al(2003)[17, 18]	Low	High
8	Bonev (2004) [19], H.A. El Maraghy et al(2004)[20]	Low	High

In Table 3 it can be seen that in general, the authors either focus on the processes or the structures that are required to execute the processes. Very little work has been done to develop both of these simultaneously. Therefore, there is a need to develop an approach which focuses on simultaneously developing the process plans and the kinematic configurations. This will not only help in increasing the production of the industry, but also save in terms of production time, ramp up time (time taken to incorporate changes) as well as improvement in the long term cost-benefit ratio. The drawback of this will be the initial cost of the industry. This issue is addressed in chapter 5.

1.4 Objective

The objective of this thesis is divided into four parts:

- Improvement & Development of Existing Approaches bringing them closer to co-evolution
- Proposal of a New Hybrid Approach which caters for the shortcomings of the existing ones.
- Modeling of design process using design modeling techniques.
- Using available data presenting an approach which reduces the initial cost of production.

The overall objective is to improve the process planning and kinematic configuration approaches on the basis of co-evolution. The previous work only focused on the one of these aspects in their concerned hierarchy. Due to the concept being relatively new, the problems associated with co-evolution are yet to be fully explored. The thesis focuses on developing a new pathway which brings the design approaches closer to co-evolution. Furthermore, if this evolved approach is not presented in a globally understandable and relatively simple mathematical and illustrative technique, the approach may fail to serve its purpose. Also due to limitations in the evolutionary state, if the current approaches are incapable of accommodating these changes, then a new hybrid approach becomes a necessity. And finally, it is a known fact that the initial cost of RMS is high, therefore contribution towards reduction in initial cost of production is also an objective of this thesis.

There are many issues that need to be addressed if the ideal approach is to be developed for co-evolution of products processes and structures. It should be noted that no single approach may be sufficient to address all the issues of co-evolution because of the vast number of unknowns that are involved. These include the future trends, the future variations in the market, and the inability of the machines to develop complex parts. Considering all this, two approaches were selected from the top of the evolution axis (Figure 11): the process plan and corresponding kinematic configuration approach and the machine structure configuration approach.

1.5 Scope

The field of manufacturing is very vast and the systems associated along with it are all different pathways of knowledge. Therefore, this thesis is limited to RMS. It has already been proved that RMS is overall the most viable system available. RMS can be used to make a variety of products. These include automobile parts and intrinsic shapes. The general focus of RMS is on metallic products.

RMS has two levels of control of the automated machines, one at the system level and the other at the floor level. The thesis is focused on the system level control of RMS machines. The floor level control is now redundant and is considered a saturated area of research. The system level control is done by developing algorithms which control the automated machines by applying the process plans on the kinematic configurations present in the factory to produce the desired product. These algorithms address different issues in the industry such as product complexity, the reconfigurability of machines and so forth. The products considered for this thesis have orthogonal features, are considered to be metallic and all the features should be machinable. The machines should have parallel machining capabilities, should be reconfigurable and modular. This thesis is focused on (1) the identification of the possible improvements of RMS based on co-evolution, (2) the development of algorithms which address the issues in the industry today and (3) providing possible generic solutions for the co-evolution problem.

Chapter 1 was the introduction of manufacturing systems and the concepts like co-evolution, process planning and so forth. The general and the specific literature survey were also included in this chapter. Finally, from that survey the objective of this thesis was drawn.

The next chapter (chapter 2) covers the two approaches considered in this thesis in detail along with a common case study. Both approaches are applied on this case study and a comparison is carried out based on this study. Furthermore, the limitations of the two approaches are discussed. At the end of this chapter the improvements in light of co-evolution and possible future works [25] are discussed.

In chapter 3 a new approach based upon the concepts discussed in chapter 2 is presented. This approach named configuration and plan generation approach (CPGA) improves the existing machine structure configuration approach (MSCA). The improvements include the production rate and the parallelization of machining operations both of which are lacking in the existing MSCA.

In chapter 4, the Petri-net model of CPGA is introduced. The Petri-net model is first discussed in detail in chapter 4 and after that the Petri-net model of CPGA is presented. The reachability graph of the model is also explained in the chapter which generates the usage of each element of the model. The reachability set is required to fully describe the reachability graph of the model; therefore this is also a part of this thesis.

Finally, in chapter 5 a new hybrid approach based upon the improvements discussed in chapter 2 is presented. This approach called Machine Adaptive Retainability Approach (MARA) adds available machine structures and the existing process plans as inputs allowing the reduction in initial costs. The algorithm of the approach is also presented along with its implementation on different industrial parts.

The results and discussions are then presented and conclusions are drawn at the end.

Chapter 2:

Existing Methodologies and their Analysis

In chapter 2, a detailed study and analysis is carried out of the existing approaches relevant to this research. To understand and develop the concept of co-evolution, a literature survey was presented in chapter 1. The conclusion of that survey is that there are a lot of approaches in RMS, but they need improvements in light of co-evolution in order to address the industrial issues in a better and coherent manner. Many approaches exist for RMS, using Figure 11 this random amount was cut down to 7, out of which 2 were selected for improvement in this thesis on the basis of relevance to RMS, machine structure and configuration analysis. These approaches are:

1. Process Plan and Configuration Generation Approach (PPCGA)
2. Machine Structure Configuration Approach (MSCA)

In this chapter, the 'Process Plan and Configuration Generation Approach' is initially explained followed by the 'Machine Structure Configuration Approach'. Inputs which include: machining features, cutting tool charts and the topological interactions are discussed and after that, the processing of the same. This includes: the exploration of the complete methodology of the approach, the graphical representation of different steps in the approach and the explanation of these steps using a suitable case study. The processing of both approaches is explained with the same case study to develop a suitable comparison. After that, the output from the approach is presented to study the level of evolution of the approach. Next, these same steps (inputs, processing and outputs) are presented for the 'Machine Structure Configuration Approach'. Later, a comparison and analysis of both approaches is carried out to highlight the level of evolution, the focus in the methodologies, the possible steps for merging both approaches for improvement and the limitations of the approaches. Technical improvements in these approaches have been proposed in the end.

2.1 Process Plan & Configuration Generation Approach (1st approach) [35]

This approach was presented by A. Baqai in his thesis dissertation in April, 2010. Since this approach was presented after the publication of [25], therefore this approach was not included in the evolution axis. Hence, to find suitable approaches presented in and after 2010, a separate survey was undertaken. This approach was deemed suitable because it was already evolved from other approaches in terms of co-evolution. Generation of structural configurations requires the inputs of functional specifications and process plans. In the context of flexible manufacturing systems process plans are generated with the knowledge of the structural configurations. The inputs and controls for the generation of process plans and RMS configuration can be using existing methods are shown in Figure 12. As can be seen from the Figure 12 (and has been discussed in chapter 1), the conventional approaches either have the inputs part model and the structure/ architecture; giving the output of process plan, or part model and the process plan as inputs, with the structure as the output. The details of this approach can be found in chapter 3 of [35].

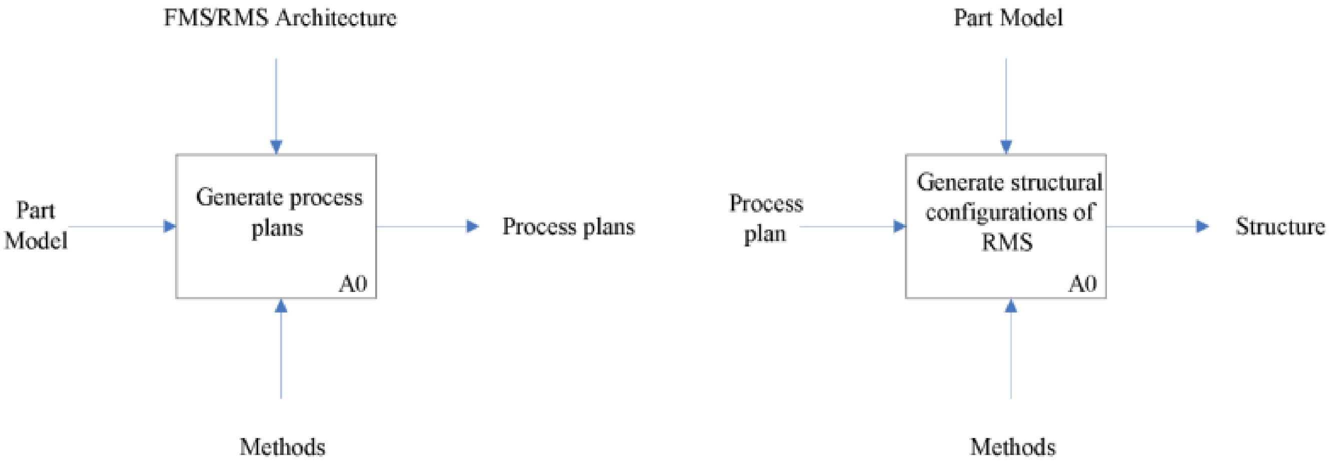


Figure 12: Activity diagrams for generation of process plans and RMS configurations. [7]

2.1.1 Inputs

Inputs of any approach are the prerequisites of that approach. These may include: charts, available data, or some sort of hand calculations of the engineer. There are three inputs of this approach:

1. Machining Features
2. Topological Interactions
3. Cutting Tool Charts

A detailed explanation of these inputs is presented in the following text:

2.1.1.1 Machining Features

Features are defined as generic shapes with which design and manufacturing engineers associate certain attributes knowledge useful in reasoning about the products [36].With a CAD point of view, a machining feature can be defined as a continuous volume that can be removed by a single machining operation in a single set-up [35]. When particularly applied to machining and manufacturing domain, a feature is the combination of a geometrical definition (enriched with technical characteristics) and a semantic definition inspired by process planning engineers. According to the French process planning community GAMA [37], a machining feature is a semantic set characterized by a collection of parameters used to describe an indecomposable object relative to one or more activities related on the design and the use of products and systems of production [1].

Etienne et al [38] divided the definition of a machining feature in two parts, i.e. Machining Enabled Geometrical Feature (MEGF) and the machinable feature [39]. MEGF is defined as an elementary geometrical semantic set characterized by parameters used to describe an indecomposable geometrical object relative to the process planning activity. The second concept called machinable feature, supports the manufacturing knowledge. In fact, one machinable feature characterizes the possibility of linking at least one Tool/ (Operation - Sequence) couple and a geometrical description from a MEGF. Figure 13 shows three different types of features. The feature on the left is a simple drill hole. The one in the middle is a chamfer on top of the drilled hole. This chamfer is again a separate feature. The one on the right is a bore hole which has the same centre as the drilled hole. Therefore, this bore hole is again a separate feature.

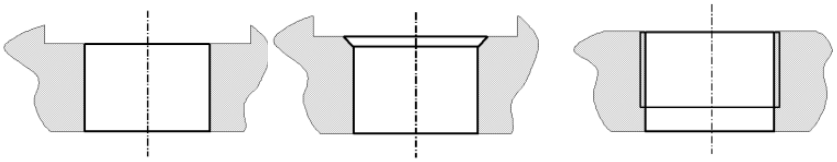


Figure 13: Types of Features.

2.1.1.2 Topological Interactions

In CAD, two volumetric features are defined as interacting features if their boundaries intersect, so that they share a non-empty, common volume. More than two volumetric features are called interacting features if every one of them interacts with at least another one and all of them form a connected volume. Feature interactions are divided according to three types of topology variations caused by their interaction: merging of faces, loss of concave edges, and splitting of faces [40].

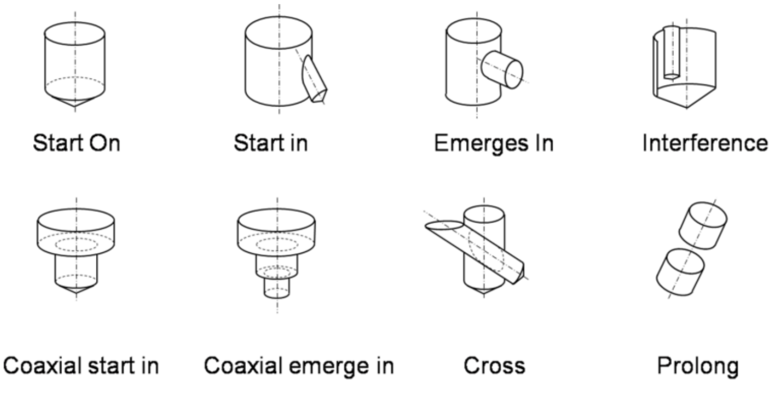


Figure 14: Types of machining feature interactions [35].

However in manufacturing domain, the focus is on the topological relations, which permit to characterize a neighborhood relation between two entities with respect to machining operations. These topological relations are very much important with respect to the positioning of part and the sequencing of machining operations. These interactions also directly influence the determination of operational mode associated to each machining feature. The possible interactions between features like: starts coaxial, emerges coaxial, start on, start in, bore on, bore through, tangent to, not possible at the same time, secant with (planes and cylinders), cross, interference, prolong … etc are shown in Figure 14. These interactions will be used at the time of creation of precedence relationship matrix.

2.1.1.3 Cutting Tool Charts / Machining Database

The cutting tool charts is a concept defined and implemented by Villeneuve [41,39]. Cutting tool charts form the knowledge base to be utilized during the processing of activity2. These charts look like tables (where production routing specialists can store the validity domain of a machining process.).

Multiple extensions of this concept have been proposed. F. Langlet [38], proposed a new implementation of cutting tool charts, so as to render them more flexible by allowing the modification and management of the parameters, more interactive in having a link with the data base interfaced in Access. Tool association in process planning is implemented through "Output – Sequence – Entity" methodology. The concept of OSE [42] is an evolution of cutting tool charts.

2.1.2 Processing

The working of the approach is explained in the following steps. Part CPEF10 urane (Figure 15) is used as case study to explain each step. In Figure 15 the green coloured features represent planes, the yellow ones holes and the blue ones chamfer. 'Ech' represents 'size ratio'. There are a total of 7 features, which have been assigned operation identification number (op-id) in Table 5.

Table 4: Abbreviations used in Figure 15

Sr. no.	Abbreviation	Meaning
1	PL100	Surface Finish (Outer surface)
2	PL101	Surface Finish (Surface created by CY103)
3	CY103	Intermediate Hole
4	CY105	Through Hole
5	CY107	Small Side Hole (Right)
6	CY109	Small Side Hole (Left)
7	CH111	Chamfer (Between PL101 and CH111)

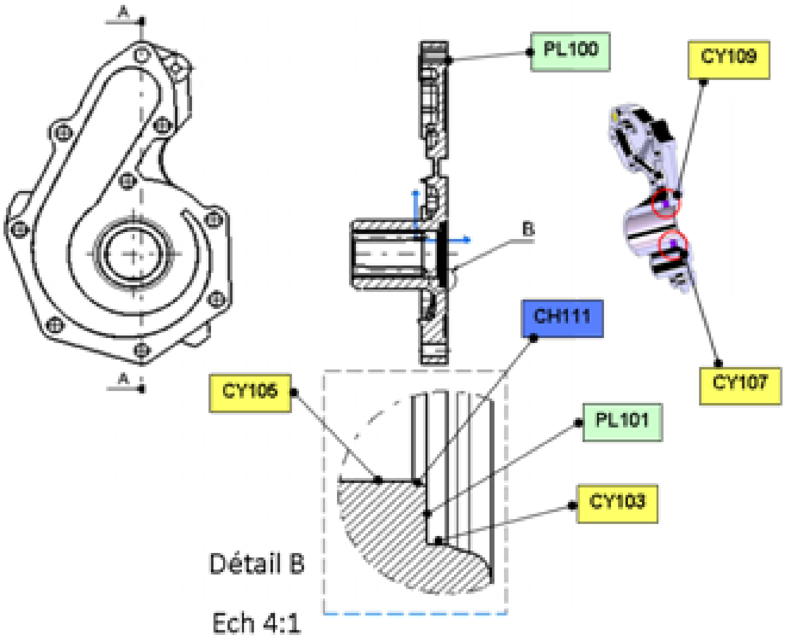


Figure 15: Part CPEF URANE [43]

Taking the example of the 1 present in the third row and fifth column (1(3, 5)); this 1 represents: the feature at the top of the column 5 (Cy103) has a precedence relationship with the feature at the left end of the row 3 (PL100). More specifically the feature PL100 will immediately be followed by CY103. Similarly the 0's will be indicating no precedence relationships. Now, form this it can be concluded that the feature having no precedence should have 0's in every box of that column. In Table 5, that feature is PL100 (column 3). All the column elements other than the name and the operation identification numbers (**OP-ID**) are 0.

Table 5: Precedence Matrix of Part CPEF10 URANE.

NOM		PL100	PL101	CY103	Cy105	CY107	CY109	CH111
	OP-ID	1	2	3	4	5	6	7
PL100	1	0	0	1	0	1	1	0
PL101	2	0	0	0	1	0	0	0
CY103	3	0	1	0	0	0	0	0
Cy105	4	0	0	0	0	0	0	1
CY107	5	0	0	0	0	0	0	0
CY109	6	0	0	0	0	0	0	0
CH111	7	0	0	0	0	0	0	0

The model in this approach is used for the graphical representation of the system. Certain concepts along with their graphical representation are explained as follows:

1. Operations ⟶ :

Conventionally machining operations represent material removal activity. But, in case of this approach operations represent any activity that can consume time, is directed towards the final realization of the part, or is performed in parallel with the machining operations. For example: machining operations, tool change operation, spindle change operation, overturning of the part, part rotation etc. The "arrow" can represent all the operations.

2. Posts and start/ End of activity on a post ○ :

A machining post comprises of one or many machine structures. A single post has a single part position. but, if rotation is added in that particular post, the part become more accessible and further loading/ unloading can be avoided. A single post may have multiple spindles allowing parallel machining.

3. Start/end of an activity/ several activities● :

This (black circle) is an intermediate state between two operations (arrow).This not only allows the representation of start / end of an activity, but also permits to display the precedence relationship between two parallel machining operations. To represent the relationship between two parallel machining operation, a dotted line '---------' is used. Furthe details can be found in [35].

Now, from Table 5 the first machining operation that can be initially performed is operation number 1. The other operations that can be performed using the same spindle are operations 2, 3, 4 and 7. Since there are no operations that are performed prior to operation 1 and this operations has the most number of operations posterior to it, therefore this operation now 'must' be performed first. Figure 16 shows the model of step 1. The white circle represents the start of activity on the first post and the first structure. Next, operation 1 takes place (represented by the arrow). Finally, the black circle represents the end of the activity.

Same spindle to group 1	**1**	**2**	**3**	**4**	**5**
Same operation to group 1					
Same Axis to group 1	**1**				

Figure 16: Model of Step 1 for CPEF10

In the next step, separate from the remaining operations those which can be performed on the same post and structure. Table 6 shows the relationship of the axis directions. For Table 6:

- 1 Represents that both operations (Row and column wise) have the same tool direction.
- 0 Represents that both operations (Row and column wise) have different tool direction.

In Table 6, considering the example of the red coded '1' in the 4th column and 5th row (1(5; 4)); 1 shows that the operations 2 and 3 (PL101 and CY103) have the same spindle directions. Similarly all the 1's in the table (except operation ID's) represent that all the corresponding operations in their subsequent rows and columns have the same spindle directions. Consequently all the 0's (except op-ids) show that the respective operations in their subsequent rows and columns have different directions.

Table 6: Same Spindle Directions.

NOM		PL100	PL101	CY103	CY105	CY107	CY109	CH111
	OP-ID	1	2	3	4	6	7	5
PL100	1	1	1	1	1	0	0	1
PL101	2	1	1	1	1	0	0	1
CY103	3	1	1	1	1	0	0	1
CY105	4	1	1	1	1	0	0	1
CY107	6	0	0	0	0	1	1	0
CY109	7	0	0	0	0	1	1	0
CH111	5	1	1	1	1	0	0	1

After this, the operations that can be performed on the parallel structures are considered. E.g. holes on face +x and –x. The model after step 3 is shown in Figure 17. For Table 7:

- 1 Represents that both operations (Row and column wise) have the alternate tool direction.
- 0 Represents that both operations (Row and column wise) have same tool direction.

Table 7: Spindle Alternate Directions.

NOM		PL100	PL101	CY103	CY105	CY107	CY109	CH111
	OP-ID	1	2	3	4	6	7	5
PL100	1	0	0	0	0	1	1	0
PL101	2	0	0	0	0	1	1	0
CY103	3	0	0	0	0	1	1	0
CY105	4	0	0	0	0	1	1	0
CY107	6	1	1	1	1	0	0	1
CY109	7	1	1	1	1	0	0	1
CH111	5	0	0	0	0	1	1	0

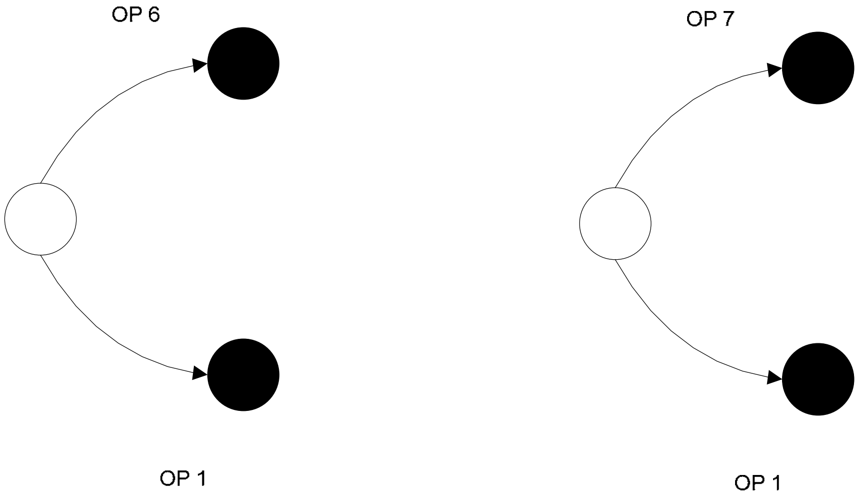


Figure 17: Step 3 for CPEF10

The opposite of Table 6 is the table of spindle alternate directions. Table 7 represents the table of spindle alternate directions. The 1's in this table (other than op-ids) show that the subsequent operations in their respective rows and columns have alternate spindle directions from each other. And consequently, the 0's show that they have same spindle directions. This table can be used to find parallel operations i.e. the operations that have alternate spindle directions can be performed in parallel. For example, considering the 1 in 7th row and 5th column (1(7; 3)) of Table 7. This ‘1’ shows that Op 1 and Op 5 can be performed in parallel due to their alternate spindle directions. Similarly the 1 in 8th row and 5th column (1(8; 3)) shows parallel machining capability as well (between Op 1 and Op 6). The two models in Figure 17 show both these possibilities. The model on the left shows that the operation Op 6 may be performed in parallel with Op 1 provided that there is parallel machining capability with twin spindles. Similarly the model on the right represents the possibility that Op 7 may be performed in parallel with Op 1.

It has already been shown that the black circle represents the end of an activity. This same circle is also used for the representation of the start of an activity. The model for the part CPEF10 is not complete at this point. The remaining operations should be followed by the operations 1, 6 or 5. Now, considering operations after **tool** or **spindle** change (Figure 18), there are many operations that can be followed by the said operations. To reduce the possibilities to a single operation, the rules of the approach are followed. The rules are explained in the following lines: The order of the operations should be in such a way that the operation having maximum operations posterior to it should be performed first followed by the operation having the next highest number of machining operations posterior to it and so on. The operations having same tool and spindle directions should be performed together and if the possibility exists; perform the parallel machining operations.

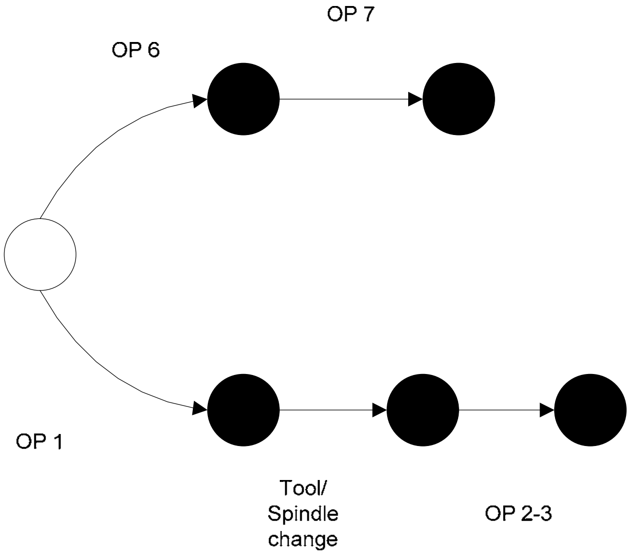


Figure 18: Step 4 for CPEF10.

Operation 7 is followed by operation 6 because they have the same tool and spindle directions (Figure 18). There are no other operations that can be performed with the tool used in PL100. Therefore a tool change takes place after op 1 in Figure 18. After the tool change, Operation 2 and operation 3 (PL101 and CY103) can be performed by the same tool, because if the proper tool is used with a flat face, then the plane is automatically formed below the hole. If not, then op 2 should be followed by a tool change and then, op 3 can take place. The first possibility (using a single tool) is considered in this work. After this, again a tool change takes place (Figure 19) because there are no other feature requiring that tool. After the tool change, there is only the possibility of op 4 (drill hole) because the other remaining operation is op 5 which is a chamfer. Chamfers are generally performed at the end of the machining operations. After operation 4 takes place the final tool change takes place for the chamfer (op 5). In the end, the chamfer operation takes place completing all the operations on the work-piece.

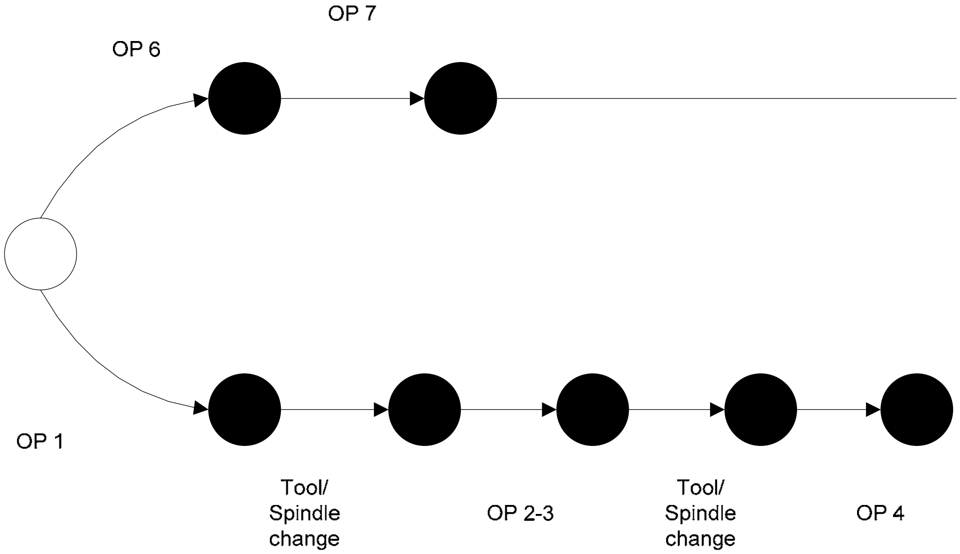


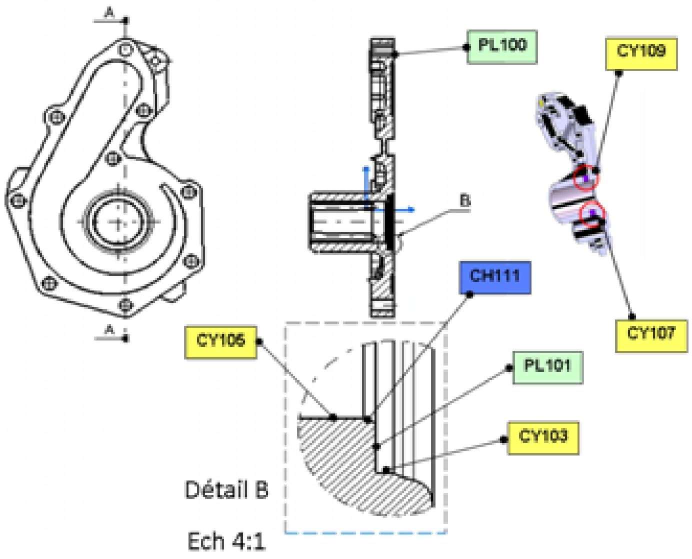
Figure 19: Step 5 for CPEF10.

2.1.3 Outputs

There are two main outputs of this approach (Figure 20):

1. Process plans
2. Corresponding KCs

The sequence of operations discussed in ‘processing’ is one of the many possible process plans that could have been used to develop this particular product. The algorithm used in this approach generates many of the possible process plans. The algorithm then selects the process plan that takes minimum time to develop the product. To achieve that, parallel machining if available; is also used.



No. of Posts	6
No. of Structures	6 2 parallel 4 single
No. of Post Changes	4
Structure 1: 2 Axis	
Structure 2: 1 Axis	
Structure 3: 1 Axis (parallel to structure 4)	
Structure 4: 1 Axis (parallel to structure 3)	
Structure 5: 1 Axis (parallel to structure 3)	
Structure 6: 1 Axis (parallel to structure 3)	

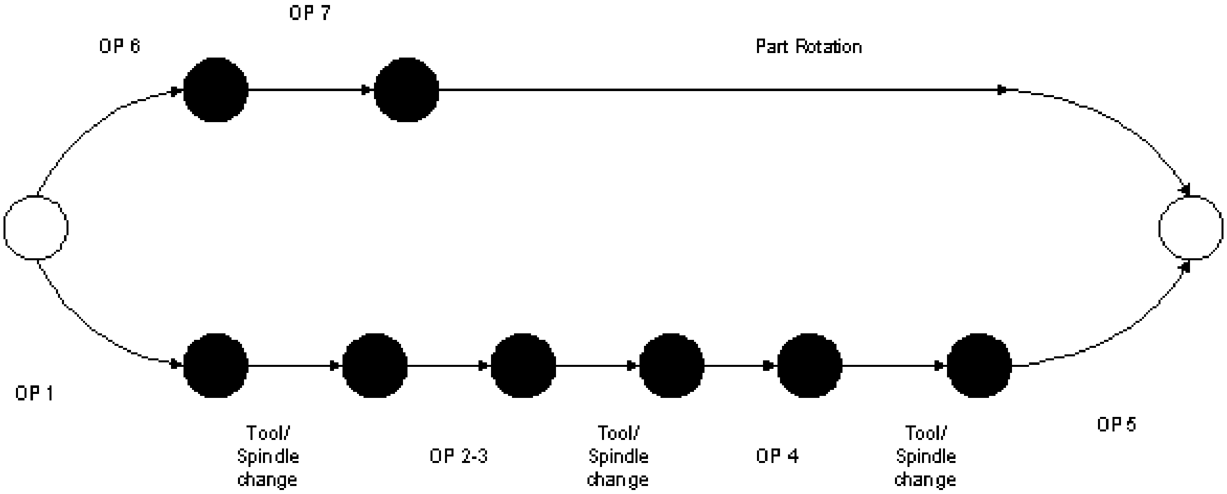


Figure 20: Part CPEF10 and its features along with the kinematic configuration and the process plan

Once the most suitable plan is selected, then the corresponding kinematic configuration required for that particular process plans is generated. Keeping the concept of co-evolution in mind, this approach focuses on finding the process plan first and then the corresponding kinematic configuration. Therefore, the approach focuses more on the process plans than the kinematic configurations. Nevertheless, the approach is closer to co-evolution as compared to the other approaches due to the consideration of many aspects in process planning as well as the configuration generation and the possibility of generation of kinematic configuration generation for each corresponding process plan.

2.2 Machine Structure Configuration Approach (2nd approach) [5]

The second approach under consideration here is the machine structure configuration approach. The approach was presented by A.I. Shabaka and H.A. ElMaraghy in 2007. The approach is given high priority in the review paper of co-evolution. It is used world over for research and development purposes. The main advantage of this approach is that it finds the minimum configuration required for the required part. The part CPEF10 urane is used again for this approach to develop a proper comparison with the process plan and configuration generation approach.

2.2.1 Inputs

There are three inputs in this approach:

1. Part (and work-piece) Dimensions
2. Operation Precedence Graph
3. Tool Approach Dimensions

2.2.1.1 Part Dimensions

These include length, height, width, diameter of hole and so on. Initially these are required to check the size constraints of the machine against those of the work piece. If the size of the work-piece is greater than the maximum size the available machines can accommodate, then the part simply cannot be made with the available machinery. Also, the part dimensions are also required for collision checks to avoid collisions, locating different features and for selection of tools.

2.2.1.2 Operation Precedence Graph

This captures the precedence constraints, which define order of succession among operations (see Figure 59 and Figure 60 in ‘Appendix A’; the precedence graph of part CPHC10). Each node (circle) represents an operation and the arcs (arrows) show the direction of operation precedence. An operation that has an arc pointing towards it cannot be done until the node before the same arc has been performed. Clustering or grouping of operations is based on constraints. There are three types of such constraints, logical, tolerance datum and other.

Logical constraints are between those operations which are logically related to one another. For example the sequence of operations in making a hole is the drilling, boring and then reaming. Neither reaming can be performed before drilling nor can boring be performed before drilling for the same hole and so on. Tolerance Datum constraints as the name implies are between two operations when a group of operations must be performed on the same machine and with the same set-up positions to preserve tolerances with respect to position and the relative positioning of the operated features. Finally other constraints refer to those constraints which exist between operations but are neither tolerance datum nor logical. A Precedence Graph is used for the clustering process. A sample of a precedence graph is shown in Figure 21. The numbers within the circle represent the operation number and the numbers on the line represents the precedence relationship, where:

- Tolerance datum constraint : 2
- Logical constraint : 3
- Other constraint : no number

In some cases these are replaced by letters:

- Tolerance datum constraint : D
- Logical constraint : L
- Other constraint : No Letter

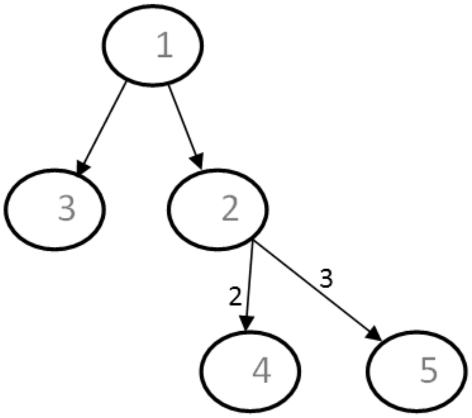


Figure 21: Sample Precedence graph

The precedence graph (Figure 21) starts off at operation 1. After operation 1, there are two arrows showing the possibility that any of the two operations can performed once operation 1 is completed. The possible operations are operation 2 (right arrow) and 3 (left arrow). Similarly once operation 2 has been preformed; it can be followed either by operation 4 or operation 5. The numbers on the arrows as discussed before show the constraints. For example, after operation 2, the '2' on the left arrow shows that a tolerance datum constraint exists between operation 2 and operation 4. Similarly the '3' on the right arrow represents that a logical constraint exists between operations 5 and operation 2.

The precedence graph (see Figure 21) is used to develop a precedence matrix as shown in Table 8. The operations are arranged in the first row and first column of the matrix. To represent a 'precedence relationship'; a number (other than 0) should be present in the specific entry in the matrix. For example, the 1 present in the 2nd row and the 3rd column of the matrix shows the existence of precedence relationship between operation 2 and operation 1. No operation can have a precedence relationship with itself. Therefore, the diagonal entries should all be 0. The starting entry in the precedence graph was operation 1. Hence, this operation is performed first and is followed by operations 2 and 3 as shown in the sample precedence graph. And since the arrows attaching these operations to operations 1 have no number on them, therefore in the precedence matrix, this precedence relation should be represented by 1 in the corresponding cell. The cells (2, 3) and (2, 4) show this relationship. The '1' in the cell (2, 3) represents operation 2 is preceded by operation 1. Also, the '1' in the cell (2, 4) shows operation 3 is preceded by operation 1. The opposite of this statement is that operation 1 is followed by operation 3. This is shown by the '-1' in the cell (4, 2). After operation 2, operations 4 and 5 can be performed. These operations have tolerance datum and logical constraints. Operation 4 is preceded by operation 2; shown by the '2' (tolerance datum constraint) in cell (3, 5). The precedence of operation 2 to operation 5 is shown by the '3' (logical constraint) in cell (3, 6).

Table 8: Sample Precedence Matrix.

Op. No.	1	2	3	4	5
1	0	1	1	0	0
2	-1	0	0	2	3
3	-1	0	0	0	0
4	0	-2	0	0	0
5	0	-3	0	0	0

The development of the precedence graph and the precedence matrix requires the complete understanding of the part, the manufacturing operations and RMS. Since this is one of the inputs of the approach, therefore the development of the precedence matrix and graph is generally the responsibility of the engineer. An error at this stage is highly undesirable because due to the fact that this is the input, the error will affect the whole approach leading it towards an incorrect output. Part CPEF10 was used for this approach as well. Advantage of this is that this will allow the development of a suitable comparison between the approaches.

The operation precedence graph for the part CPEF10 is shown in Figure 22 along with its precedence chart/ matrix in Table 9. As in the 1st approach, operation 1 is the first operation and all other operations are performed after it. But, this approach focuses on finding the minimum machine structure configuration. Therefore, the possibility of parallel machining operations is ruled out. The operation precedence matrix and graph are therefore made in a corresponding manner as well. Operations 5, 6 (side holes) or operation 3 can be performed after operation 1. After operation 3, operation 2 and operation 4 can be performed. In the end, the chamfer CH111 (operation 7) is carried out but for that to happen, both operations 2 and 4 should be completed. This is shown by the 2 'arrows' directed towards operation 7. The precedence chart is developed from the precedence graph (Figure 22) in a similar fashion to the example (Figure 21 and Table 8) and is shown in Table 9.

Table 9: Precedence Chart for CPEF10 URANE.

NOM		PL100	PL101	CY103	CY105	CY107	CY109	CH111
	OP-ID	1	2	3	4	5	6	7
PL100	1	0	0	1	0	1	1	0
PL101	2	0	0	0	0	0	0	1
CY103	3	0	1	0	2	0	0	0
CY105	4	0	0	0	0	0	0	1
CY107	5	0	0	0	0	0	0	0
CY109	6	0	0	0	0	0	0	0
CH111	7	0	0	0	0	0	0	0

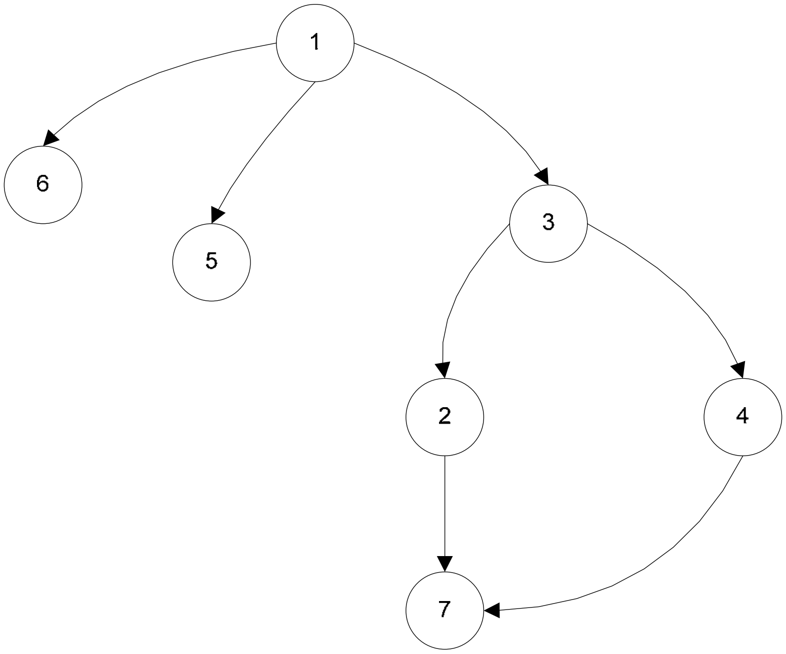


Figure 22: precedence graph for CPEF10 URANE.

2.2.1.3 Tool Approach Directions (TAD)

It represents all the possible direction from where the tool can approach to develop the feature. Table 10 shows the input TAD format developed by H.A. ElMaraghy et al (2007) [5]; the first column represents the operation numbers and the top two rows show the possible TAD directions. In general, these may include any particular direction. But, one of the assumptions of this approach is the orthogonal dimensions. Thus, only the +x, -x, +y, -y, +z, and the –z directions are considered in TAD. The rest of the cells of Table 10can either be filled by 0's or 1's. These are explained below:

- 1 represents the possible TAD for the respective operation.
- 0 represents the TAD which cannot be used for the corresponding operation.

For example, in Table 10, the '1' in the cell (3, 2) shows that the operation 1 can be performed using the +x tool approach direction. The '1' in the cell (3, 3) shows that the operation 1 can also be performed using the –x direction. But, the '0' in cell (3, 4) shows that the operation 1 cannot be performed using the +y direction. Using the same principles, the rest of the cells of Table 10 are filled by '0's' and '1's'. In light of this example, the TAD for the part CPEF10 URANE was made and is shown in Table 11.

Table 10: Sample Tad Table.

Op. No	Tool Approach direction					
	+x	-x	+y	-y	+z	-z
1	1	1	0	0	0	0
2	1	0	0	0	0	1
3	1	1	0	0	0	0

Table 11: TAD Table for CPEF10 URANE.

TAD/Operations	+x	-x	+y	-y	+z	-z
PL100	1	1	1	1	0	1
PL101	0	0	0	0	0	1
CY103	0	0	0	0	0	1
CY105	0	0	0	0	0	1
CY107	0	0	1	1	0	0
CY109	0	0	1	1	0	0
CH111	0	0	0	0	0	1

2.2.2 Processing

Once all the inputs have been defined and presented, the approach can now be implemented on the part CPEF10. The processing of the approach consists of four main steps:

1. Clustering of operations.

Clustering can also be called grouping of operations. Different operations are grouped together into clusters reducing the size as well as the complexity of the precedence graph and matrix. The clustering stage is explained step by step along with the suitable precedence matrix and graph in the following text. Starting from Figure 22 and combining operations 2 and 7; C1 is obtained as shown in Figure 23. Now, C1 contains both operations 2 and 7. It is also known that operation 4 was followed by operation 7 and operation 3 was followed by operation 2. Since both these operations are now part of C1, therefore both operations 3 and 4 should have an arrow pointed towards C1. After this, combining operations 4 and cluster C1; C2 is formed as shown in Figure 24. Again, taking a look at the operation 4 and cluster C1, both are preceded by operation 3. Hence, once C2 is formed an arrow should be pointed towards C2 from operation 3 as can be seen in Figure 24.

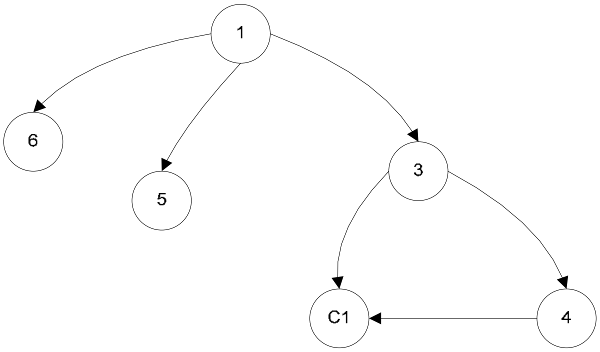


Figure 23: Clustering Step 1 for CPEF10.

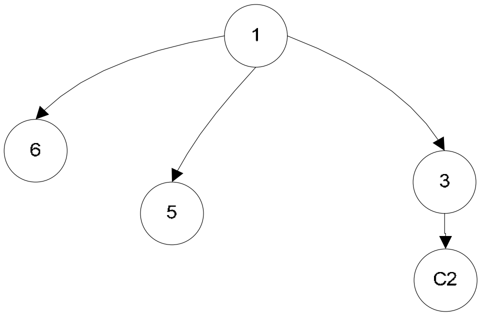


Figure 24: Clustering Step 2 for CPEF10.

In the third step, joining 3 and C2 from Figure 24; C3 is obtained as can be seen in Figure 25. Operation 3 is followed by cluster C2. And C2 has no other arrow pointed towards it. But, operation 3 has an arrow pointed towards it from operation 1. Thus, only one arrow should be pointed towards C3 (due to operation 3 and none due to C2). Finally, in the end joining operations 5 and 6 because of the same TAD as well as the same tool requirements, Figure 26 is obtained.

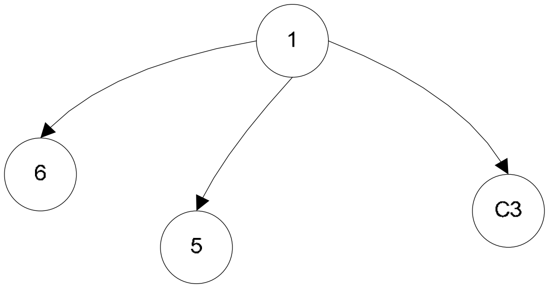


Figure 25: Clustering Step 3 for CPEF10.

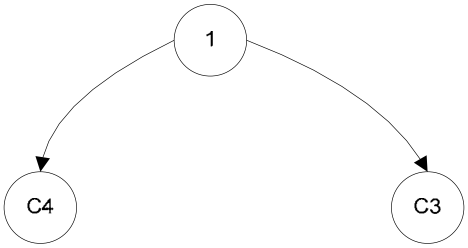


Figure 26: Clustering Step 4 for CPEF10.

2. Using all possible TAD of each operation generate the required TAD for the specific cluster.

   The TAD Table forFigure 26 is shown in

Table 12. Table 14 shows the TAD of operations within C3 and Table 15 shows the TAD of operations within C4. All the operations within C3 have a single TAD: -z (Table 14). Therefore the overall TAD of C3 should also be-z. Similarly, both operations in C4 have TADs +y and –y (Table 15). Hence, the overall possible TADs of C4 are –y and +y as well. The precedence table of Figure 26 is shown in Table 13. The red color coded 2 is used in Table 13 to show the tolerance datum constraint existing within C3.

Table 12: TAD Table after Clustering.

TAD/Operations	+x	-x	+y	-y	+z	-z
PL100	1	1	1	1	0	1
C3	0	0	0	0	0	1
C4	0	0	1	1	0	0

Table 13: Precedence Table after Clustering.

	PL100	C3	C4
PL100	0	1	2
C3	-1	0	0
C4	-2	0	0

Table 14: TAD Table of C3.

TAD/Operations	+x	-x	+y	-y	+z	-z
CY103	0	0	0	0	0	1
CY105	0	0	0	0	0	1
PL101	0	0	0	0	0	1
CH111	0	0	0	0	0	1

Table 15: TAD for C4 Cluster

TAD/Operations	+x	-x	+y	-y	+z	-z
CY107	0	0	1	1	0	0
CY109	0	0	1	1	0	0

3. Separate the operations' TAD in such a way that the overall tool approach directions remain at minimum level.

In case of part CPEF10 URANE it is clearly evident the only TAD for all operations within C3 is –z and for all the operations in C4 it can either be +y or –y. Due to lack of other information it seems that it doesn't matter which TAD is used. Hence, +y is randomly selected for operations in C4 and the only possible TAD (-z) for C3 is selected.

4. Using overall TADs, generation of the required machine Structure.

Comparing the TAD of the three: PL100, C3 and C4, Table 16 is obtained. As discussed before the TAD for C4 has been selected to +y. To make overall TAD minimum PL100 should either be –z or +y as shown in Table 17.

Table 16: TAD Table for PL100, C3 and C4.

TAD/Operations	+x	-x	+y	-y	+z	-z
PL100	1	1	1	1	0	1
C3	0	0	0	0	0	1
C4	0	0	1	1	0	0

Table 17: Overall TAD Table.

TAD/Operations	+x	-x	+y	-y	+z	-z
PL100	0	0	0	1	0	1
C3	0	0	0	0	0	1
C4	0	0	0	1	0	0

2.2.3 Outputs

The two outputs of the machine structure configuration approach are:

1. Minimum machine structure
2. Corresponding Process Plan

From the work done in processing (Section 2.2.2), it can be concluded that for the part CPEF10, the machine required should have the regular three axis (x, y and z) for surface milling and boring etc, plus a rotation axis which can rotate the tool from –z to the –y direction. The rotation axis should be around x axis. Therefore, the minimum machine structure is achieved for the part CPEF10. The process plan for the part from this approach can be seen in Table 17.The operation sequences in Clusters C3 and C4 can be seen within their respective tables.

2.3 Comparison and Analysis

Since the same part was used as case study in both the approaches, a proper comparison can be developed between both the approaches:

- The Process plan and configuration generation approach is focused on **Processes**; Machine structure configuration approach is focused on **machine Structure**.
- 1st approach considers **multiple platforms**; 2nd approach doesn't.
- 1st approach considers **parallel operations**; 2nd approach doesn't.
- 1st approach is focused on **time reduction**; 2nd approach is not in its essence.
- Initial **cost** for the machine structures is **high** for the 1st approach, for 2nd approach it is **low**.
- **Minimum machine structure** is generated in the 2ndapproach; machine structure with low production time is generated in the 1st approach.
- **Combinatory Explosion in 1st approach.**
- Needs **constraints** to **reduce solution space** in **1st approach.**
- **Complex parts verification** required for **1st approach**

Based upon the above mentioned comparison, improvements are suggested and are discussed in the following section.

2.4 Improvements

T. Tolio et al [25] in the conclusion of the review paper suggested that all approaches have areas requiring evolution. Therefore, one can argue that no approach in its current state is fully evolved under the outlying principles of co-evolution. Hence, based on this and the principles of co-evolution, improvements are suggested in the following text:

2.4.1 Addition of Multiple Platforms

The first improvement is the addition of the 'possibility' of multiple platforms in the 2nd approach. This will enhance the 2nd approach and give it a wider scope as compared to the limited scope which it currently has using only a single platform. The problems that will be associated with are:

- Difficulty in selection of minimum machine structure configuration due to parallel axis in the system.
- A more complex system of clusters.
- Multiple tool approach direction tables due to multiple platforms.

2.4.2 Using Existing Machine and Sequencing Data

Co-evolution was proposed when the following factors started playing role in the industry:

- The problem of determining the system configuration which better fits the production requirement over time.

- At the same time the problem of accommodating production changes by designing reconfigurable machines and auxiliary equipment, and adjusting the production plan and schedule.

2.4.2.1 Technical reason for these issues

Whenever a new part comes into the industry, the algorithms start generating the **process plans** for it **without considering the previous machine structure** already employed and therefore the resulting process plans will generate a loop of changing process plans and configurations.

2.4.2.2 Proposed Solution for the Issue

One of the solutions can be the accommodation of the already employed process plan, the previously employed kinematic configuration and the previously employed product in the algorithm.

The previous product should act as a benchmark in this case; if the previous product is from the same part family as the new product then the algorithm should consider the already employed process plan, the previously employed kinematic configuration in its calculation so as to **reduce the costs** of changing the Machinery of the plant.

- A sample output of the algorithm in case of different part family:

#. Error; the part is of a different part family. Major changes in structure and configuration required.

- A sample output of the algorithm in case of same part family:

the part belongs to the same part family. Only minor improvements required.

After the algorithm has detected that the part belongs to the same part family then the algorithm runs as it is for other parts up to the step where all the process plans have been generated. After the generation of all the process plans, it selects those which come with the least number of physical changes (configuration and/or tool type) with reference to the previously employed process plans and kinematic configurations. Following are the 2 possible methods to achieve this.

2.4.2.2.1 Method # 1

The algorithm runs a stepwise analysis of the process plans with the previously employed process plan. E.g. it first compares the first operation of both plans then the second and so on.

2.4.2.2.1.1 Pseudo Code of Method#1

```
Integer I, j=1; Cpp = 0
```

```
For j=1 to # of process plans          // loop1
    For I = 1 to # of operations       //assign all operations' TAD of loop as
                                       tadop1, tadop2 etc
        If Reftadop1 ≠tadop#1          // Reftadop = the Tool approach direction of
                                       the previously employed process plan.
        Then Cpp=Cpp + 1               //Cpp= Changes in process plans
    Next                               // loop 2 starts again
Next                                   // loop 1 starts again
```

In the end the algorithm checks which process plans has the lowest Cpp and applies it as the new process plan.

2.4.2.2.2 Method # 2

The algorithm runs an overall analysis of the process plans with the previously employed process plan.I.e.it counts the overall changes in the operations without considering the order.

2.4.2.2.2.1 Pseudo Code of Method#2

```
Integer I =1; Ckc=0

For I=1 to # of process plans
    If reftadoverall = tadoverall      // reftadoverall represents the overall tool
                                       approach directions required by the
                                       reference process plan and similarly
                                       tadoverall is the represents the overall TAD
                                       for the new process plan considered in this
                                       loop.
    Then Ckc =Ckc+1;                   // Ckc represents the changes in kinematic
                                       configurations. I.e. if over TAD are 3 then a
                                       3-axis machine is sufficient and so on.
Next                                   // loop starts again
```

2.4.2.3 Comparison of the 2 methods

Both these methods are compared using the following case study:

2.4.2.3.1 Case Study

Table 18 shows TAD of a previously employed process plan in a certain manufacturing setup and Table 19 shows the tool approach directions of the newly proposed process plan. If method # 1 is used, there are many changes in process plans. Comparing both tables (Table 18 & Table 19) the Op1 has a tool approach direction change, similarly op2, op3, op4 and op5 have tool approach direction changes. The operations op6 and op7 have same TAD's. Therefore for method 1 Cpp is 5. Applying method#2; it can be observed the overall TADs of Table 18 is 3 (y+, y- and z+) whereas the overall TAD of Table 19 is 4(y+, y-, z- and z+).

Observing the results it can be seen that the sequence of operations is very different in both these plans but the overall kinematic configuration that will be required has only 1 difference z-. Another point which can be clearly seen is that the combined effect of both these methods yields a much better understanding of the changes that will accompany the new product, process plan and configuration system.

Table 18: TAD Table for a random part.

TAD/ Operation No.	**x+**	**x-**	**y+**	**y-**	**z+**	**z-**
op1	0	0	0	0	1	0
op2	0	0	0	1	0	0
op3	0	0	0	0	1	0
op4	0	0	1	0	0	0
op5	0	0	0	0	1	0
op6	0	0	1	0	0	0
op7	0	0	0	0	1	0

Table 19: TAD Table for the new part.

TAD/Operation No.	**x+**	**x-**	**y+**	**y-**	**z+**	**z-**
op1	0	0	0	1	0	0
op2	0	0	0	0	1	0
op3	0	0	1	0	0	0
op4	0	0	0	0	1	0

op5	0	0	0	0	0	1
op6	0	0	1	0	0	0
op7	0	0	0	0	1	0

2.4.3 Addition of Angular Holes

Addition of angular holes in the 1st approach is another suitable improvement. For this, new TADs are generated for each new direction of the hole. The TAD will be a new one with a whole column dedicated for each new TAD of angular holes. For example: for an angular hole of 265 degrees around x-axis then the algorithm automatically captures the axis of rotation and it will be considered as a completely separate entity. This separate entity on basis of the tool used for this operation can be arranged in the sequence.

2.4.4 Addition of Collision Check

In both the approaches there isn't any sort of collision check. Generated solutions are required to be verified for absence of collisions. Initial Solution is to verify the dimension of the tool holder and the tools and then improving the algorithm to check whether collision will take place by running a simulation.

2.4.5 Production Rate Improvement

The improvement with respect to time requires accommodation of a lot of different aspects in the algorithm and any or all can be used for the improvement of the approaches. For example:

- Time Sequencing.
- Tool Speeds Optimizations.
- Milling tool type.
- Tool cutting speed
- Intelligent algorithm (Ability to change direction of cutting as per requirement).

2.4.6 Improvement in Cutting/ Bending of Sheet Metal

The concept of development of algorithm for the cutting/ bending of shhet metal was first presented by A. Ma'rkus in [31]. The paper presented the concept of developing the algorithm, discussed the probable mathematical model of the problem but, didn't provide any viable solution to the problem. Hence, to this date there is no proper algorithm developed for the cutting/ bending of sheets. There are only mathematical models for that. Therefore developing an algorithm for sheets is a new avenue of research.

Two approaches, the 'process planning and configuration generation approach' and the 'machine structure configuration approach' are presented in this chapter. A common case study was taken as an example and a comparison was carried out between the two approaches. On the basis of that comparison and other factors, improvements were suggested at the end. Now, based on those improvements an algorithmic model for the evolved approach is presented in chapter 3.

Chapter 3:

Configuration and Plan Generation Approach (The Algorithmic Model)

Using the approaches studied in chapter 2, an evolved approach is presented in chapter 3. A brief introduction of 'machine structure configuration approach' is given at the start, followed by the introduction to the 'configuration and plan generation approach'; the approach presented in this thesis. This approach is evolved from the 'machine structure configuration approach' using the concepts available in the 'process plan and configuration generation approach'. The approach has more focus towards process plans and production rate and also has the parallel machining capability. The algorithm of the approach is introduced in this chapter as well which is required for the implementation of the approach on different automated systems. A case study is used to further explain the working of the algorithm and the results of the case study are then discussed.

3.1 Improvement in Production Rate

In recent times, H.A. El Maraghy has done considerable work on the CAPP of RMS or RPP. The author has used machine structure configuration approach. The first step in that technique is gaining complete knowledge of the machines available and the operations to be performed. This includes the tool approach direction (TAD), size and the precedence graph (See section 2.2.1.1, 2.2.1.2 and 2.2.1.3 for details).

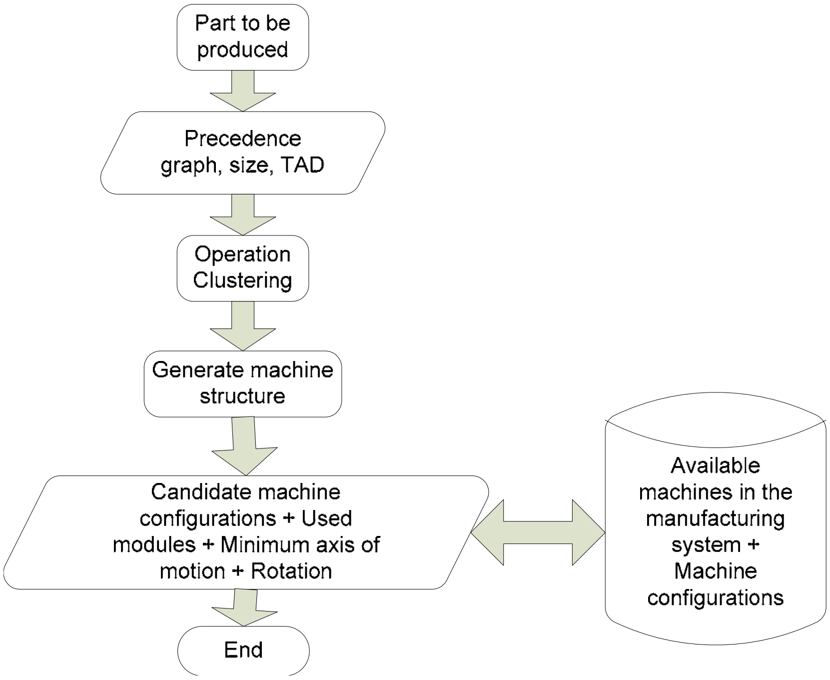


Figure 27: Machine structure configuration approach.

The second step after having complete knowledge of the operations that are to be performed on the part is the formation of operations clusters. The Figure 27 shows a complete flow chart of the machine structure configuration approach. Using this methodology, a code using Matlab was generated and then the results were compared with the existing algorithms. The code starts off by taking the prerequisites i.e. the precedence graph, the size and the tool approach directions as inputs in the form of matrices from an excel file. Then it moves on to making clusters of the operations as per the precedence graph. Since the clusters are formed, the code selects the tool approach directions for each operation cluster that will generate the minimum overall tool approach directions. After that the minimum tool approach directions are calculated, by using the minimum tool approach directions, the minimum axis machine and the machine configurations that are required to perform all the operations on the machine are selected on basis of available machinery.

Size check can be performed on the visual basis. Even if the size check is not performed on visual basis, it can still be performed on the machine level because if the work-piece is larger than the allocated size then the G-M code will not run triggering a halt to the process. Also, if there is a need of performing the size check within the code then it can be performed by providing (a) the original size of the work piece and (b) the machine dimensions. Using these two as input, the, “if greater than” command can incorporate this check into the code. If the size of work-piece is greater than the machine work dimensions then the code will end at that instant giving an error. The third input is the precedence relationship matrix.

3.2 Configuration and Plan Generation Approach

Using the machine structure configuration approach as the basis and implementing certain principles from different approaches, the configuration and plan generation approach (CPGA) was developed. The flow chart of CPGA is shown in Figure 28.

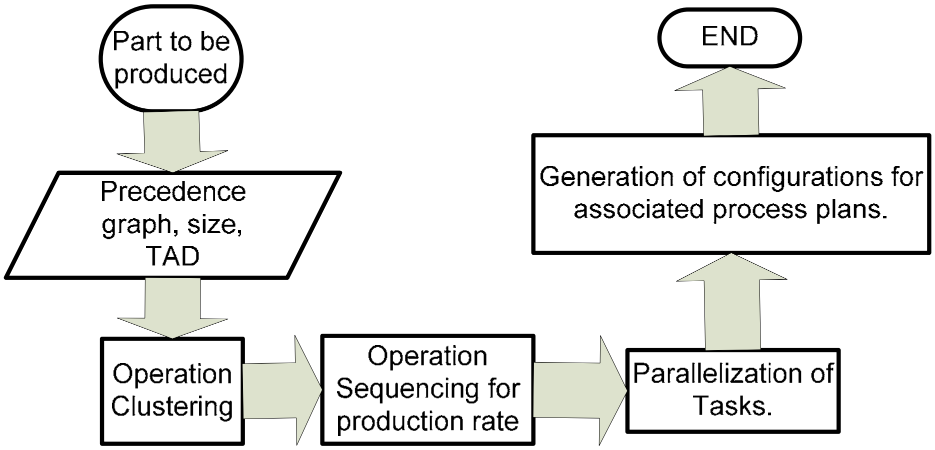


Figure 28: Configuration and Plan generation approach.

The approach as can be seen from Figure 28 was developed with the purpose of improvement in the operation sequencing of the machine structure configuration approach as well as the parallelization of the tasks. The flow chart is same as that of machine structure configuration approach in the beginning up to operation clustering but moves towards operation sequencing after that. In the next step the possibility of parallel operations is considered and in the end the generation of structures for the associated process plans takes place. An algorithm was made for the approach. To explain the working of the algorithm, it is divided into four sections: inputs and size check (Figure 29), finding the TADs and rotations required (Figure 30), parallelization of tasks in the algorithm (Figure 31) and the production rate improvement and the end of the algorithm (Figure 32). A detailed explanation of the algorithm is made in the following text:

The algorithm starts off with the three inputs (precedence graph, size, TAD). As in Figure 29, the operation clustering (see section 2.2.2 for details) is done after the input. After the clustering stage the size check is performed to verify whether the part is small enough to fit into the machine for the machining purpose or not. This can be achieved by using a simple if statement. If the part is too large than algorithm stops else it moves to the next step of generation of TAD.

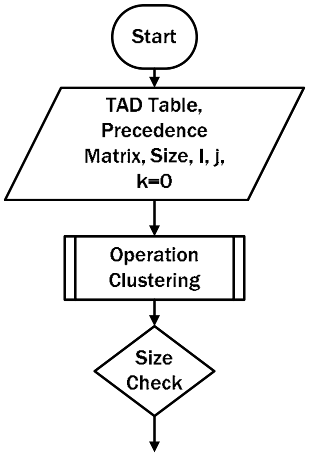


Figure 29: Inputs and size check in the algorithm

After the completion of size check, a loop starts (I < No of operations) where I is initialized as 0 (Figure 30). This loop generates the appropriate TAD for each operation (see section 2.2.2 for details). The example of how this takes place for a sample part is presented in the case study as well. Using the appropriate TAD's for each operation, the rotations that will be required for the operation cluster are separated. Since the default TAD is the –z the angles required to rotate it to +y or any other TAD can be calculated. For example, to rotate the tool from –z to +z direction, a 180^0 rotation is required. Similarly, from –z to +x a 90^0 or a 270^0 rotation can be used. Once the rotations of all the operations have been calculated, the loop ends causing an exit from the loop to find the rotations required.

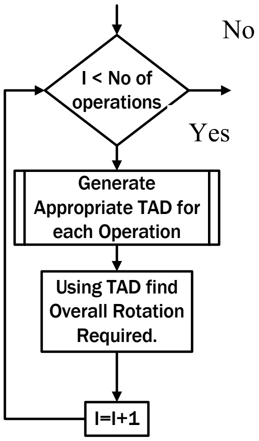


Figure 30: Finding the TADs and rotations required.

Once the previous loop ends; using the rotations and the minimum TADs, the configuration of the machine that is required for the operations (Figure 31) can be found. For example, if the TAD is only '–z' then the machine configuration required is a simple fixture that has only one movement in the '–z' direction. After this, the algorithm moves into another loop which use the combinations of the minimum TAD's gives all the possible machine sequences that are available and thus forms the process plans. Later, nested loop separates the plan into those which can be done in series (only one tool machining at a time) and parallel (multiple tools machining at a time).

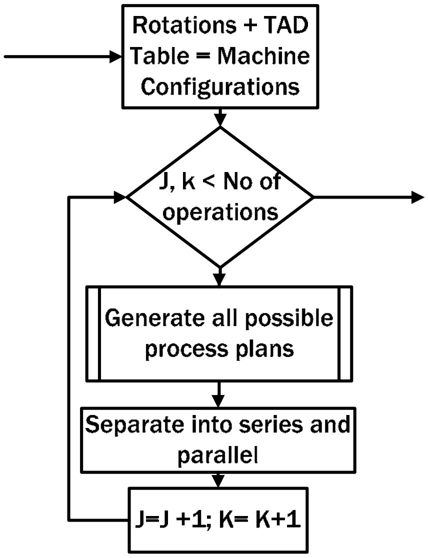


Figure 31: Parallelization of tasks in the algorithm.

Later, the algorithm moves into its final loop (Figure 32), where the process plans are the inputs and each one of them is checked for the number of TAD change takes place. For example; if one process plan has overall only one TAD change, then it will take less time as compared to the one which has more than one TAD change. The reason for this is that the tool will have to move from one TAD to another again and again resulting in wasted time and efforts. In the end, the process plan which has the minimum number of TAD change will take the minimum time and therefore will be separated. The case study using part CPHC10 is used to explain step by step how the algorithm works and in the end the most suitable sequence is separated. The complete algorithm for this approach is shown in Figure 33.

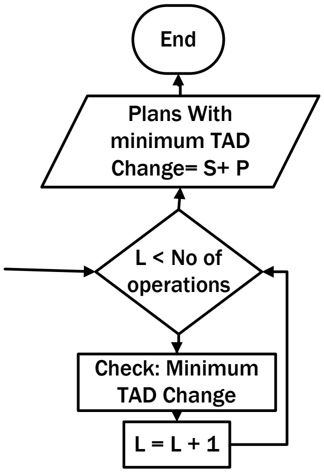


Figure 32: Production rate improvement and the end of algorithm.

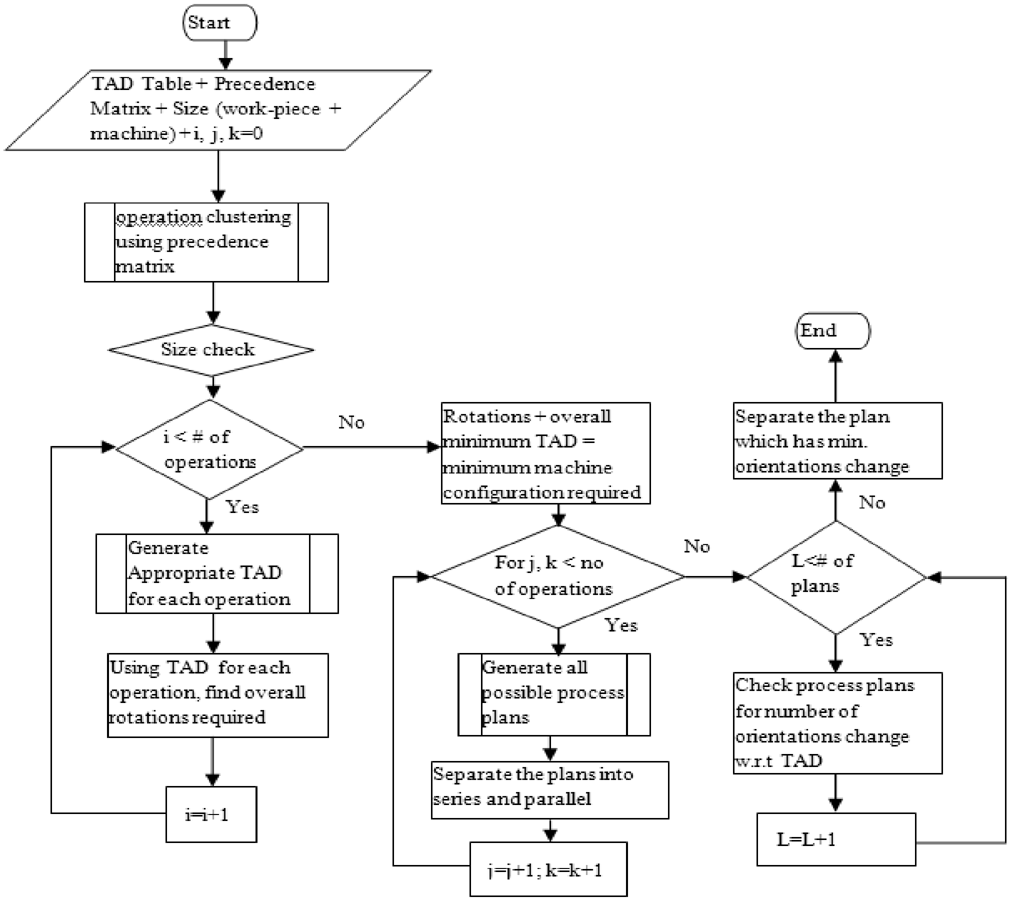


Figure 33: The Algorithm for the improved approach

3.2.1 Case Study

The algorithm in Figure 33 can be further explained with the help of a sample part. The part CPHC10 is taken as the sample part and its specifications are preset in the appendix A at the end of the thesis. There are 34 operations to be performed on the part, 16 clusters were formed from those 34 operations. The important point about this case is that each operation within the operation cluster has the same TAD's. Hence overall TAD of any single cluster remains the same. The TADs of the clusters are displayed in Table 20. The clusters 1 and 10 are of surface milling and surface finishing while the rest are mostly drilling, boring and reaming of holes therefore there is only one possible TAD for each one of them. The precedence graph of the CPHC10 part is shown in Figure 34.

Table 20: TAD Table of CPHC10

Cluster No	Tool Approach direction					
	+x	-x	+y	-y	+z	-z
1	1	0	1	1	1	1
2	0	0	0	0	0	1
3	0	0	0	0	0	1
4	0	0	0	0	0	1
5	0	0	0	0	0	1
6	0	0	0	0	0	1
7	0	0	0	0	0	1
8	0	0	0	0	0	1
9	0	0	0	0	1	0
10	1	0	1	1	1	1
11	0	0	0	0	0	1
12	0	0	0	0	0	1
13	0	0	0	0	0	1
14	0	0	0	0	0	1
15	0	0	0	0	0	1
16	0	0	0	0	1	0

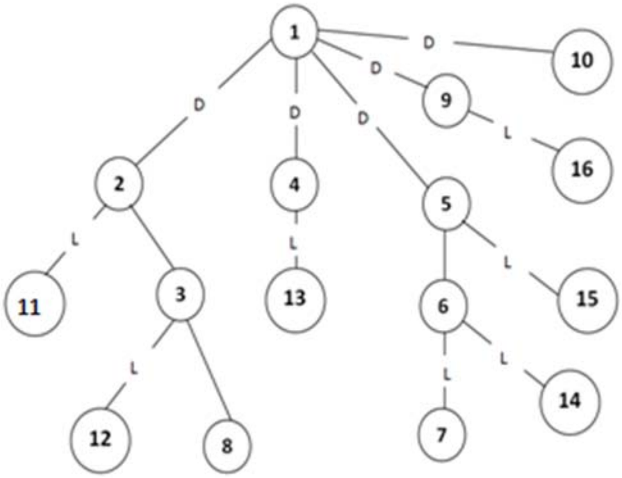


Figure 34: Precedence Graph of CPHC10

The precedence graph of the part CPHC10 is converted to precedence chart / matrix (see section 2.2.1.2 for conversion method) and forms Table 21. The Table 21, in mathematical terms is a sparse matrix and is added as an input in the algorithm. Many techniques exist to convert a sparse matrix into a less space and computation time consuming form. In general however, in automated manufacturing, these sparse matrices do not consume too much space. Therefore, even without the use of mathematical techniques, the computation time is very less for the computer codes. Now, after the inputs, the algorithm after simply checking the size constraints moves on to the tool approach directions. Applying all the techniques mentioned in section 2.2.2, the resulting TAD table is shown in Table 22.

.

Table 21: Precedence chart of CPHC10

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0	1	0	1	1	0	0	0	1	1	0	0	0	0	0	0
2	-1	0	3	0	0	0	0	0	0	0	2	0	0	0	0	0
3	0	-3	0	0	0	0	0	3	0	0	0	2	0	0	0	0
4	-1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
5	-1	0	0	0	0	3	0	0	0	0	0	0	0	0	2	0
6	0	0	0	0	-3	0	2	0	0	0	0	0	0	2	0	0
7	0	0	0	0	0	-2	0	0	0	0	0	0	0	0	0	0
8	0	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0
9	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
10	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	-2	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	-2	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	-2	0	0	0	0	0	0	0

Table 22: Required TAD Table of CPHC10

Cluster No.	**Tool Approach direction**					
	+x	-x	+y	-y	+z	-z
1	0	0	0	0	0	1
2	0	0	0	0	0	1
3	0	0	0	0	0	1
4	0	0	0	0	0	1
5	0	0	0	0	0	1
6	0	0	0	0	0	1
7	0	0	0	0	0	1
8	0	0	0	0	0	1
9	0	0	0	0	1	0
10	0	0	0	0	0	1
11	0	0	0	0	0	1
12	0	0	0	0	0	1
13	0	0	0	0	0	1
14	0	0	0	0	0	1
15	0	0	0	0	0	1
16	0	0	0	0	1	0

It can be seen that the only axis required are ‘+z’ and ‘–z’. Therefore, a **3-axis machine** will be sufficient for part CPHC10 if the **overturning** of the part for the –z direction operations is carried out. In case the tool is required to be rotated to the ‘–z’ direction, then a fourth ‘rotational’ axis is also required. Hence, in this case, a **4-axis machine** is required. After machine configuration is selected, the algorithm moves on to the next step: the generation of all the possible process plans. To generate the process plans, the algorithm utilizes the data of the precedence matrix. All the operations that can be performed on the matrix which do not have a precedence relationship allow for different process plans. This can be explained using a three operation example shown in Figure 35.

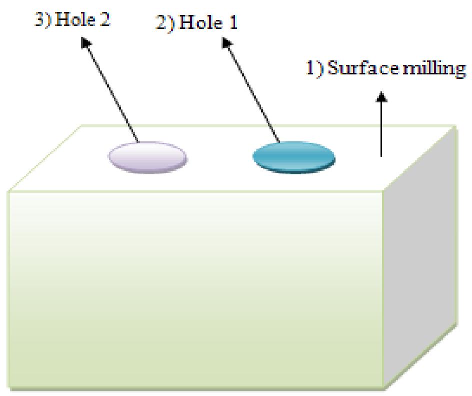


Figure 35: 3 Machining operations.

The three operations are linked to each other by a datum constraint which forces the surface milling to be operated before either of the holes. Therefore, operation 1 will be surface milling. But there are no other constraints between the two holes; this takes the form of the precedence graph in Figure 36:

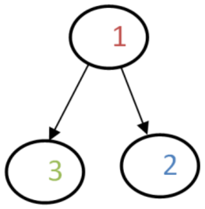


Figure 36: precedence graph of example

By observing the graph, it can be said that there are two possible sequences that can be followed:

- Surface milling, then hole 1 then hole 2
- Surface milling, then hole 2 then hole 1

Similarly, in case of CPHC10 there are a total of 150 different combinations that can be made. Now, to select the best one which is suitable for the available machinery and is the fastest, the algorithm moves on to the next step which is to separate the combinations into series and parallel combinations. Series combinations refer to those set of operations which are performed on the same machine. And parallel as the name implies refer to the set of operations performed using two or more spindles simultaneously. An example (Figure 37) of parallel machining is the drilling of two holes simultaneously in the +x and the –x direction:

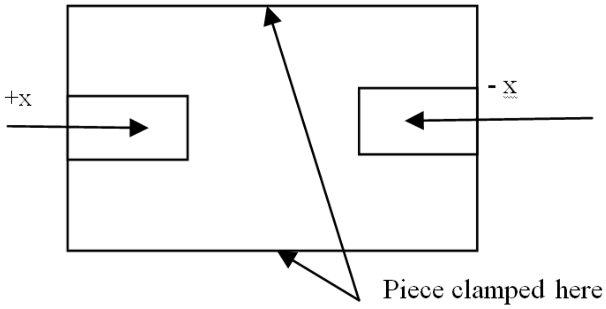


Figure 37: Parallel machining

Since in Table 22, CPHC10 has 2 operations in –z direction, whereas the rest are in the +z direction. Therefore, it can also have parallel operations performed on it. Now, it completely depends upon the user whether he has parallel operations capability or not and obviously it is a tradeoff between time and accuracy because two tools working simultaneously will give more vibrations and the accuracy will suffer.

Coming back to the algorithm, using the TAD, it is only a matter of using the final TAD table and finding the operations that can be performed in parallel as well. If the manufacturing structure has the capability to do parallel operations, only then is this utilized otherwise it is discarded. After series and parallel combinations have been formed the next step is the selection of the best suited one for the manufacturer.

Thus, the algorithm moves into the final loop where the selection of the best suited process plans takes place. Here, the algorithm simply skims through each of the process plans and calculates the number of tool approach direction changes. To put it very crudely: If the tool approach direction changes is more the process plan will take more time for machining the part, if it is less the plan will take less time. This can be illustrated using two of the operation sequences of part CPHC10 as shown in Table 23.

Notice that the operation sequence 1 has three TAD changes:

1. Before operation 9
2. After operation 9
3. Before operation 16

While the operation sequence 2 has only one TAD change:

- Before operation 9

Table 23: Sample Problem.

	Operation No.	TAD			**Operation No.**	TAD	
		+z	-z			+z	-z
Operation sequence 1	**1**	0	1	**Operation sequence 2**	**1**	0	1
	10	0	1		**10**	0	1
	2	0	1		**2**	0	1
	11	0	1		**11**	0	1
	3	0	1		**3**	0	1
	4	0	1		**4**	0	1
	6	0	1		**6**	0	1
	5	0	1		**5**	0	1
	7	0	1		**7**	0	1
	8	0	1		**8**	0	1
	9	1	0		**15**	0	1
	12	0	1		**12**	0	1
	13	0	1		**13**	0	1
	14	0	1		**14**	0	1
	15	0	1		**9**	1	0
	16	1	0		**16**	1	0

Therefore, considering both of the operation sequences; there are primarily two advantages that the operation sequence 2 holds over the operation sequence 1. The first one is obvious enough; since it has only one TAD change, therefore it will take less time to finish. The second advantage is that since more operations are carried out with the same orientation of the TAD, therefore the tolerance change which can occur in operation 1 (if the work-piece is dislodged from its fixed position) will not occur. For example; consider the operation sequence 1 of Table 23. It is evident that to perform operation 9 (it is to be carried out in the opposite direction), the vice or any other clamping device which holds work-piece needs to be opened. After that, overturning of the piece takes place to perform operation 9. After operation 9, the work-piece is again overturned to perform operations 12, 13, 14, 15 and then finally, an overturn again in order to perform operation 16. Illustratively (Figure 38):

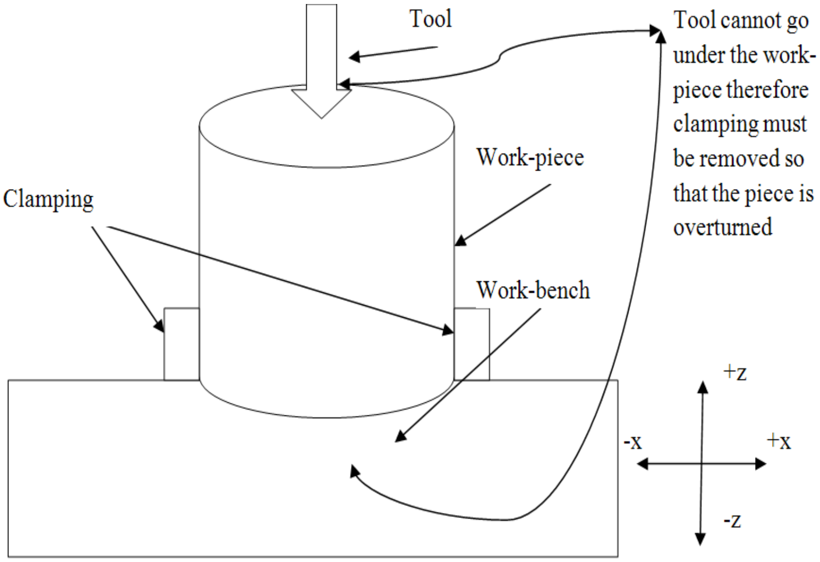


Figure 38: Accessibility of tool

Coming back to the algorithm, a simple counter can be used to count the number of tool approach direction changes in the operation sequences. Then, the operation sequence with the minimum number of the TAD changes can be selected. Finally, the series and parallel operations' process plans are separated and their associated kinematic configurations are selected as discussed before.

3.2.2 Results & Discussions

For the part CPHC10, only a three axis machine is required. However, if there are more TAD's involve in some other part, there will be a need of a 4 or a five axis machine depending on the requirements which already has been discussed before. The final operating sequence that should be followed is more than one in case of part CPHC10. This is based upon two main factors:

1. Production rate
2. Tool Approach Directions

One of the resulting appropriate operation sequences along with the appropriate TAD is shown in Table 24. A three axis with re-fixturing or a 4-axis with machine with the work piece overturning ability is required.

Table 24: Appropriate Serial Operation Sequence of CPHC10

Operation sequence	**Op. No.**	TAD		Re-fixturing Required	**Rotations**		
		+z	-z		X	Y	Z
	1	0	1		0	0	0
	10	0	1		0	0	0
	2	0	1		0	0	0
	11	0	1		0	0	0
	3	0	1		0	0	0
	4	0	1		0	0	0
	6	0	1		0	0	0
	5	0	1		0	0	0
	7	0	1		0	0	0
	8	0	1		0	0	0
	12	0	1		0	0	0
	13	0	1		0	0	0
	14	0	1		0	0	0
	15	0	1		0	0	0
	9	1	0		180	0	0
	16	1	0		0	0	0

The part CPHC10 needs to be rotated and re-fixturing is required for operation 9, but due to the technique of selection of optimized production rate, this is required only once. If this technique was not applied however, this re-fixturing may have been required more times thus causing delay.

3.2.2.1 Parallel operations:

After achieving machine structure configuration approach for single post solution; the approach moves on to the TAD table for multiple post solutions (Table 25). Observing the cluster no 9 in Table 25, it has TAD +z while TAD of cluster 8 is –z. Therefore, these operations can be performed in parallel. Similarly operations 15 and 16 can be performed in parallel as well.

In the conventional techniques for RMS, production rate is not incorporated into the approach for RMS whether it is machine structure configuration approach or any other. Therefore, the techniques and the algorithm mentioned in this thesis if applied properly can save the producer a lot of time and as it is a famous quote: “Time is money”, provide them with extra revenue as well. Thus, using the algorithm and the techniques mentioned in this thesis: check whether the work-piece size is suitable for the machine or not, get the required **machine configuration,** then generate all the operation sequences for the **Process Plans** and finally **select** the most appropriate operation sequence based upon TAD, production rate and reduction in tolerance change.

Table 25: Multi post Solution

Cluster No	Tool Approach direction					
	+x	-x	+y	-y	+z	-z
1	0	0	0	0	0	1
2	0	0	0	0	0	1
3	0	0	0	0	0	1
4	0	0	0	0	0	1
5	0	0	0	0	0	1
6	0	0	0	0	0	1
7	0	0	0	0	0	1
8	0	0	0	0	0	1
9	0	0	0	0	1	0
10	0	0	0	0	0	1
11	0	0	0	0	0	1
12	0	0	0	0	0	1
13	0	0	0	0	0	1
14	0	0	0	0	0	1
15	0	0	0	0	0	1
16	0	0	0	0	1	0

There are many different approaches for the different manufacturing systems available in the market today. These different manufacturing systems require unique solutions appropriate for their specific nature of problems. A technique which further enhances the machine structure configuration approach and incorporates the time and the tolerance change reduction was introduced along with an algorithm which can be used to apply this technique on the manufacturing system. A step by step description of the algorithm and the technique was given and taking the part CPHC10 as an example was illustrated as well.

The concept of mapping has already been presented in the machine structure configuration approach which relates the processing requirements of the part and the structural requirements of the machine. The result was the generation of the required machine capabilities, which is further enhanced in this thesis by the reduction in the production rate and the tolerance change reduction. Given the tool approach directions, the precedence graph and the size of the work-piece required as well as the machine dimensions, a link was developed between the **CAD** drawing of the required part and the **CAM** of the part.

The said algorithm is highly simplified and the technique to apply the algorithm was explicitly discussed so that any programmer has no problem in applying it on any of the language software (MATLAB, FORTRAN etc.). Its robustness can be checked and further improved by using layered part family. It may cause combinatory explosion in case of huge number of features which include angular holes. The algorithm and the techniques are generic in nature and thus they can be applied on not only RMS, but any manufacturing system which has the flexibility and the problems associated with it and require a solution. This work is a step forward in the complete generation of the process plans starting from a simple drawing to the finished product.

Now, after this approach was developed, there was need of a modeling technique to make it accessible and convert it to a globally understandable method. The Petri-net model was selected and is discussed in detail in chapter 4.

Chapter 4:
The Petri Net Model

4.1 Introduction

The Petri net was first introduced by Dr. Carl Adam Petri in his PhD dissertation [44] submitted in 1962 to the faculty of mathematics and physics at the Darmstadt University, West Germany. Basically, Petri net is a modeling tool which is present in both mathematical and graphical form. It has been used throughout its history to represent different systems.

4.1.1 Need for the Model

The Petri-net model allows the development of a universal model of any given approach. The main aspects of the Petri net model which make it an attractive choice for modeling systems is that it is concurrent, asynchronous, distributed, parallel, non-deterministic, and/or stochastic. The Petri net model has its usefulness both as a graphical tool and as a mathematical modeling tool. As a graphical tool; the model is used to represent systems in the form of flow charts and as a mathematical model it can be used to set up state equation, algebraic equations and similar mathematical equations which govern the behavior of any given system. In case of the Algorithm (CPGA), this approach allows the development of a universal model allowing it to be more accessible to the research society. Also, the model allows easier modeling of the approach as compared to the algorithm. The mathematical model can then be developed if need be.

In chapter 3, an algorithm, using the MSCA was developed (Figure 33). After that a code using Matlab was generated and then the results were compared with the existing algorithms. In this chapter, the Petri net model of the same algorithm is developed and then the results (the co-evolved process plan based upon production rate) were compared. The results using both the techniques matched perfectly. The Petri net model similar to the algorithm starts off by taking the three main sets of variables i.e. the precedence graph, the size and the tool approach directions as inputs. After that clusters of the operations are formed as per the precedence graph. When the clusters have been generated, the Petri net model selects the TAD for each operation cluster that will generate the minimum overall TAD. The overall TAD will then of course direct the selection of the machine configuration for that particular part. In the end the Petri net model will select the process plan with the minimum production rate.

4.1.2 Basic Concepts

To develop the Petri net model of this algorithm which is based on CPGA, some basic concepts that were utilized are explained in the following text. As discussed before, Petri net is a graphical and mathematical modeling tool for the description of distributed systems. It is a directed graph with two kinds of nodes: one is called the place and the other is called transition.

- Place represents a resource or any condition which may be held.
- Resource represents action or events that may occur.

Their graphical illustration is shown in Figure 39:

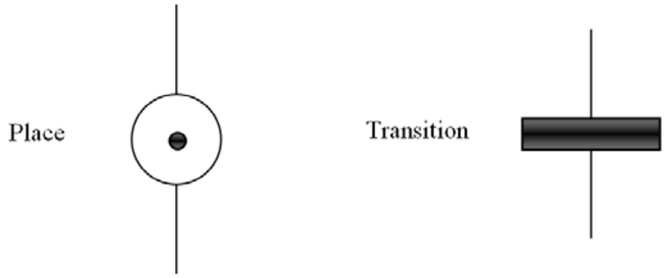


Figure 39: Graphical illustration of place and Transition.

Table 26: Typical Interpretations of Transition and Places. [45]

Input places	Transitions	Output places
Preconditions	Events	Post conditions
Input data	Computation step	Output Data
Input signal	Signal Processor	Output signal
Resource needed	Task or job	Resources released
Conditions	Clause In Logic	Conclusions
Buffers	Processors	Buffers

There are other interpretations of place and transition as well depending upon the type of system under consideration. Some of their interpretations are listed in Table 26. Including the nodes and the transitions, there are four elements of a Petri net. The other two comprise of token and arc. The token is a requirement for any transition to take place. The arc develops a link between a transition and a place. It cannot be between two transitions or two places. Each arc has its specific weight associated with it which is shown as a number on top of the arc. If there is no number then the arc weight is one and only one token is required to fire the transition. If the arc weight is two it will require two tokens and so on. Therefore, it can be concluded that the arc weight represents the minimum number of tokens to fire the transition. The interlinking and functions of all four elements can be better understood by Figure 40.

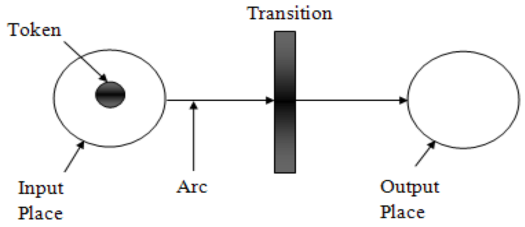


Figure 40: Graphical illustration of place and Transition.

In Figure 40, because there is a token in input place, the transition is ready to fire and once the transition has fired, the token will move to the output place. A transition is said to be enabled if and only if the number of tokens in the input place is greater or equal to frequency of related arc and the number of tokens in the inhibitory place is smaller than arc frequency. The arc frequency is given by a number above the arc. If there is no number above the arc then the arc frequency is 1 and one token is required to fire the transition.

4.1.3 Properties of Petri-net

The properties of Petri nets which specifically contribute to the modeling of the algorithm are discussed here. If there is still a need of further understanding of this concept then reference [46] should be utilized and there is a lot material available on the internet on Petri nets as well. Figure 41 shows sequential action in which each transition is an action. In case of algorithm each process will show a sequential action.

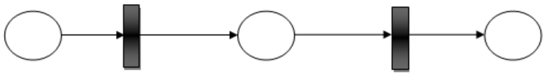


Figure 41: Sequential Transitions. [47]

The dependency shown in Figure 42 illustrates: when there are two places before a transition then both these places must have one token at least for the transition to fire. And if the weight of the arc is other than one then it will require corresponding number of tokens in the respective places. Another way of looking at this is that if the number of tokens is not sufficient then the transition will not fire. For example; if one of the input places has one token and the other is empty then the transition will not fire.

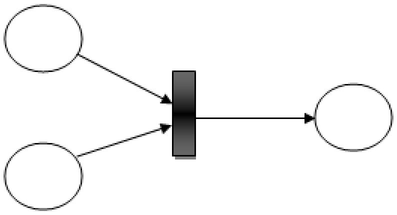


Figure 42: Dependency. [47]

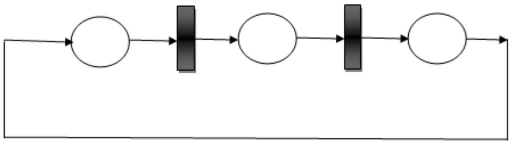


Figure 43: Cycles. [47]

Figure 43 shows the concept of cycles which in algorithms are the 'loops'. Cycles can help to represent these loops if the input and outputs of the loops are properly controlled in the form of other combinations of places and transitions. Figure 44 shows buffers which can store a number of tokens for a time being. In case of algorithms, it is used for numerous purposes. One such purpose is the controlling exit from the loops. In Figure 44 when the transition 2 is fired then it will send one token to place 3 and one token to buffer. And now the token is stored until the place 1 acquires a new token. Therefore if place 1 has a loop before it, the loop can be easily controlled using the buffer i.e. until the loop is not finished there will be no token in place 1 and therefore the transition 1 will not fire thus successfully controlling the loop. This will be further explained when the Petri net model of algorithm will be discussed.

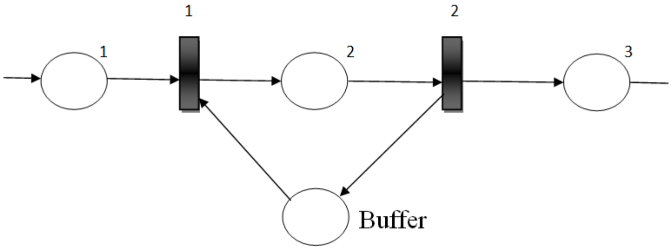


Figure 44: Buffer [47]

Decision making can be accomplished in many ways such as using the "If-else" statement or the "whether" statement in programming. To represent this in Petri net there are numerous combinations. Figure 45 shows the application of 'if-else' statement used in this chapter for the Petri net model. When the token reaches the input place it has two choices. Either fire the 'if' transition or fire the 'else' transition. Both these transitions hold a specific condition to fire. If the 'if' statement is satisfied the transition 1 is fired and token moves to place 1 otherwise it moves to place 2.

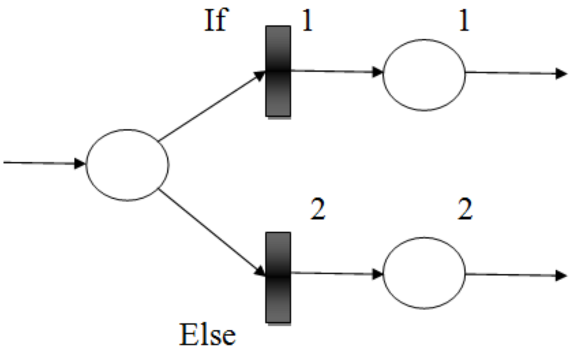


Figure 45: If-Else Statement Petri net Model. [47]

4.2 Petri Net Model of CPGA

Using the properties of Petri nets, a model was developed which is shown in Figure 50. To overall explain the model using a single figure is a cumbersome task. The model is thus divided into 4 sections: section 1 (Figure 46), 2 (Figure 47), 3 (Figure 48) and 4 (Figure 49). The description of places is shown in Table 27, and the description of the transitions is shown in Table 28.

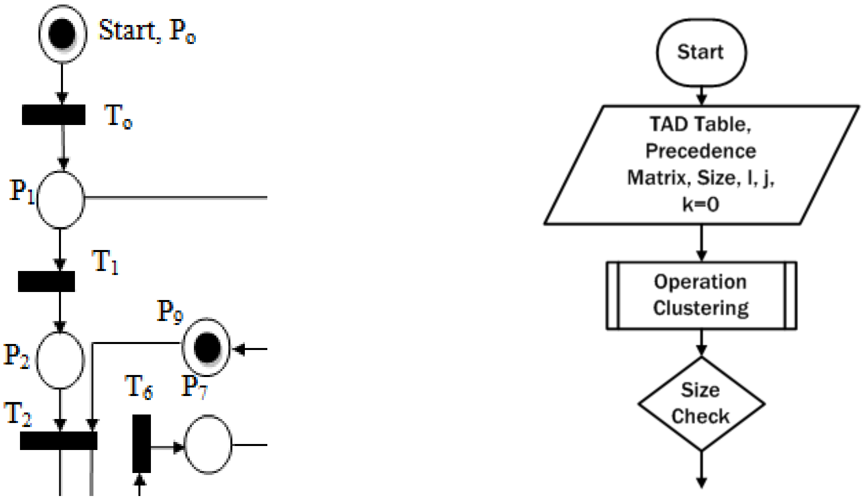


Figure 46: Section 1 of the Petri net model

The Petri net model starts off at place P_0 (Figure 46). This place as shown in Table 27 is the initialization of the model as well as the input place for the model. It can be seen that the token is present at P_0. Therefore the transition T_0 (operation clustering) is ready to fire. Once T_0 is fired the token moves to place P_1; thus the model moves to the size check which is done by the ‘if-else’ statement. The transition T_1 is fired if the size check is cleared and the size of work-piece is less than or equal to the allocated machine maximum size limit. And the transition T_{19} is fired if the size heck fails. In case the size check fails, the token moves to the place P_{25} and the model ends. In case the size check is cleared the token moves to place P_2 after which the first cycle (loop) of the model is to begin.

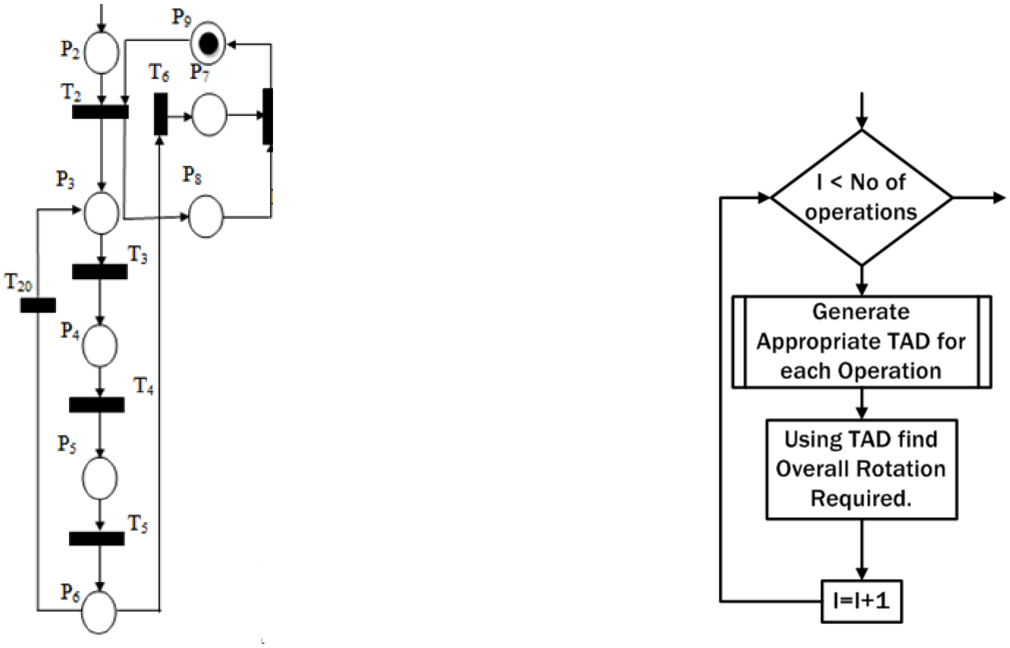


Figure 47: Section 2 of the Petri net model

Moving on to the section 2 of the Petri net model, it is worth noting that the transition T_2 requires tokens at two places P_9 and P_2. This has been designed so that once the transition T_2 has fired; one token will move to place P_8 (Figure 47) and the other to P_3. Therefore a token in P_8 will give the indication that the initial token is now in the subsequent loop. Coming back to the token in P_3; it is now for the first time in the cycle or loop and as labeled in Table 27. This is an indication that the first operation is under consideration for the selection of the TAD and corresponding rotation. Now the token fires the transition T_3 which is the generation of appropriate TAD for that particular operation. Thus the token moves to P_4 indicating that the appropriate TAD's have been selected for the given part. After that the token fires T_4 and therefore selecting the appropriate rotations that will be required for the corresponding TAD for that operation. The token is now at P_5. Here the TAD and rotations both have been selected for the first operation. A token in P_5 fires the transition T_5 indicating that now the counter has added 1 to the value of "I" which was 0 initially. Now P_6 holds the token faced with two possible transitions (decision) if the value of 'I' becomes equal to or greater than number of operations then the transition T_6 is fired otherwise the transition T_{20} is fired. In this case right now the value is just 1 so T_6 is fired and the loop starts again. When the value of 'I' becomes equal to the number of operations then T_6 is fired and the token moves to P_7. This is an indication that all the operations have their appropriate TAD and their corresponding rotations selected thus moving on to the second loop. It should be noted that right now there is a token present in P_8 as well which came to P_8 when initially T_2 fired. Therefore having tokens in both P_7 and P_8 allows transition T_7 to fire, resulting in the tokens travelling to places 'P_9' and 'P_{10}' (Figure 50). The token in P_9 indicates that the cycle or 'loop' has ended and the token has now moved out of the cycle. Whereas the token in P_{10} indicates that the minimum machine configuration required for the operations has been obtained and now the model is ready to enter another cycle.

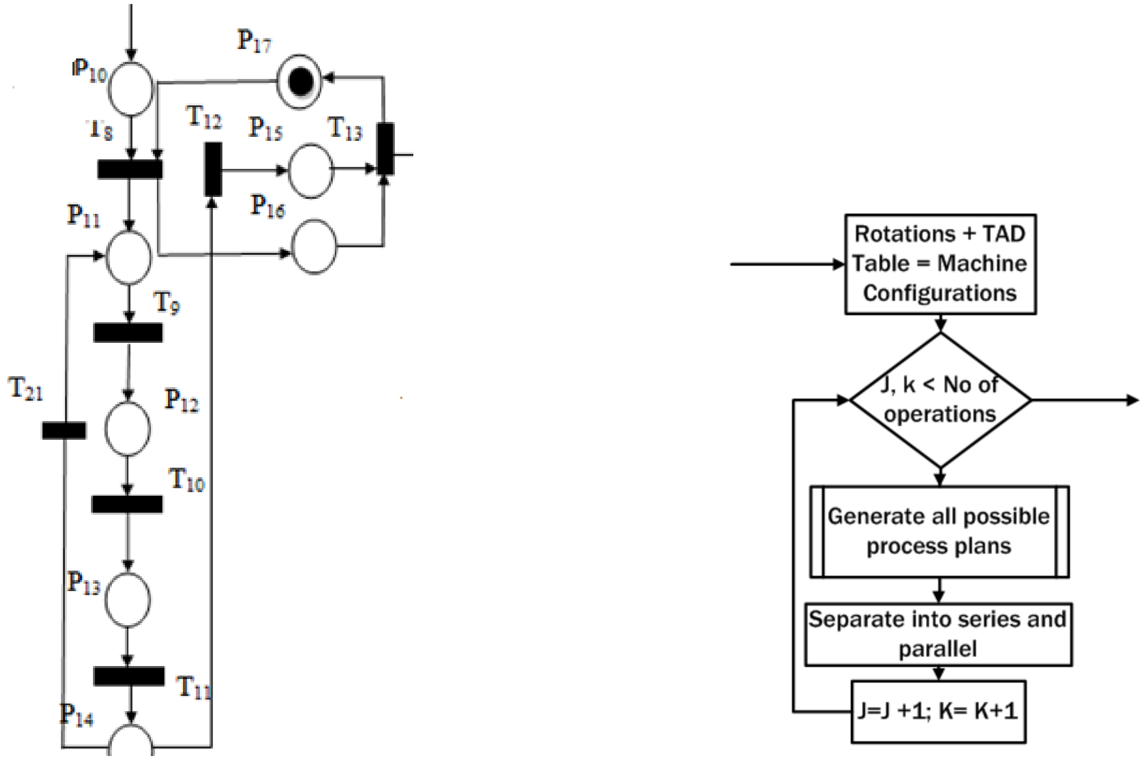


Figure 48: Section 3 of the Petri net model

The aim of the second cycle, as was the case with the algorithms' second loop is to generate all the available process plans. The model enters the second loop similar to the way it entered the first loop; the token in P_{10} and the token in P_{17} allows the transition T_8 to fire. Therefore one token goes to P_{11} and the other to P_{16}. Token at P_{16} indicates that the second cycle is in progress. Token at P_{11} indicates that the model is ready to generate process plans using the precedence matrix. As before (T_3,T_4 and T_5), sequential transitions T_9, T_{10} and T_{11} fire which indicate the 'generation of all process plans', 'separation of process plans into series and parallel' and 'increment of 1 in the values of j and k which were initially 0' respectively. Similar to T_6 and T_{20}, in this cycle T_{12} and T_{21} play the role of 'if-else'; and since the loop has just run for the first time, therefore T_{21} will fire. When this cycle is completed, the model exit is in the same manner as in the first cycle and then it enters the final cycle (Figure 49) where it selects form all the process plans based upon production rate.

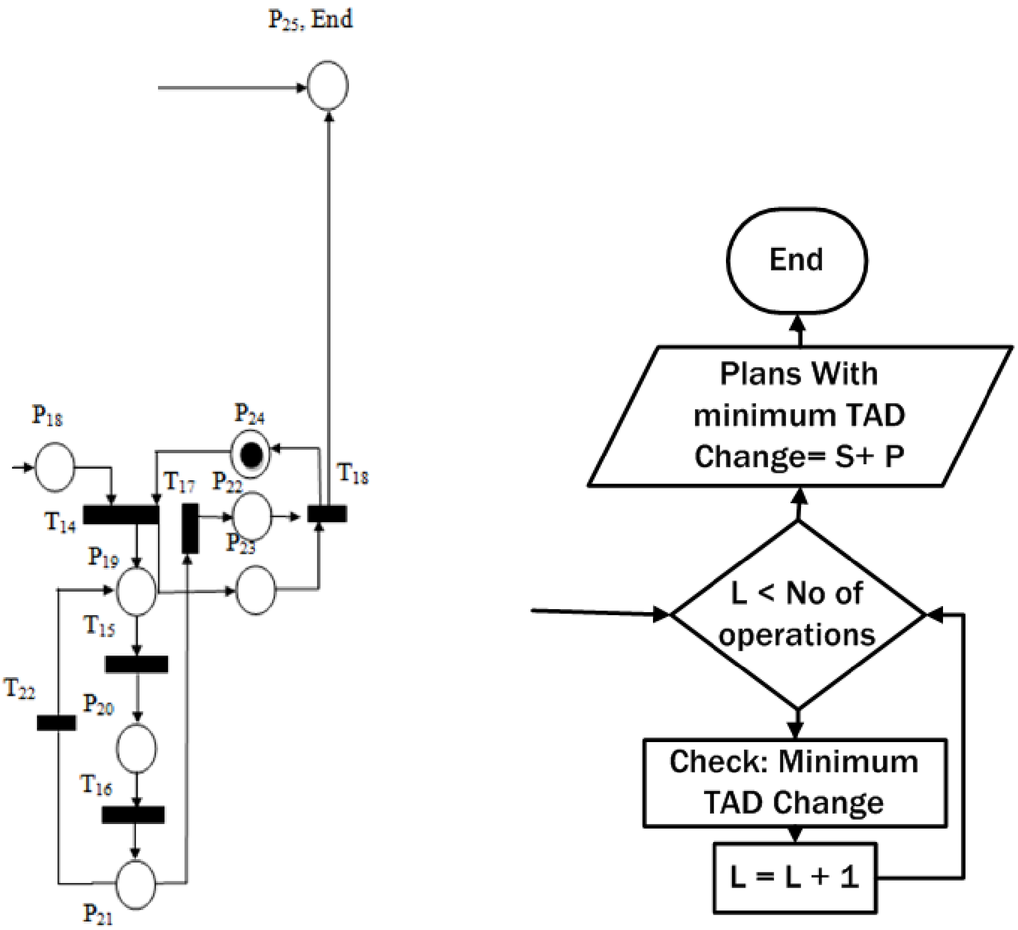


Figure 49: Section 4 of the Petri net model

When in the Petri net model, the token reaches P_{18}, T_{14} is ready to fire and once it fires, one of the tokens moves to P_{19} representing the start of loop (Algorithm ready for calculation). At first, the T_{15} automatically fires and the token moves to P_{20}. Here, as in the algorithm, the minimum TAD change is calculated for the particular process plan. Next, the transition 'T_{16}' is fired. Then, the token moves to place P_{21} (L< No. of operations). An 'if-else' statement is again generated and the loop ends in a similar fashion to the ones before it. The model reaches the end when the token reaches the place P_{25}. The complete model is shown in Figure 50.

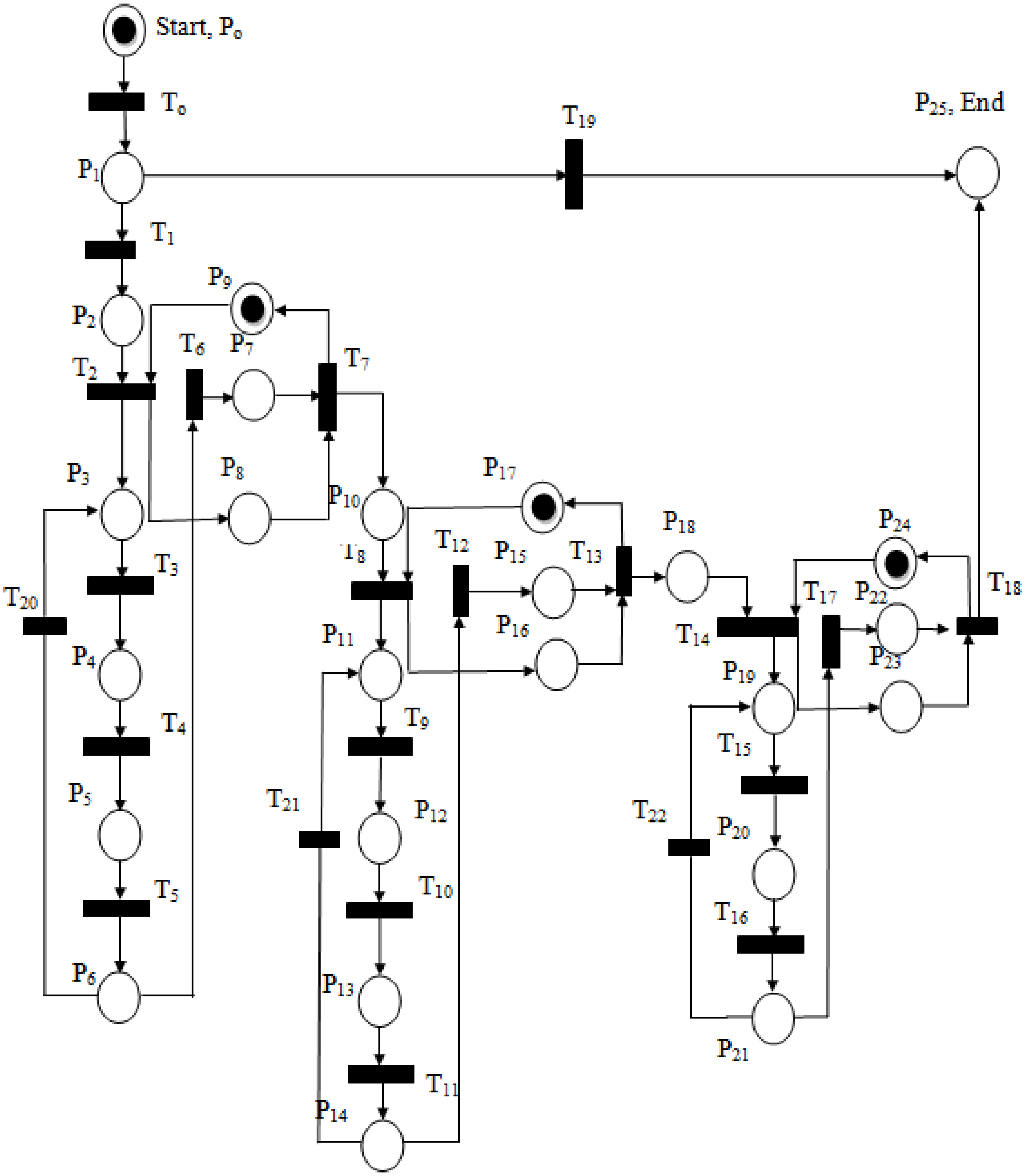


Figure 50: The Petri Net Model of the CPGA.

Table 27: Descriptions of places in the Petri net model

Rank	Place	Descriptions
1	P_0	Initialization of algorithm. Input : TAD Table + Precedence Matrix + + Size (work-piece + machine) +I, j, k=0
2	P_1	Algorithm ready for size check
3	P_2	Size check passed, Machine suitable for the work-piece. Algorithm ready for first loop
4	P_3	Tool approach direction (TAD) table ready to be configured for optimum TAD for each operation
5	P_4	Appropriate TAD obtained for each operation.
6	P_5	Required rotations obtained for the particular operation.
7	P_6	Iteration complete.
8	P_7	Rotations and overall minimum TAD obtained.
9	P_8	First loop of algorithm in progress.
10	P_9	First loop of algorithm not in progress.
11	P_{10}	Minimum machine configuration obtained.
12	P_{11}	Precedence matrix ready to be used to obtain all process plans.
13	P_{12}	All process plans generated.
14	P_{13}	Plans separated into series and parallel.
15	P_{14}	Iteration complete.
16	P_{15}	First Loop completed.
17	P_{16}	Second loop of algorithm in progress.
18	P_{17}	Second loop of algorithm not in progress.
19	P_{18}	Algorithm ready to find best available process plan.
20	P_{19}	Using TAD, algorithm ready to calculate number of orientations change for each process plan.
21	P_{20}	Number of orientations change obtained for each process plan.
22	P_{21}	Iteration complete.
23	P_{22}	Second loop complete.
24	P_{23}	Third loop of algorithm in progress.
25	P_{24}	Third loop of algorithm not in progress.

Table 28: Descriptions of transitions of the Petri Net Model.

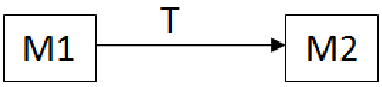
Rank	Transition	Descriptions
1	T_0	Operation clustering using precedence matrix.
2	T_1	Size check (Size <= then machine dimensions).
3	T_2	Initialization of loop.
4	T_3	Generate Appropriate TAD for each operation.
5	T_4	Using TAD for each operation, find overall rotations required.
6	T_5	I = I + 1.
7	T_6	I = Number of operations.
8	T_7	Calculation of minimum machine configuration required.
9	T_8	Initialization of loop.
10	T_9	Generate all possible process plans.
11	T_{10}	Separate the plans into series and parallel.
12	T_{11}	j = j + 1; k = k +1
13	T_{12}	J, k = Number of operations.
14	T_{13}	Getting value of l.
15	T_{14}	Initialization of loop.
16	T_{15}	Check process plans for number of orientations change w.r.t. TAD.
17	T_{16}	l = l + 1.
18	T_{17}	l = Number of process plans.
19	T_{18}	Separate the plan which has min. orientations change.
20	T_{19}	Size check (Size > then machine dimensions).
21	T_{20}	I < Number of operations.
22	T_{21}	j, k < number of operations
23	T_{22}	l < Number of process plans.

Table 27 and Table 28; show the descriptions of places and transitions respectively. The application of the model is further elaborated in section 4.4. Reachability graph is used to identify the relationships and/or dependencies between two transitions. There are many cases in which there may not be an obvious relationship between two transitions but nevertheless it exists. To find and observe these relations a reachability graph is used.

4.3 Reachability Graph of the Petri-net model

The reachability graph of the Petri-net tells of the finiteness of the model. If the reachability graph of the Petri net model is finite then the model is finite and vice versa. Another interpretation of reachability graph is that it tells of the time based availability of the model. For example in case of a manufacturing plant, the reachability graph can tell about the percentage of time a certain station is vacant or occupied. Further details of the reachability graph can be found in [48].

An example of the reachability graph is shown in Figure 51. In this figure, the M represents the 'Marking' which is a set containing the number of tokens in each place. Figure 51 is the reachability graph (left) and the reachability set (right) of the Petri net model (Figure 50). M1 represents the state of the Petri net model where the token is in the input place and no token exists in the output place. This is illustrated in the reachability set by a 1 in the input place and 0 in the output place in the 2nd row i.e. M1. Once the transition has fired however, the token moves on to the output place leaving the input place empty. This is shown in M2 row of the reachability set with a 0 in the input place and a 1 in the output place. Now, since the Making M1 turned to Marking M2 when the transition T fired, therefore the T is present on the arc connecting M1 to M2 in the reachability graph. And since the marking is moving from M1 to M2 therefore the arrow is direct towards M2.



	Input Place	Output Place
M1	1	0
M2	0	1

Figure 51: Sample Reachability Graph and Reachability Set

The reachability graph of the Petri net model (Figure 50) is shown in Figure 51. The reachability set of the same model is shown in Table 29. The reachability graph starts off with the initial state of tokens in the Petri net model. This initial state is represented by M0. There are four tokens in the initial state of the model; one each at P_0, P_9, P_{17} and P_{24}. Therefore the reachability set of the model has 4 1's in the second row (M_0 Row) at P_0, P_9, P_{17} and P_{24} locations. The initial transition is T_0. Once this transition is fired; as discussed before, the token at the place P_0 moves to P_1. Therefore the 1 present at P_0 at M_0 moves to P_1 in row M_1. Also, the arrow is labeled T_0 moving from M_0 to M_1 in the reachability graph (Figure 52).

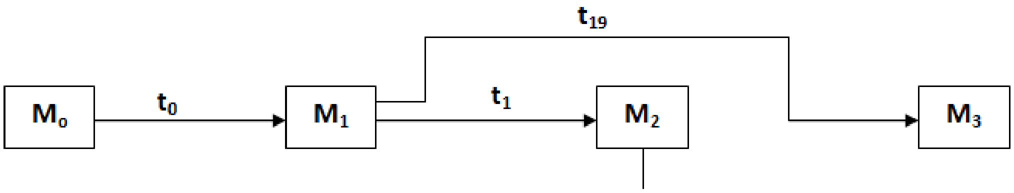


Figure 52: A Portion of the complete reachability graph.

After this there are two options for firing: T_1 and T_{19}. If T_{19} fires then the token moves towards the end of the model (M_3), and if the transition T_1 fires (size check cleared), then the token moves on to the place P_2 (M_2). The end is represented by M_3 and the size check clear is indicated by M_2. It can be seen in the reachability set that the tokens (1's) remain at places P_9, P_{17} and P_{24} while the token at P_1 in M_1 has moved to the place P_{25} indicating the end of the model. In a similar fashion the reachability graph (Figure 53) and the Reachability set (Table 21) continue to represent different states of the model.

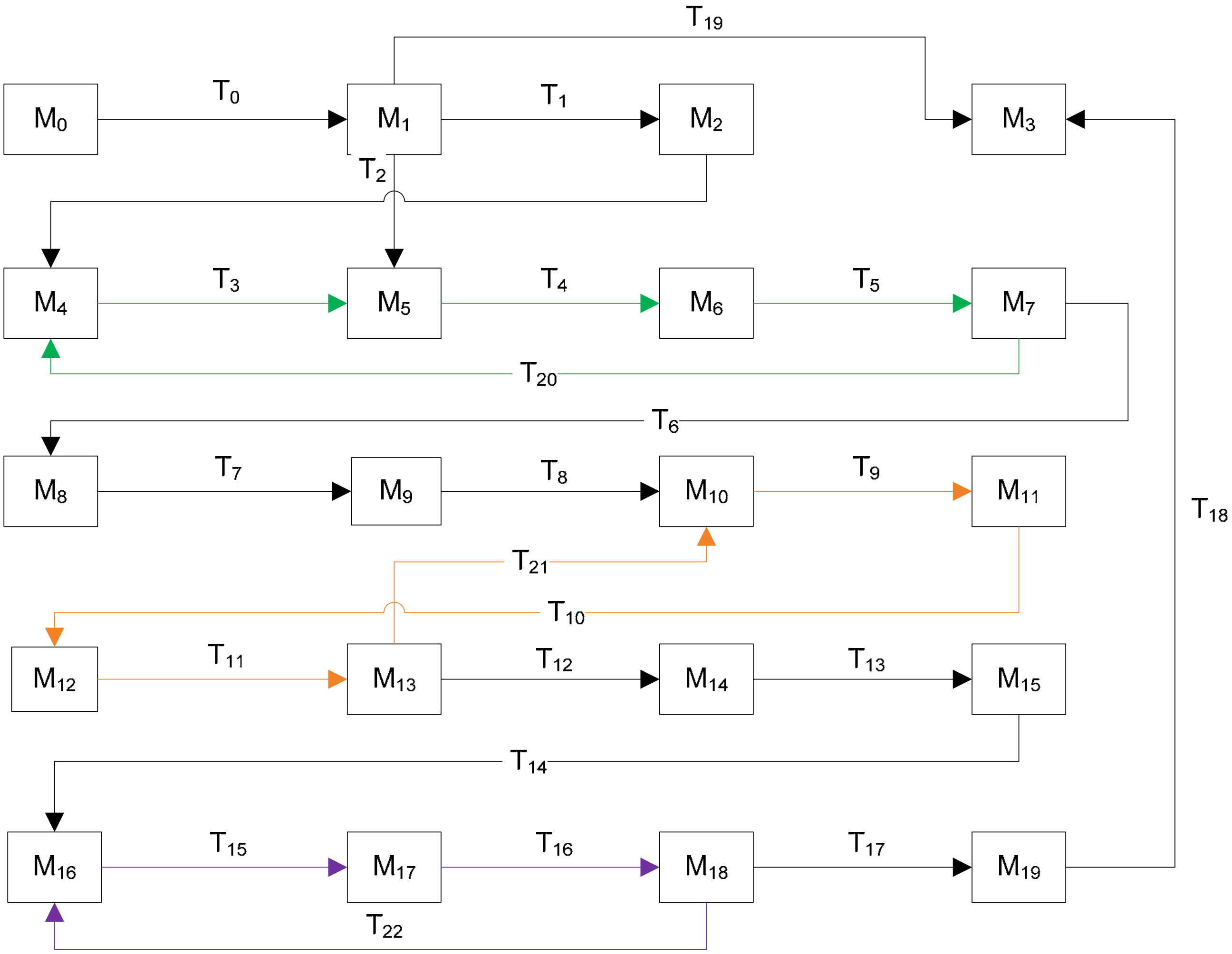


Figure 53: Reachability Graph of the CPGA Petri-Net Model

Table 29: Reachability Set of the CPGA Petri Net Model.

	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	P_{19}	P_{20}	P_{21}	P_{22}	P_{23}	P_{24}	P_{25}
M_0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0		1	0	0	0	0	0	0	1	0
M_2	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1
M_4	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_5	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_6	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_7	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_8	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_9	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
M_{10}	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0
M_{11}	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0
M_{12}	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0
M_{13}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0
M_{14}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0
M_{15}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0
M_{16}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0
M_{17}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0
M_{18}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0
M_{19}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0

4.4 Case Study

An engine oil pump body is taken as a case study. In literature it is also known as part CPHC10. The isometric view of CPHC10 is shown in Figure 54.

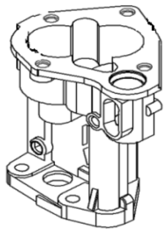


Figure 54: Engine oil pump body (part CPHC10)

The part has 34 operations to be performed in total which are present with their specifications in appendix A. It should be noted that the part has neither angular holes nor the number of operations too high. The possibility of combinational explosion and complexities that can arise due to the presence of angular holes is a separate area for further study. The part has several distinctive features which are present on the same face, for example the four small holes which have been highlighted in red along with the large protrusion which will require boring, reaming and surface milling. Therefore a logical conclusion would be to initially complete all these tasks which are present on the same face provided there are no similar machining operations present on any other face. In case of similar machining features, the time taken to change the face of machining will be compared to the time taken to change the tool and since in this case the objective is to reduce the machining time, therefore the process which takes less time will be preferred. Different algorithms generate different machining process plans for the part CPHC10. The comparison is made between the minimum machine structure configuration approach and the algorithm presented in the thesis. The optimum process plan according to the Petri net model is shown in results. Table 30 shows the operation sequence of the part CPHC10.

Table 30: Appropriate operation Sequence of CPHC10 [49]

Feature	**Cluster no.**	**Description**	**Op.**	**TAD.**
Pl 100, Pl 109	1	Planar Surface	M	X,Y,-Z
Cy117,Cy118	2	2 holes with same dimensions	B	-Z
Cy 102, Cy 103, pl 116	3	2 holes with same dimensions and a plane at end	B, M	-Z
Cy 112, Cy 113, Cy 114, Cy 115	4	4 holes	B	-Z
Cy 108, pl104	5	Hole & its bottom plane	B,M	-Z
Cy 107, pl106	6	Hole & its bottom plane	B,M	-Z
Ch 105	7	Chamfer	Ch	-Z
Ch119,Ch 120	8	Chamfer	Ch	-Z
Cy 110, pl111	9	Hole & its bottom plane	B,M	+Z
Pl 100, Pl 109	10	Finishing Planar Surface	F	X,Y,-Z
Cy117,Cy118	11	Finishing of 2	R, F	-Z
Cy 102, Cy 103, Cy 116	12	Finishing of 3	R	-Z
Cy 112, Cy 113, Cy 114, Cy 115	13	Finishing of 4	R	-Z
Cy 107, pl106	14	Finishing of 6	R,F	-Z
Cy 108, pl104	15	Finishing of 5	R,F	-Z
Cy 110, pl111	16	Finishing of 9	R,F	+Z

Certain abbreviations used in Table 30 which are explained below:

B: Boring Operation
M: Milling Operation
Ch: Chamfer Operation
F: Facing Operation
R: Reaming Operation

The Petri net model of the machine adaptive retainability approach was presented in this chapter. The reachability graph and the reachability set were also developed for the model. A detailed study of the Petri nets was carried out and the complete model was divided into sections for the better understanding of its working. The model not only helped in the developing the mathematical model of the approach, but also converted the approach into a universally understandable form. In section 2.4: improvements, it was discussed that if the previous architecture, the previously employed parts' specifications and the process plans are utilized, the initial cost of production can be reduced. This can only be achieved once the process plans for the new part have been substantially developed. Using all this data, the initial cost of production can be reduced and the approach to achieve this is discussed in chapter 5.

Chapter 5:

Machine Adaptive Retainability Approach

5.1 Introduction

Even if the most suitable process plan is developed along with the most suitable kinematic configuration, the issue of the initial cost remains. To address this, the section 2.4 ‘Improvements’ included many ways of improving the two approaches explained in that chapter.

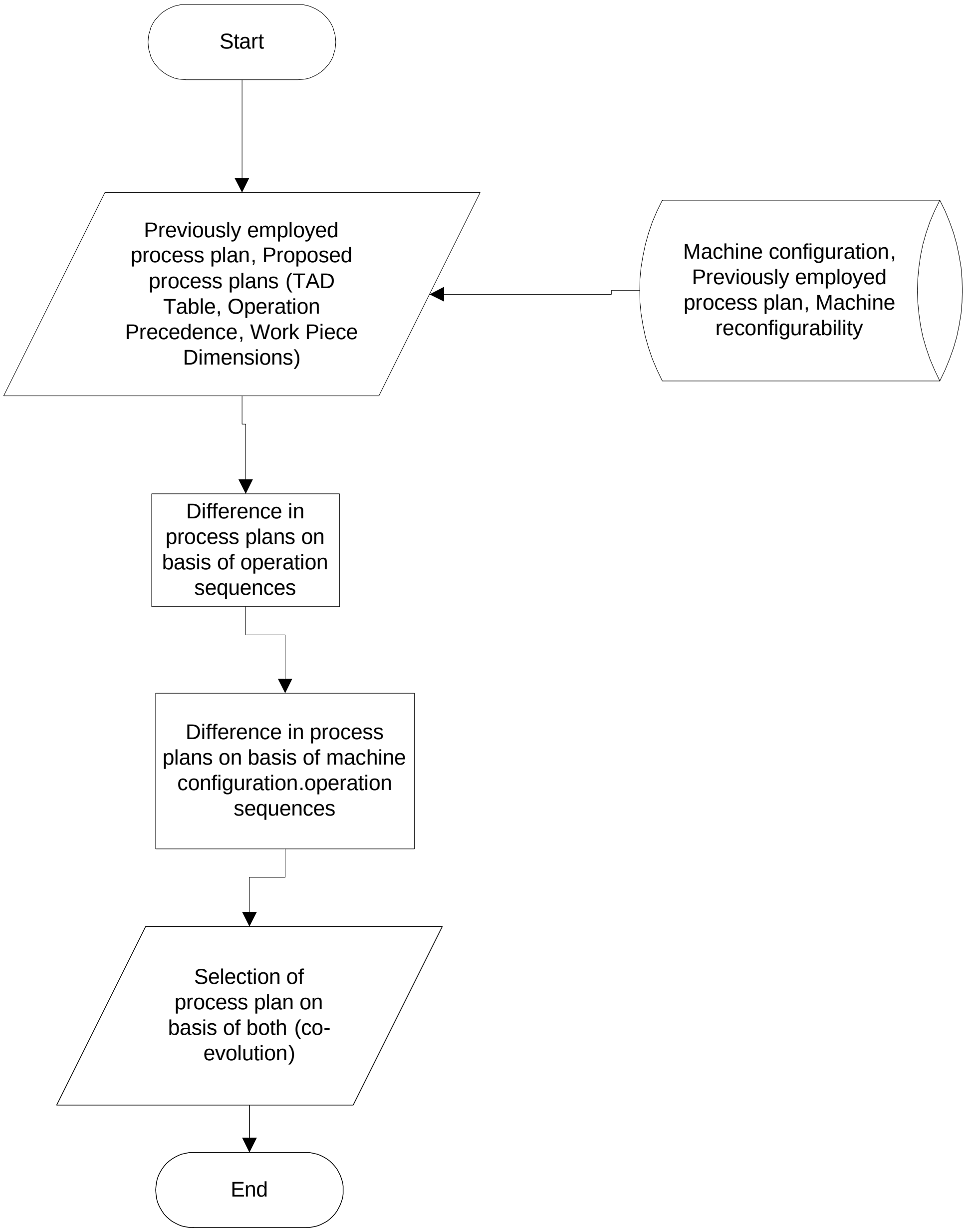


Figure 55: Machine adaptive retainability approach.

It should be noted that there were some improvements that did not have any direct linkage with the approaches. One of these was the section 2.4.2 ‘Using Existing Machine and Sequencing Data’. The improvement suggested in this section is: Using existing machinery and the process plans of the existing part as inputs so that a suitable approach that can address the issue of initial cost of production. One such approach is developed and is presented in this chapter. The approach is named machine adaptive retainability approach and is discussed in the following text.

Figure 55 shows the flow chart of the approach. The approach starts off by taking the previous data from the industry; the available machinery, the previously employed process plans and part specifications as well as the developed process plans for the new part (chapter 2 and 3). After that this approach compares the possible new process plans with the previously employed process plans. And it also compares the difference in the kinematic configurations of the two plans. In the end based on these two criterions, the process plan is selected from the new available plans.

The assumptions made during this approach are presented later in this chapter. The inputs of the approach include the dimensions of the work-piece, the tool approach directions, the previously employed process plans and the feasible process plans for the new part. The approach consists of comparison stage, after that decision making and finally the selection of the process plan. The output is the proposed machine configuration in case the current configuration is not sufficient, the candidate operation sequences and their tool approach directions.

5.2 Assumptions

The assumptions made during the development of this approach are as follows:

- All the machines are reconfigurable.
- All machine structures have the basic three translations; i.e. x, y and z axis.
- Since the basic translations are present, therefore the rest of the combinations which can be produced are ignored. And only the two possible rotations are considered.

The approach starts off by taking the input discussed in the next section:

5.3 Inputs

Following are the inputs required for the machine adaptive retainability approach:

1. Part dimensions (size)
2. Previously employed process plan
3. Feasible process plans

5.3.1 Size

The size of the work piece is required to check whether the machine has the capability to perform the required operations or not. If the size of the work piece is greater than the machining workspace then the operations cannot be performed on the specified work piece.

5.3.2 Previously employed process plan:

The data required from the previously employed process plan is the tool approach directions, the operation sequences, the tools used, and the machinery utilized. This approach using the previously employed process plans for any specified part, selects from the new feasible process plans for the new part, the one which is nearest (with conditions explained later in this chapter) to the previously employed process plans in order to reduce costs of the machinery.

5.3.3 Feasible process plans

The feasible process plans for the part are taken as an input for the approach. The plans can be taken from the chapter3 of this thesis or any other approach as per requirement of the manufacturer.

5.4 Processing

The algorithm for the approach is presented in Figure 56**.** The coordinates are all with respect to the work piece coordinates. The abbreviations and the terminologies used in the flow chart are as follows:

Tad:	Tool Approach Direction.
PEPP:	Previously employed process plans.
PPP:	Proposed process plan.
L, j, k, I:	Variables initialized as 0.
Reftadop:	TAD of the operation of the reference or previously employed process plan.
Tadop:	TAD of the operation of the proposed process plan. It should be noted that the operation should have the same serial wise location as the corresponding Reftadop.
CPP:	Counter for the difference in PPP and PEPP's operations.

CKC:	Counter for the overall kinematic configuration difference between PPP and PEPP.

The algorithm starts off with the inputs (previously employed process plan, proposed process plans and work piece dimensions) and then moves on to the size check. If the machine workspace is not sufficient for the work piece then the algorithm stops then and there. After this step the algorithm moves into the first loop. Here it compares the first operation of the first feasible process plan with the previously employed process plan; after that the second and the third operation and so on. if the operation has the same tool approach direction as that of the subsequent operation of the old process plan then the algorithm moves on to the next operation. In case they are different, a counter counts the change. When all of the operations have been compared; the changes in the process plan as a whole are saved. After that the algorithm moves on to the second proposed process plans, comparing it again with the previously employed process plan. The result is a different number of changes. After that the algorithm moves on to the third proposed process plan, and then to the fourth up to the final proposed process plan. It should be noted that if the number of operations is different for the previously employed and the proposed process plans then the excess operations will automatically have a counter change of 1 each. For example if the new process has 10 operations as compared to the previously employed plan with 5 operations then the counter will have the value of the difference 5 stored in it.

The next step in the algorithm is the comparison of the overall tool approach directions of the proposed process plans with the overall tad of the PEPP. The algorithm first calculates the overall tool approach directions of the previously employed process plan. After that it moves on to the first proposed process plan, then to the second, after that to the third continuing up to the final proposed process plan. An operation wise check of the process plans is made. Initially the TAD of the first operation of the process plan is saved into memory then it is compared with the TAD of the second operation. If both are the same then the counter remains 1. If it is different; then the counter counts 2 and the TAD of the second operation is saved on the memory as well. Later the in algorithm both these TADs are compared with the TAD of the third operation; which if different is again saved in to the memory and in case of being same as either of the operations is ignored. In this way the algorithm compares all the operations of the process plan and finally the overall TAD of each process plan is now stored in the memory. The algorithm has now stored the TAD of each operation as well as the overall TAD of the operational sequences. An overall TAD comparison is made between the proposed and the previously employed process plan. In case there is no difference between the previously employed and the proposed process plan, the algorithm sores the difference as 0; if there is a single change the algorithm stores it as 1 and so on. The further explanation of the complete algorithm is made in the section 'case study'.

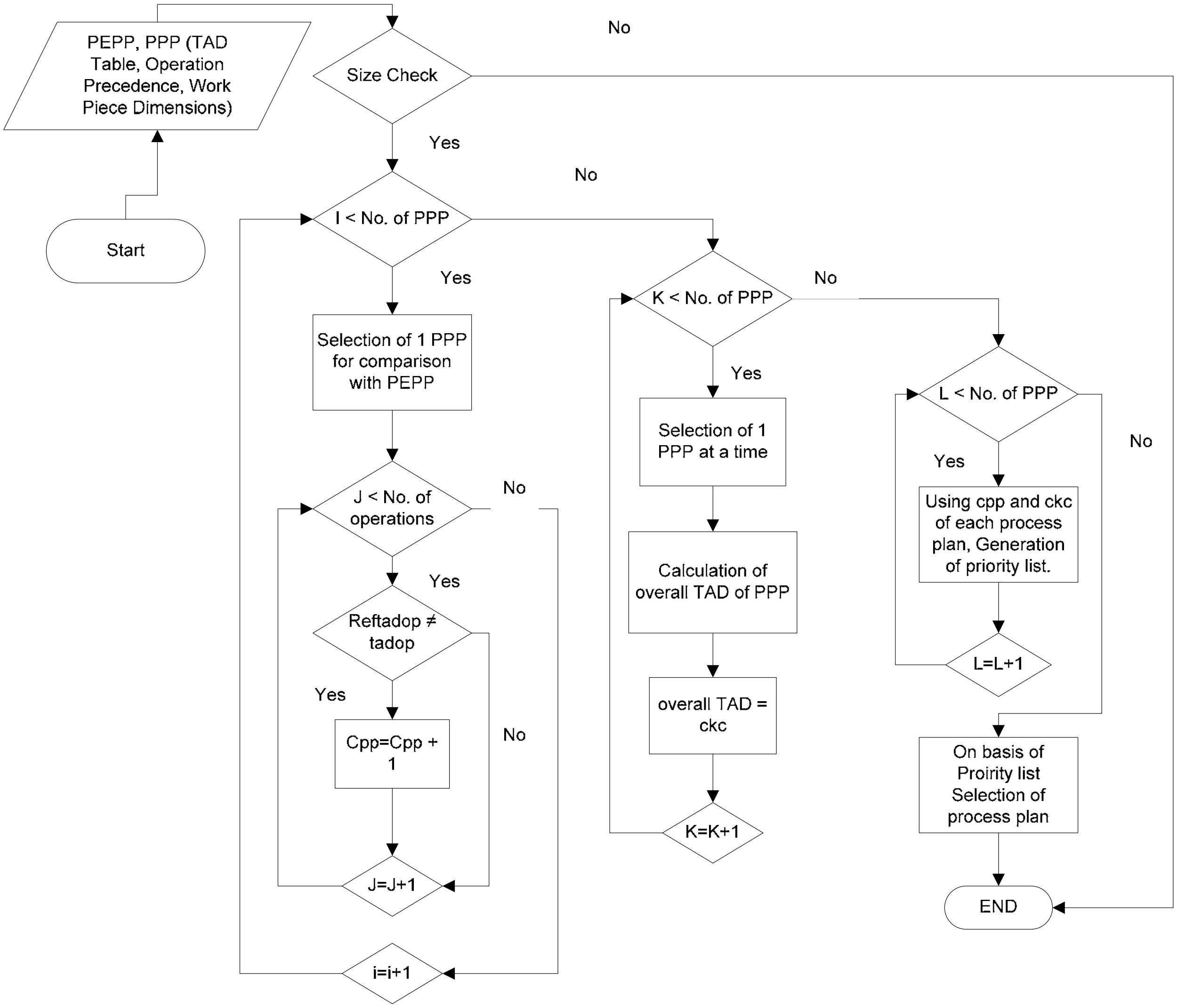


Figure 56: Algorithm for the machine Adaptive Retainability approach

The final stage in the algorithm is the utilization of the data stored. For each proposed sequence, there are currently two sets of information (1) the difference in the proposed and the previously employed sequence and (2) the overall TAD difference. The plan having an overall TAD change of 0 is the most preferred process plan for that particular RMS machine. If the number of plans having 0 overall TAD change is more than 1 than the difference in the sequence separates them. The plan having less difference in the sequence will be selected.

5.5 Case Study

Parts ANC-090 and part ANC-101 were used in [5] to apply the machine structure configuration approach. For the case study it is assumed that a certain industry has been producing the part ANC-090 and now it intends to switch to the production of part ANC-101. The parts are shown in Figure 57 and Figure 58. The Part CPHC10 is used as a case study as well whose results are present in Appendix B to develop a continuation with the previous Appendix A and form a complete extended approach. The operation sequence along with the TAD of the operation for part ANC-090 (Figure 57) which the company has been using is presented in Table 31. The same for a proposed process plan for part ANC 101 (Figure 58) is presented in Table 32.

Table 31: Applied Sequence for ANC-090

Op. Id.	TAD	Description
1	+z	Planar surface
2	-z	Planar surface
3	-z	Four holes arranged as a replicated feature
4	-z	A step
5	-z	A protrusion (rib)
6	-z	A protrusion
7	-z	A compound hole (Drill)
8	-z	Boring
9	-z	Reaming
10	-z	Six holes arranged
11	-z	in a replicated feature
12	-z	A step

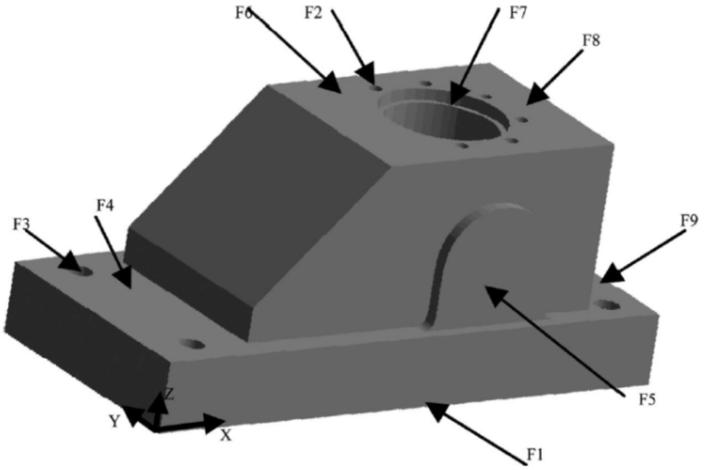


Figure 57: Part ANC-090 and its features

Table 32: Proposed Sequence for ANC-101

Op. Id.	TAD	Description
1	+z	Planar surface
2	-z	Planar surface
3	-z	Four holes arranged as a replicated feature
4	-z	A step
5	-z	A protrusion (rib)
6	-z	A protrusion
7	-z	A compound hole (Drill)
8	-z	Boring
9	-z	Reaming
10	-z	Nine holes arranged as a
11	-z	replicated feature
12	-z	A step
13	+x	Two Pockets arranged as a replicated feature
14	-a	A Boss
15	-a	A compound hole (Drill)
16	-a	Boring
17	-a	Reaming
18	-x	A Pocket
19	+z	A compound hole (Boring)
20	+z	Reaming

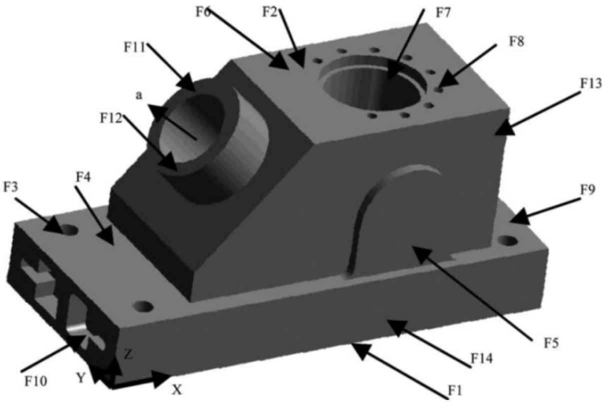


Figure 58: Part ANC-101 and its features.

Initially the comparison takes place between the first operation of the first proposed process plan and the first Operation of the previously employed process plan. Form Table 31 and Table 32, it can be seen that both of these have the same tool approach directions i.e. +z. Then it compares the second operation in the sequence. These too have the same TAD as well therefore the algorithm moves on to the third and then the fourth and so on up to the twelfth operation all of which have the same TAD (-z). after this operation the PEPP ends and for the comparison with the new process plan the rest of the operation of new process plan are compared with a 0 TAD therefore all of these provide an increase in CPP. For example operation 13 has TAD +x and in PEPP there is no operation 13 therefore it is compared with TAD=0 and the CPP is increased by 1. The same is repeated for operation 14, 15 up to operation 20. Therefore the total CPP for this sequence is 8.

Now the overall TAD of the PEPP and the new process plan is compared. The overall TAD is used to identify the machines capable of performing all the operations of a certain process plan. For example, if the overall TAD is 3 then a 3-axis machine is sufficient to perform all the operations of the process plan, if it is 3 then a rotation will also be required and the minimum requirement will be a 4-axis machine. In this case however the PEPP has an overall TAD of 3, (x, y axis are for positioning of the tool and –z for the TAD and +z will require the overturning of the work piece), while the Overall TAD of the new process plan is 4, (x, y for positioning of the tool and –z, +x for the TAD). The –a direction is the new axis of motion for the angular hole.) To achieve all of this a 4-axis machine at least with one axis of rotation is required. Therefore this concludes that the CKC is 1 for this process plan because a new axis is required as well.

5.6 Results & Discussion

The results and the priority analysis is this approach is carried out only when there are at least a couple of PPP's. The priority of one over the other through the Machine adaptive retainability approach can then be developed. Hence, another one of the PPP's for the new part is shown in Table 33:

Table 33: Proposed Sequence #2 for ANC-101

Sr. No.	Operation no.	TAD
1	1	+z
2	14	-a
3	15	-a
4	16	-a
5	17	-a
6	2	-z
7	3	-z
8	4	-z
9	5	-z
10	6	-z
11	7	-z
12	8	-z
13	9	-z
14	10	-z
15	11	-z

16	12	-z
17	13	+x
18	18	-x
19	19	+z
20	20	+z

In the second PPP the angular hole and its features have precedence over other operations. Therefore they moved up to the 2nd, 3rd, 4th and 5th operation in the operation sequence. These are the operations numbered form 14 to 17. Now, in this situation when the each operation is sequentially compared with the operations of PEPP, the situation is considerably different. As in the previous case initially the first operation of PEPP (Table 31**)** is compared with the new PPP (Table 34). Both have the same TAD therefore CPP remains 0. After that the second operation in the sequence is compared, which in PPP has the TAD –a, and in PEPP its –z. therefore the CPP is increased by 1, it is further increased when the third fourth and the fifth operation is compared. Therefore this PPP has a considerably higher CPP in comparison with the first PPP. The overall TAD of this PPP is same as that of the first PPP; therefore this will also require a rotation axis for the operations to be performed. In this regard both these PPP's remain the same. A third PPP is shown in Table 34. Also, the results drawn from the case study with different PPP's are shown in Table 35.

Table 34: Proposed Sequence #3 for ANC-101

Sr. No.	Operation no.	TAD
1	1	+z
2	2	-z
3	5	-z
4	6	-z
5	4	-z
6	7	-z
7	8	-z
8	9	-z
9	10	-z
10	11	-z
11	14	-a
12	15	-a
13	16	-a
14	17	-a
15	12	-z
16	3	-z
17	18	-x

18	19	+z
19	20	+z
20	13	+x

Table 35: Analysis of the PPP's for ANC-101

Sr. No.	PPP	CPP	CKC
1	PPP #1	8	1
2	PPP #2	12	1
3	PPP #3	10	1

It can be seen that the PPP#1 has less CPP as compared with the other PPP's while the CKC remains the same. Therefore the PPP#1 should be preferred over the other process plans. A number of techniques are available for the problems associated with RMS, which generally focus on either developing the process plans for a certain machine configuration or try to find the most candidate configuration for a certain process plan. The issue which is generally not considered is the cost of changing the configuration as well as the process plan for new part.

Machine adaptive retainability approach following the concepts presented in machine structure configuration approach and co-evolution was presented in this chapter. It introduced the concept of developing the new part's process plans and kinematic configurations using the previous part's information. The kinematic configuration includes the machine's capability and the reconfigurable machine tools required to develop the part. The complete part information plus the previous part's knowledge is used as an input to initially develop a comparison between the currently employed process plan and the proposed process plans. This generate a deciding factor for the proposed process plans and concludes whether any one of these is a suitable candidate for the new part basing upon the current scheme. The required machine capabilities are then generated. This helps in understanding the machine structures required for the subsequent process plans thus prioritizing the most suitable one. The approach is more suitable if the both the previous and the new part to be produced belong to the same part family.

Finally utilizing this information and including the previous data in the analysis, a suitable process plan along with the machine structure is proposed. This is the most useful portion of this algorithm. This should not only help in the selection of the process plans but also significantly reduce the cost of the new machine structure which may have been required in case the previous information is ignored. This approach will help in automating and improving the process of machine as well as the process plan selection in commercial computer aided manufacturing (CAM) systems. It should be noted however that this approach may be applied after some sort of sorting is done to select only the best few proposed process plans, if that is not the case, the approach will become tedious and redundant. In the current CAM systems the current machines and their configurations, plans are completely ignored when a new part is presented for manufacturing. This can be an important step in further developing the artificial intelligence (AI) of the current automated RMS. In the future this work will be taken further to develop the complete generation of suitable process plan for certain configurations.

Conclusion and Future Works

6.1 Conclusion and Future Works

This thesis falls in the domain of Reconfigurable Manufacturing Systems Designs. This thesis is aimed to address different issues in the current manufacturing industry such as the initial cost of production, the issues of co-evolution i.e. the problem of determining the operation sequence better suited for the machine configuration. At the same time, determining the machine configuration well equipped for the production of the part family in a time efficient manner with improved quality. The approach used to address these issues is elaborated in the following lines:

A detailed literature review on the current approaches in the market (Machine structure configuration approach, Process planning and configuration generation approach, Constraint based approach for flow lines, Reconfigurable process planning for generation of operation sequences……..). This review revealed that the approaches are either focused on the development of the process plans or the kinematic configuration of the machines.

Development of the need and the problem statement of this work: The design methodologies of the current time are directed towards two main directions: development of the operation sequences and then the selection of the appropriate machine configuration for it. OR: the development of the machine architecture and then, selection of the new process plan. The current approaches require the knowledge base of the machine if they intend to develop the associated process plan. And if the aim is the development of the kinematic configuration, they require knowledge of the operation sequences as well as the part dimensions.

Presentation of an approach to address the issues mentioned above: The work done by T. Tolio and the introduction of the concept of co-evolution is the cornerstone of the work. Two existing methodologies were used as the base for its development: ‘Machine Structure Configuration Approach’ presented by H.A. ElMaraghy and the ‘Process Plan and Configuration Generation Approach’ presented by A. Baqai. The approach called ‘Machine Configuration Generation Approach’ is evolved from the MSCA, by applying the techniques of PPCGA in light of co-evolution.

Development of an algorithm for the implementation of the approach: Keeping in mind the automated nature of RMS, the development of an algorithm for the implementation on a running industry becomes a necessity. The algorithm developed for the approach presented implements two main features of the PPCGA that are non-existent in MSCA: the parallelization of tasks and the operation sequencing.

Development of a graphical model for the algorithm: The Petri net model was used for the graphical representation of the system. The advantage of using this model is that it not only converts any single system into a globally understandable form, but also develops the mathematical model of the system. The Petri net model added the missing piece of the puzzle to convert the approach into a globally recognized form.

Development of an approach to address issues left untouched by co-evolution: The concept of co-evolution focuses on the development of the ideal system and the process plan for the changing products. The result is that the initial cost of production rises without check. The 'Machine Adaptive Retainability Approach' was developed to address this particular drawback of co-evolution. Using the existing machine structures and the process plans applied on the existing parts, this approach selects the most suitable plans for the new part on basis of the initial cost of production.

Certain future works that have not been addressed in this work are discussed as follows: (1) The addition of angular holes in the algorithm will not only enhance the algorithm, but also add a whole new generation of parts that can be addressed using the same algorithm. (2) Combinatory explosion may occur if the number of features exceeds a certain limit. The analysis to check this problem requires a product with a considerable number of features. (3) The issue of the development of algorithms for sheet metal bending are discussed, but have not been addressed in this thesis. Very little work has been done for the automation of this process hence providing a rich area for research. (4) Further evolution of the approach is possible and can be achieved if the system is improved in such a manner that more parts and part families are accommodated into the algorithm and other features such as collision check, tool speeds and surface finish control are added to the algorithm.

These future works open up different avenues of improvement for the approaches presented. It is very important to search for other approaches as well which, when coupled with the ones presented, reach a higher level of evolution (For Example: Approaches presented by J. Dou.). In the end, the work which was initially aimed at the improvement of machine structure configuration approach ended up co-evolving the approach as well as addressing the initial production cost. The approach is yet to reach perfection and further research work may yet bring it closer to it.

Appendix A

This appendix contains the details of the part CPHC10 used in chapters 2, 3, 4 and 5.

Part CPHC10

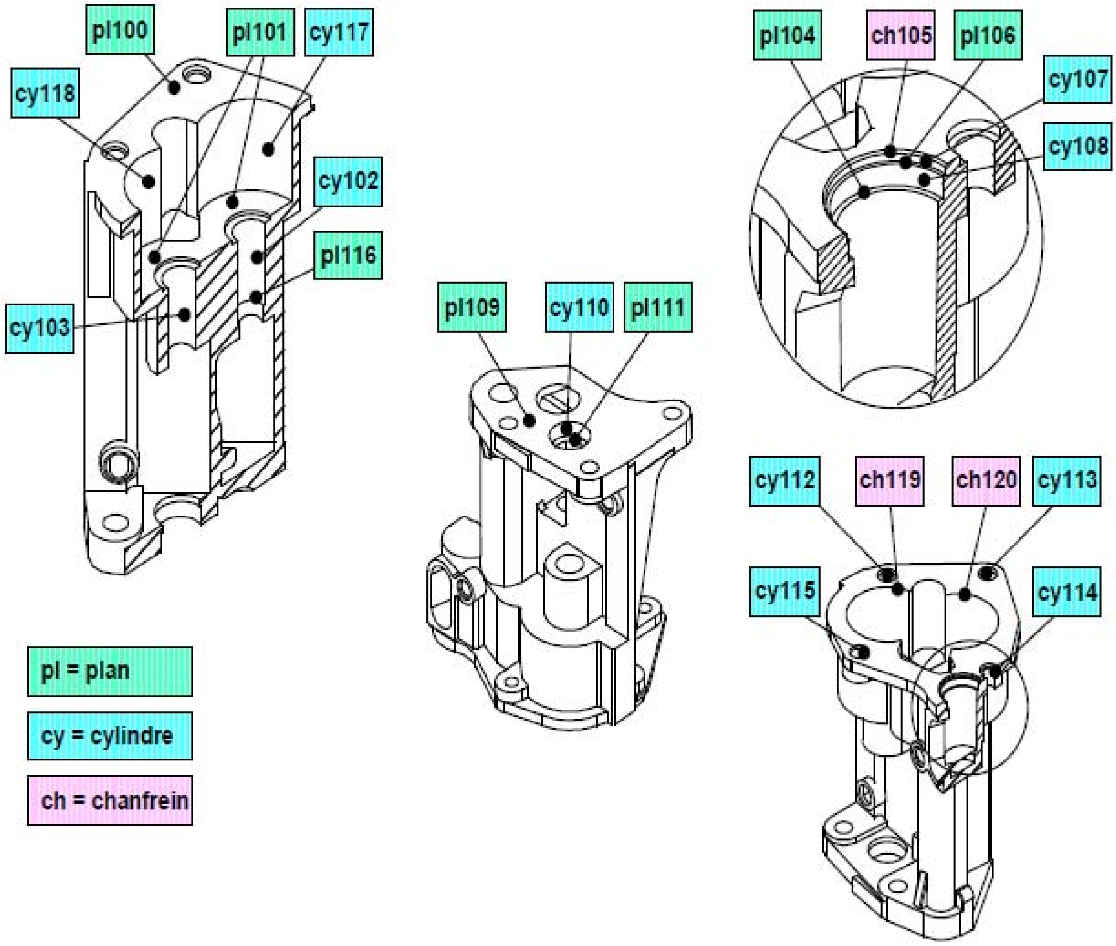


Figure 59: Part CPHC10 and its Features

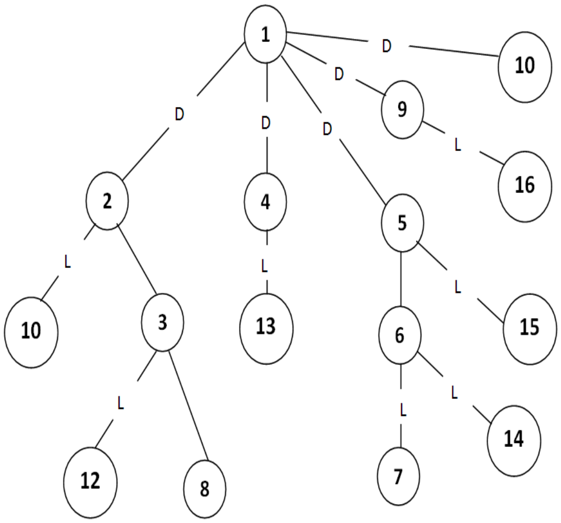


Figure 60: L: Logical, D: Dimensional Constraints

Table 36: Appropriate operation Sequence of CPHC10

Feature	Cluster	Description	Op.	TAD.
Pl 100, Pl 109	1	Planar Surface	M	X,Y,-Z
Cy117,Cy118	2	2 holes with same dimensions	B	-Z
Cy 102, Cy 103, pl 116	3	2 holes with same dimensions and a plane at end	B, M	-Z
Cy 112, Cy 113, Cy 114, Cy 115	4	4 holes	B	-Z
Cy 108, pl104	5	Hole & its bottom plane	B,M	-Z
Cy 107, pl106	6	Hole & its bottom plane	B,M	-Z
Ch 105	7	Chamfer	Ch	-Z
Ch119,Ch 120	8	Chamfer	Ch	-Z
Cy 110, pl111	9	Hole & its bottom plane	B,M	+Z
Pl 100, Pl 109	10	Finishing Planar Surface	F	X,Y,-Z
Cy117,Cy118	11	Finishing of 2	R, F	-Z
Cy 102, Cy 103, Cy 116	12	Finishing of 3	R	-Z
Cy 112, Cy 113, Cy 114, Cy 115	13	Finishing of 4	R	-Z
Cy 107, pl106	14	Finishing of 6	R,F	-Z
Cy 108, pl104	15	Finishing of 5	R,F	-Z
Cy 110, pl111	16	Finishing of 9	R,F	+Z

Appendix B

Using the same part for the machine structure retainability approach, following results are generated:

Table 37: Appropriate operation Sequence of CPHC10 [MSRA]

Feature	Cluster no.	Description	Op.	TA D.
Pl 100, Pl 109	1	Planar Surface	M	-Z
Cy117,Cy118	2	2 holes with same dimensions	B	-Z
Cy 102, Cy 103, pl 116	3	2 holes with same dimensions and a plane at end	B, M	-Z
Cy 112, Cy 113, Cy 114, Cy 115	4	4 holes	B	-Z
Cy 108, pl104	5	Hole & its bottom plane	B,M	-Z
Cy 107, pl106	6	Hole & its bottom plane	B,M	-Z
Ch 105	7	Chamfer	Ch	-Z
Ch119,Ch 120	8	Chamfer	Ch	-Z
Cy 110, pl111	9	Hole & its bottom plane	B,M	+Z
Pl 100, Pl 109	10	Finishing Planar Surface	F	-Z
Cy117,Cy118	11	Finishing of 2	R, F	-Z
Cy 102, Cy 103, Cy 116	12	Finishing of 3	R	-Z
Cy 112, Cy 113, Cy 114, Cy 115	13	Finishing of 4	R	-Z
Cy 107, pl106	14	Finishing of 6	R,F	-Z
Cy 108, pl104	15	Finishing of 5	R,F	-Z
Cy 110, pl111	16	Finishing of 9	R,F	+Z

Now, the part has changed and some of its features removed i.e. Cy 112, Cy 113,Cy 114,Cy 115 therefore Cl. no 4 and 13 have been eliminated. New proposed process plans are shown in Table 38 and the results in Table 39.

Table 38: Proposed operation Sequence (Seq.) of CPHC10-1 [MSRA]

Seq. No.	PPP#1	TAD	PPP#2	TAD
1	1	-Z	1	-Z
2	2	-Z	9	+Z
3	3	-Z	16	+Z
4	5	-Z	2	-Z
5	6	-Z	3	-Z
6	7	-Z	5	-Z
7	8	-Z	6	-Z
8	9	+Z	7	-Z
9	10	-Z	8	-Z
10	11	-Z	10	-Z
11	12	-Z	11	-Z
12	14	-Z	12	-Z
13	15	-Z	14	-Z
14	16	+Z	15	-Z

Table 39: Selection of operation Sequence of CPHC10-1 [MSRA]

Sr. No.	PPP	CPP	CKC
1	PPP#1	2	0
2	PPP#2	4	0

This concludes that PPP#1 is appropriate as per approach.

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