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A NEW METHODOLOGY OF PROCESS DESIGN FOR
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A NEW METHODOLOGY OF PROCESS DESIGN FOR RECONFIGURABLE MANUFACTURING SYSTEMS

By

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ABSTRACT

A NEW METHODOLOGY OF PROCESS DESIGN FOR RECONFIGURABLE MANUFACTURING SYSTEMS

By

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In response to the increasing complexity of the manufacturing environment and the rapid change of market requirements, a new methodology for process design is applied in Reconfigurable Manufacturing Systems (RMSs). The methodology is used to model, design, and reconfigure the processes and to facilitate collaborative manufacturing among different companies or different departments within one company. The methodology can help to manage the enormous quantity and variety of process data generated from the changes in functional requirements, production facilities, and manufacturability. It can also improve system's flexibility to new production and adaptability to new process technology.

In this thesis, in order to apply the methodology in a real industrial practice, a case study has been conducted to capture the processes and to set up a process model for making a variety of pulleys at Focus: Hope in Detroit, Michigan. Based on the process model, a hierarchy approach of constraint management is represented for reconfiguring processes efficiently in reconfigurable manufacturing systems. A unique aspect of this process model is that it uses a grammar-based approach to capture both processes and constraints in hierarchy

structure, which facilitates a way to apply a multilevel multiple criteria decision-making model (MMCDM) for process selection. Within the MMCDM model, the grammar-based approach helps to decompose a complex selection problem into several manageable chunks; therefore, an effective multiple criteria decision-making method - Analytic Hierarchy Process (AHP) could be applied to the process selection at any abstract level. The MMCDM model has been applied in this dissertation on selecting processes, machines, and part families for producing a part in a complex manufacturing environment. It can also be applied on those problems with a great amount of data and many decisions to be made.

To my wife, Sining Yu

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LIST OF ABBREVIATIONS

AHP: Analytic Hierarchy Process

CAD: Computer Aided Design

CAM: Computer Aided Manufacturing

DMS: Dedicated Manufacturing Systems

FMS: Flexible Manufacturing Systems

GT: Group Technology

RMS: Reconfigurable Manufacturing Systems

Chapter 1

INTRODUCTION

Today, manufacturing industries face many challenges, including global-scale competition and rapid change of process technology. In order to be competitive, a production system must be flexible enough to add new requirements and functions and be open to adopt new process technologies if needed. These requirements could be achieved by developing a new manufacturing system – Reconfigurable Manufacturing System (RMS) with reconfigurable machine tools [Koren et al. 1999]. However, the cost for hardware replacement would be tremendous for many small manufacturing companies. Due to the limited budget, many companies would like to reorganize their present production facilities and process technologies, instead of replacing them with a completely new production system. Therefore, the development of new methodologies for process design and the related software can be more helpful than before to improve the flexibility and manufacturability of a production system.

A methodology to model, design, and reconfigure into an optimal set of processes for such production systems should enable:

- Frequent introduction of new products and rapid adjustment of manufacturability to market demands;
- Rapid integration of new functions and process technologies into existing systems, and

- Easy adaptation to variable quantities of products for niche marketing.

The methodology to model, design, and reconfigure processes must be able to help the system to reconfigure quickly for a new production, be able to produce a wide variety of products in any scale of production and be able to integrate a new technology.

1.1 Manufacturing Systems

Most manufacturing industries use dedicated or flexible manufacturing systems to produce their products. The type of manufacturing system used for an industry depends on the product requirements including quantity, cost, and variety of products. Each manufacturing system differs in production throughput, equipment and production cost, flexibility of system configuration, and adaptability to new functions and process technologies. Thus, the processes being used for a particular product depend on the manufacturing systems.

1.1.1 Dedicated Manufacturing Systems

A dedicated manufacturing system (DMS) is a system designed for producing a specific part at a high volume, which uses typically transfer line technology with fixed tooling and rigid automation. When the product demand is high, the cost per part is relatively low. The economic objective of a DMS is to cost-effectively produce a specific part type at high volumes and required quality. Due to fixed tooling and fixture during the production, the process for DMS is usually designed for the production of a specific part only. It is difficult to reconfigure the processes required by the changes of functionality, manufacturing process, production facility, and manufacturability. The system configuration is also difficult to change.

1.1.2 Group Technology and Flexible Manufacturing Systems

Group technology (GT) is an approach to manufacturing in which similar parts are identified and grouped together in order to take advantage of their similarities in design and production [Groover 2002]. Similarities among parts permit them to be classified into part families. A part family is a collection of parts that are similar in geometric shape and size or require similar processing steps in their manufacture.

A flexible manufacturing system (FMS) is a highly automated GT machine cell, consisting of a group of processing stations (usually CNC machine tools), interconnected by an automated material handling and storage system and controlled by an integrated computer system. Because of the single-tool operation of the CNC machines, the FMS throughput is lower than that of DMS. The combination of high equipment cost and low throughput makes the cost per part relatively high. The objective of a FMS is to make possible the cost-effective manufacture of many types of parts, which can reduce changeover time on the same system at the required volume and quality. The process for FMS can be designed for production of a part family, which uses similar tooling and fixtures for several types of parts. Due to the flexible tooling and fixtures, it is easy to reconfigure the processes for changes within a flexible manufacturing system.

1.1.3 Reconfigurable Manufacturing Systems

As defined by Koren et al. [1999], a reconfigurable manufacturing system (RMS) is designed for rapid change in the structure of both hardware and software components, in order to rapidly adjust to the new production method, production capacity and functionality in response to changes in market or regulatory requirements. The reconfigurable manufacturing system will allow adding, removing, or modifying specific process capabilities, controls, software, or machine structure to adjust production capacity in response to changing market demands or technologies. The objective of an RMS is to provide the functionality and capacity that is needed, when it is needed. Accordingly, the process design for RMS will be quite different compared with DMS and FMS.

1.2 Process Design for Reconfigurable Manufacturing Systems

A process design methodology is very important to a manufacturing system. The design of a manufacturing system on the hardware and software components usually defines the system properties such as the manufacturability, production scale, operation and maintenance cost, and flexibility of system configuration. Different from the manufacturing system, the methodology to model, design, and reconfigure processes provides the organization of machines, processes, constraints, and other involved manufacturing resources within the manufacturing system. The methodology will be able to represent the processes in a manufacturing system and be able to apply the constraints to evaluate the alternative processes and machines in order to choose the best ones. It can reconfigure the processes quickly as needed to provide a new production and produce variety of products within the same manufacturing system. An effective methodology of process design can help to improve a manufacturing system economically by enhancing production capability and adaptability to changing market.

As a key element in integrating design and manufacturing, process planning is defined in the *Tool and Manufacturing Engineer's Handbook* [1974] as "the systematic determination of the methods by which a product is to be manufactured, economically and competitively." As part of process planning, process design could be defined as "the systematic exploration and determination of the methods by which a process is to be designed, economically and competitively."

As a reconfigurable manufacturing system provides flexible functionality and capacity in response to changes, the process for RMS should be designed based on the characteristics of RMS. The process designed for RMS should have following basic characteristics: (a) modularity, (b) convertibility, and (c) customization.

(a) Modularity

Modularity of a process for RMS is achieved by its modular construction using grammar-based approach. The modularity structure of the processes makes it possible to add/remove processes to/from the current process diagram to meet the changing manufacturing environment. For example, broaching keyway is a process module for the production of pulleys, since it can be added or removed for producing a pulley based on specific functions.

(b) Convertibility

Some of the process modules are capable of changing their internal components or functionalities. The components could be process, machine, or other resources (companies or operators) related to the process module. A process module can maintain its own functionalities by including different alternative processes as its internal components; it can also change the module functionalities by choosing an alternate machine with additional process capabilities to produce more features. For example, casting hole and drilling hole are two alternative internal processes of a module for producing holes. A machining center and a turning center are two alternate machines to run turning process. The machining center can also run milling process. Therefore, if a process module is carried out in a machining center instead of a turning center, the module can produce the auxiliary holes besides the original production functionalities.

(c) Customization

The process for RMS is designed for a given part family. The customization of process has two aspects: customized resource and customized constraints. Customized resource means that manufacturing resources (such as organizations, machines, and human) are built around the part families that are being manufactured with only the resources needed for those specific parts, thereby reducing the cost. Customized constraint means that process engineers or managers use the constraints based on individual experience to choose the best alternative processes, machines, and providers; thereby optimizing the processes. Customization enables industries to maximize the usage of manufacturing resources.

1.3 Introduction of Grammar Approach

A "grammar", as presented in Webster's dictionary, is defined as "the study of the classes of words, their inflections, and their functions and relations in the sentence." The "generative grammar" is then defined as "a description in the form of an ordered set of rules for producing the grammatical sentences of a language."

As presented in much of literature, grammar-based approaches are already applied for engineering design in different fields. Most of these grammar-based approaches are generative approaches. They can apply specific rules on a set of basic terms (such as shapes, processes, etc.) for producing a sophisticated product or generating a complex process for producing the product. Grammars model the engineering design as a linguistic formalism, allowing design to be viewed as a domain independent activity and positing interesting research hypotheses. Based on the literature reviews, three different grammar-based approaches: shape grammar [Stiny 1980, 1992; Fitzhorn 1990; Agarwal and Cagan 1998, 1999, 2000], graph grammar [Fitzhorn 1986; Pinilla et al. 1989; Fu et al. 1993; Hoover and Rinderle 1989], and process grammar [Baldwin and Chung 1995a; Chung et al. 2002; Kwon et al. 2002] are presented.

1.3.1 Shape Grammar

A shape grammar [Stiny 1980] derives designs in the language that it specifies by successive application of shape transformation rules to some evolving shape, starting with an initial shape. It can be used to describe how complex shapes are built from simple entities and how a complex shape can be decomposed into simpler sub-shapes. In particular, given a finite set of shapes (S) and its labels (L), a finite set of shape rules (R) of the form $\alpha \rightarrow \beta$ transform a labeled shape α in $(S, L)^{+}$ into a labeled shape β in $(S, L)^{0}$, where $(S, L)^{+}$ is the set of all labeled shapes made up of shapes in the set S and symbols in the set L, and $(S, L)^{0}$ is the set that contains, in addition to all of the labeled shapes in the set $(S, L)^{+}$, the empty labeled shape $<s_{\Phi}, \Phi>$. Shapes themselves can be transformed with Boolean operations.

Parametric shape grammars are an extension of shape grammars in which shape rules are defined by filling in the open terms in a general schema. An assignment, g, gives specific values to all the variables in α and β. It determines a shape rule, $g(\alpha) \rightarrow g(\beta)$, which can be applied on a labeled shape in the usual way to generate a new labeled shape. Algebras of shapes can also be augmented by weights to obtain new algebras in which the shape union operation has been redefined to reflect different possible weights on different entities [Stiny 1992].

The shape grammar has been used successfully for spatial design in the field of architecture. There are also some limited applications of shape grammar to engineering design. Fitzhorn [1990] presented a shape grammar specifying the languages of constructive solid geometry and boundary representations (i.e., realizable solids). Agarwal and Cagan [1998, 1999, 2000] have focused on developing shape grammars for a class of individual products, such as coffeemakers and MEMS resonators and associating cost expressions with the grammar rules [Agarwal et al. 1999]. Agarwal and Cagan [2000] also proposed the use of shape grammars as expert systems for geometry-based engineering design.

1.3.2 Graph Grammar

A graph grammar is a mathematical formalism for manipulating symbols representing graph vertices and edges [Schmidt and Cagan 1997]. Grammar rules assign functions and forms to vertices and connect vertices with edges. The edges of a graph signify the relationship between two vertices. A completed graph described with a set of vertices and edges expresses a design. There are two kinds of graph grammar: one is for feature design through the representation of features and their functions; the other is for process design through the representation of processes and associated tasks constraints.

1.3.2.1 Design Features

Graph grammars have been applied to a variety of design applications. The applications involve graph representations at different levels of detail, from solid models and features, to components and their behaviors, to complete devices. Fitzhorn [1986] used a graph grammar to describe physical solids. Pinilla et al. [1989] proposed a graph grammar to describe shape features such as notches and perpendicular faces. Fu et al. [1993] also presented a graph grammar for the representation and transformation of machinable features with primitive forms and to propagate constraints. Hoover and Rinderle [1989] presented a technique to transform a graph-based representation of specifications into an arrangement of physical components for single-speed mechanical power transmissions.

The grammar approach shows a flexibility of the abstraction to express a wide range of function and form relationships for the machine design problem. However, the grammar rules required for sophisticated representations may be too complicated and difficult to refine.

1.3.2.2 Process Grammar

In this dissertation, the core of the proposed grammar-based approach for reconfigurable system is a process grammar, which provides the theoretical foundation to represent, manipulate and execute the design and manufacturing process [Baldwin and Chung 1995a]. This grammar-based approach has been implemented in a system called Manufacturing Infrastructure and Design Automation System (MIDAS). In the MIDAS system, D&M processes are modeled as a collection tasks. Our process flow graph depicts tasks, data, and the relationships among them, describing the sequence of tasks for a larger activity. There are four basic elements used to represent the process flow:

- **Logical task**: It is a task that can be decomposed into a set of subtasks (logical tasks, atomic tasks, or selectors). Logical tasks are represented using oval nodes in the process flow graph.
- **Atomic task**: It is a task that cannot be decomposed into a set of subtasks. Atomic tasks are represented by using two-concentric oval nodes in the process flow graph.
- **Specification or data**: It is the input for executing a task or the output for a finished task. An output specification produced by a task can be consumed by subsequent tasks as an input specification. Specifications are represented using rectangular nodes in the process flow graph.
- **Selector**: A selector selects a specification or a parameter for a task. Selectors are represented using diamond nodes in the process flow graph.

These elements can be combined into a process flow graph using directed arcs to indicate the specifications used and produced by each task. Specifications with no incoming arcs are the first inputs to the process flow.

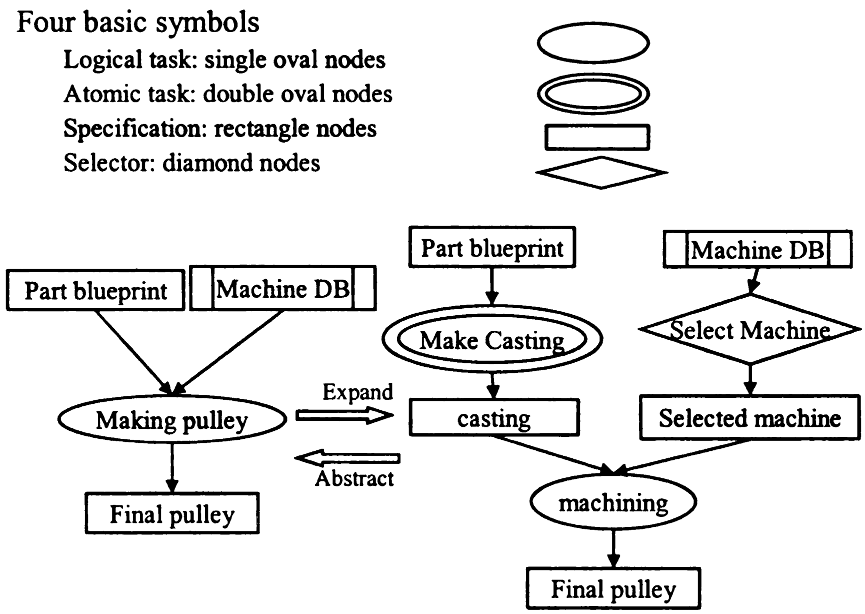


Figure 1. A process for making a pulley

Using these graphical elements, a process flow graph can be created in a top-down fashion. Figure 1 shows a high-level process flow of a process for making a pulley. Process flow graphs can describe processes in varying degrees of detail. The overall process can be seen because the details are hidden within the tasks. A graph containing many logical nodes describes what should be done without describing how it should be done (for example, specifying which tools to be used). Conversely, a graph in which all task nodes are either atomic or selectors fully describes a complete methodology for a design. In a complicated product, the overall process can be visualized more simply after the detail tasks are hidden from the overall process.

The process grammar provides the mechanism for transforming a high-level process flow graph into progressively more detailed process flow graphs. As will be discussed further, the grammar consists of a set of production rules. A production is a substitution that permits the replacement of a logical task node with a flow graph that represents a possible way of performing the task. Several production rules with the same left side flow graph imply alternative production rules for the logical task. Several production rules for a logical task imply there are alternative production rules for that task. Casting and machining are, for example, two alternative productions for the task manufacturing. This capability is critical to maintaining the usability and effectiveness of the overall framework. Therefore, the process grammar naturally captures the hierarchical design methodology and allows systematic exploration of process space.

There are two ways for applying the process grammar: expansion and abstraction. Figure 1 shows that a simple process flow graph in left side can be expanded into a detailed process flow graph with a set of subtasks or a detailed process flow graph on the right side can be abstracted into a simple process flow graph after the detailed tasks are hidden.

Note that there may be many alternatives for each of these process steps: different technologies, different vendors (companies), and so on. And at each step, there is a "make or buy" decision, as well. Also, for the overall process to critical information (such as design changes) and ideally, they need to be able to provide feedback early in the process concerning the feasibility and schedule for their part of the work.

1.4 Analytic Hierarchy Process for Process Selection

The Analytic Hierarchy Process (AHP) is a multi-criteria decision making method developed by Saaty [1980]. It can decompose a complex problem into a hierarchical order and use matrix algebra to solve the multi-criteria decision making problem. The process selection in a real manufacturing environment is a multi-criteria decision making problem. Many constraints with objective or subjective values are used to evaluate lots of alternative processes. This evaluation could be very difficult to make for a complex process. Considering the characteristics of the grammar-based approach, it is possible to decompose a complex process where an engineer or manager has to make many selections among many alternatives into a smaller number of selections at any abstract level. Therefore, the AHP method could be used to solve the process selection problem through matrix algebra in a real industry environment. This is the most important part in the dissertation and will be presented in detail in chapter 4.

1.5 Outline

Grammars are a means to generate a space of alternatives to a design problem. The generate-and-optimize approach to the design problem involves three steps [Schmidt and Cagan 1997]: the first step is the application of a method to generate alternatives; the second step is the evaluation of feasible designs among alternatives; and finally the third step is the application of an optimization technique to select the best design. This dissertation presents a methodology of process design as applied to manufacturing in the following steps: first, a grammar-based approach is applied to generate alternative processes using the case study on the production of pulleys; second, the important constraints for producing pulleys are identified, which will be used to evaluate the alternative processes; then an optimization technique, the analytic hierarchy process (AHP) method, is used to select the suitable process based on the hierarchy presentation of both processes and constraints.

In this dissertation, the proposed design methodology will be applied in an industrial case: production of pulleys. At first, we use process grammar to represent the processes for producing a pulley within a company; then we capture the important constraints for evaluating the alternative processes so as to facilitate the process design; finally, a hierarchy model for process selection is set up for the case, and an implement method of process selection is presented.

In chapter 2, the case study of pulley's production is presented. In this chapter, the processes include external processes (such as casting) and internal processes. A grammar-based approach is used to present the processes in a distributed manufacturing environment. The alternative processes are generated with process grammar, and the key constraints are captured to evaluate the alternative processes.

In chapter 3, the structures of both processes and the constraints are discussed. The common constraints used in a real manufacturing environment are listed and organized into four categories. With the process hierarchy and constraint hierarchy, the process reconfiguration is illustrated using these hierarchies with examples.

In chapter 4, the implementation of process selection is described. Based on the hierarchy structure of both processes and constraints, a hierarchy decision-making model is presented and an effective selection method is applied on the model. Some matrix calculations and the related modifications based on the specific industry case are presented.

Chapter 2

CASE STUDY

An advanced methodology to represent design and manufacturing processes is becoming essential due to the increasing complexity of the manufacturing environment and the rapid change of the market requirements. Many companies distributed around the globe can collaborate on various aspects of designing and manufacturing a product such as quotation, design, manufacturing, assembly, distribution, and service. Even within a given company, each department specializes in particular aspects of the company's business; and various departments work together to carry out various tasks such as bidding, quoting, designing, manufacturing, quality control, purchasing, etc. Within such a complex environment, if new and unexpected conditions arise during the production, an ideal process may not necessarily be the same process used previously with a different set of parameters and must be reconfigured after evaluating a new set of constraints. Alternative processes must be considered.

In a collaborative environment, tasks are interdependent: one task in one organization affects other tasks in another organization. Thus, achieving effective coordination among the participants throughout the life cycle of a product is a challenging problem. We believe that part of the solution lies in a common process representation that can be understood and shared by the participants. With such a representation, each participant can understand his or her task in relation to the overall process. Even within a company, developing a new process, buying a new machine, or hiring a novice or experienced operator can lead to more alternative processes. Furthermore, with many unforeseen changes in design or suppliers, capturing the alternative process enables us to reconfigure the process with a new set of constraints. This provides the incentive of this research based on a real industrial case.

The case presented in this chapter focuses on a collaborative manufacturing environment, which has the following characteristics:

- **Distributed participants**: the involved participants, such as the design company and the manufacturing company, may be around the world
- **Various functions**: within a company, there may be different departments such as a department of engineering, quality, and purchasing etc.
- **Frequent changes**: e.g., design change leads to reconfiguring processes
- **Interdependent tasks**: the tasks executed by different participants may interact on each other

The study will provide a new paradigm where the grammar-based process model is used to capture and reconfigure design and manufacturing processes with the constraints in a collaborative environment. To apply the model in an industrial practice, a case study has been conducted to capture the processes for making a variety of pulleys at Focus: Hope in Detroit, Michigan.

2.1 Background

Due to rapid changes in the market, manufacturing enterprises need to respond quickly while reducing costs through collaboration and use of alternative processes and resources. In a collaborative environment, process reconfiguration is necessary due to the changes in functional requirements, manufacturing processes, production facilities, and manufacturability [Nau et al. 1994]. Reconfiguring a process requires the re-evaluation of the constraints that are relevant to the process.

A variety of techniques to 'engineer' the processes are being developed to address this problem. In mass customization, many firms use process postponement, process re-sequencing, and process standardization [Feitzinger and Lee 1997]. In a distributed manufacturing environment, when a new product is introduced, group technology (GT) can support an efficient search for a similar product family and retrieve all the information about the design feature and manufacturing processes of the product [Candadai et al. 1996]. Agent-based approaches are also popular. For example, at the enterprise level, agent-based techniques have been developed to support decision-making in distributed design and facility planning teams [Ratchev et al. 2000]. This approach makes an iterative matching of design, process, and facility attributed by using multilevel resource capability representation within the extended enterprise. At the manufacturing floor level, a multiple criteria decision-making approach was developed to obtain the best machining cell structures even with conflicting objectives [Malakooti and Yang 2002]. It shows how to formulate and solve multi-objective problem (such as maximize the machine utilization rate and minimize the number of duplicated machines, etc.) by generating efficient alternatives and applying the algorithm on the machine-part cell formation.

A major challenge in the modeling process is to capture, represent, and evaluate a variety of tasks without explicit dependencies [Park and Cutkosky 1999]. They also reviewed several existing methods. For example, digraph represents processes with nodes and directed edges, but it is not effective to follow precedence relationships and detect circuits among tasks nodes in a large model. Project Evaluation and Review Technique (PERT) [Wiest and Levy 1977] is a popular model with nodes representing task completion milestones and arcs representing individual tasks. While the length of an arc is proportional to the duration of the corresponding task, PERT can predict the expected completion dates of a project. However, it neither provides the concept of process iteration (rollback) nor shows the constraints explicitly. The Structured Analysis and Design Technique (SADT) [Ross 1977] supports a structured graphical notation for specifying the tasks, information inputs, and outputs in a large and complex process model. However, it is difficult to maintain and, thus, prone to ambiguous interpretations. Petri nets are effective to capture and analyze dynamic states of a modeled system. However, Petri nets do not provide particular mechanisms for abstracting process details and cannot generate representation to help differentiate between process-related information and unnecessary details

[Murata 1989]. Other methods typically have limitations in providing multiple levels of abstraction, precedence relationships, and constraints among tasks and work products.

The grammar-based approach demonstrated here has the potential to resolve these problems [Chung et al. 2002 and Kwon et al. 2002] for the following reasons. First, as we shall demonstrate, the representation used in the grammar-based process model can explicitly capture alternative processes. In addition, the constraints are captured and evaluated to reconfigure the process. Second, the grammatical structure should be relatively easy to maintain since processes are described in a hierarchical structure. Finally, the grammatical structure of the process model prevents the formation of circuits or causal loops in the process representation.

This grammar-based approach has been implemented in a system called MIDAS. In MIDAS, detailed task descriptions can be abstracted into a simple, higher-level task. In reverse, a higher-level logical task can be decomposed into a set of subtasks (other logical and atomic tasks). An atomic task cannot be decomposed. To capture and represent a process, four basic symbols are used: Logical Tasks are represented using oval nodes, Atomic Tasks are represented using two-concentric oval nodes, Specifications or Data are represented using rectangular nodes, and Selectors are represented using diamond nodes. Databases are a special kind of Specification, which are represented using rectangular nodes with two vertical lines on two sides (left and right) of the rectangle.

The graphical decomposition of tasks into subtasks provides each participant with a shared representation of the overall process [Chung et al. 2002]. Each task uses a set of input specifications and produces another set of output specifications, which are then used by subsequent tasks as input specifications. Directed arcs indicate the specifications used and produced by each task to represent the flow of these specifications. The four basic symbols together with directed arcs are used to represent a process-flow graph. This notational system facilitates multiple layers of abstraction and the explicit representation of constraints.

The process grammar provides a mechanism to abstract a complex set of highly dependent tasks into a simple, higher-level task (logical task) or to expand a higher-level task into a set of lower-level tasks. When more than one alternative process exists, one process can be selected by evaluating a given set of constraints. Our process-flow graph depicts tasks, data, and the relationships among them, describing the sequence of tasks. This representation is easy to maintain, especially for families of related processes, such as those described here. As will be seen in this research, the process-flow graph is effective in capturing, representing, and sharing various processes being practiced at Focus: HOPE, in Detroit, Michigan.

2.2 Modeling Processes

In this study, we concentrate on the internal and external processes in a real manufacturing environment, at a company named Focus: HOPE in Detroit, Michigan. The processes are specially used to manufacture a variety of pulleys. We will represent alternative processes and the constraints used to reconfigure the processes for a variety of pulleys.

2.2.1 Genesis of Alternative Processes

In this research, we used the ontology defined in Chung et al. [2002], in combination with the process grammar, to generate alternative processes. Processes are selected based on the attributes of four kinds of entities: Tasks, Data, Resources, and Organization. Because some of these entities can change, it is not possible to simply store and retrieve detailed process plans for production within a collaborative environment. Process plans should be stored at a different level of abstraction under a different management level and specialized to fit the current circumstances.

Tasks - Many manufacturing processes can be used to produce the same part. In producing a pulley, instead of starting with casting, a pulley can be manufactured completely by machining out of a bar stock. This will be cost-effective to make a small quantity of pulleys. Process planning must be made based on dimensions and production volume. Other factors identified by Zhang et al. [1999] include the geometry complexity, tolerance, the number of setups, machining cost, alternative operations, and other specifications. A manufacturing company needs to determine what can be done in-house or by outside suppliers.

Data – The design requirement contained in the blue print of a part (such as material, geometry, and tolerance etc.) must be considered to choose different processes. A material must be selected from a material database. Alternative processes must be adopted depending on the selected material. For example, polymeric materials cannot be produced with the same process used for ceramics because completely different resources and expertise are required. Also, based on the geometry and the tolerance, alternative processes can be used to produce the preferred part.

Resources - A process planner selects and assigns a machine from the list of available machines for a task. Each machine may have distinct process capabilities and accuracy. Even for the same type of machines, the dimension, tolerance, or position accuracy of the part can be different. A combination of machines, instead of one, can be used to meet the design requirement, which generates alternative processes.

Organization - Choosing another supplier can result in alternative processes as each company brings in a different process capability or professional practices with other organizations. Cost and lead-time are two main attributes when choosing a supplier. Some other attributes such as quality status, location, and credit history will be considered as well. Within a company, various departments may have distinct roles in a project. Based on the function of different departments, a task may be assigned to more than one department.

2.2.2 Representing the Overall Process

This study has been carried out through a series of the interviews with the people involved in making pulleys at Focus:HOPE. Due to many different kinds of pulleys manufactured in this plant, a sample of twenty pulleys was selected to understand the processes involved in making the pulleys. Using the symbols and arcs defined earlier, the common process reflecting all twenty pulleys after a series of abstraction is represented in Figure 2.

Capturing the Overall Process

The processes shown in Figure 2 start with a set of drawings and other requirements such as time constraints and production quantity requested by Company A. Based on the drawings, Company B (Focus:HOPE) starts the quotation processes that includes not only the cost to manufacture the pulley but also all of other related costs including cast, tools, gauges, human resources, etc. Based on a set of quotation prices from various companies' bids for the project, Company A decides on a supplier. Once Company B is chosen as the supplier, Company B has to evaluate a set of companies for casting, gauges, and tooling typically based on its past experience dealing with each of the companies.

A similar bidding process is necessary for Company B in selecting the suppliers for gauges, casting and tooling. From the selected suppliers, the casting, gauges and tooling will be ordered. Most of these are made in a small quantity initially to test these parts in the production. At the same time, the detailed process plan such as a sequence of machining processes, assignment of resources and operators, and other processes necessary to produce the pulley is worked out.

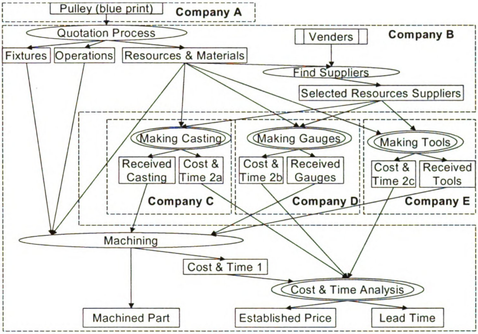


Figure 2. Overall process of making pulleys

Manufacturing Environment

Figure 2 illustrates the complete process to make a pulley at Focus:HOPE. The input/output specifications for each process task also reflect the necessary data flows among the tasks. Five companies (denoted as Companies A, B, C, D, and E for convenience) are working together to produce a pulley. Company A, which designed the pulley, sends a document with the requirements for the pulley to

Company B; Company B makes a macro-level process plan, including Quotation Process for the pulley, finds suitable suppliers for casting, tooling, and gauging; manufactures the pulley; and analyzes the time and cost. Companies C, D, E are selected by company B to provide materials such as casting and consumable resources such as cutting tools and gauges.

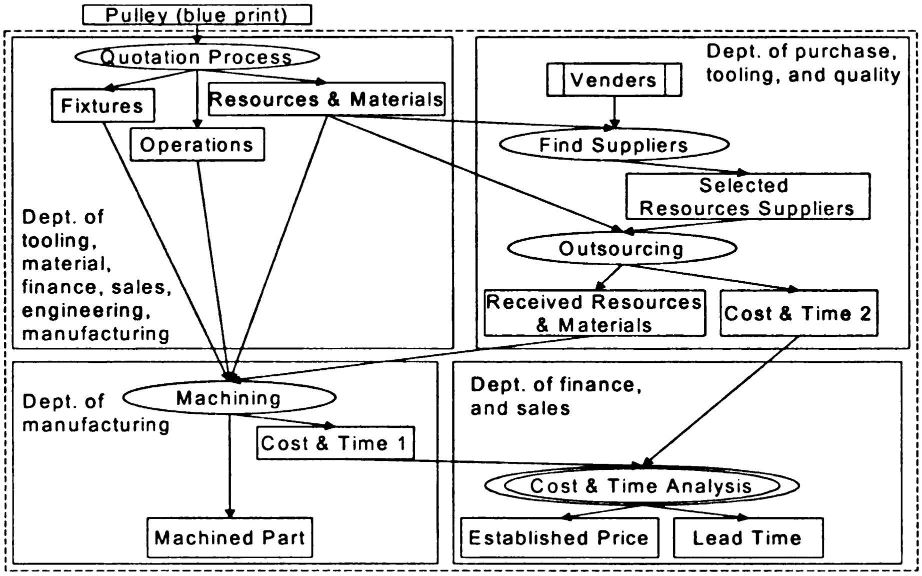


Figure 3. The process flow in company B

Figure 3 shows the process to manufacture a pulley within Company B after abstraction. In this scenario, many departments such as sales, finance, materials, engineering, purchasing, and quality are engaged to execute the quotation process and to determine the required fixtures, operations, and consumable resources (such as gauges and cutting tools). In the quotation process, macro-level process planning is carried out to estimate the total cost to produce a pulley. The purchasing department finds one casting supplier from its casting provider list; the tooling department orders the cutting tools from a tool supplier; and the quality department orders the required gauges from gauge providers. The manufacturing department starts the production of the pulley once the required consumable resources, such as cutting tools, are available. Finally, the finance and sales departments calculate the total cost and time to determine the price and the lead-time of the pulley.

Alternative Processes

As shown in Figure 2, Company B performs tasks such as Quotation Process, Find Suppliers, Cost & Time analysis, Machining and Outsourcing (ordering the required casting, gauges, and tools). Each supplier executes their tasks of making or purchasing casting, gauges, and cutting tools. All the processes will be described in the following sections.

Quotation process - As shown in Figure 4, the logical task, Quotation Process, can be decomposed into four main atomic tasks: Feature Analysis, Assign Resources, Operation Analysis, and Capability Analysis. For example, Gauges, Tools, and Casting from the suppliers have to pass a Capability Analysis. Here, the failure in the Capability Analysis will be resolved by reselecting another fixture, cutting tools, or gauges in order to meet the requirement. Iteration may be required to find an acceptable match.

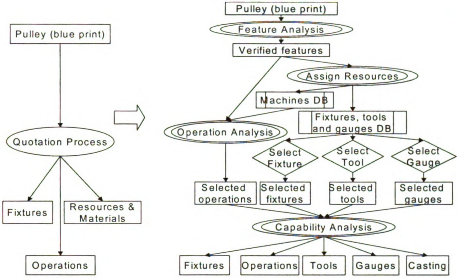


Figure 4. A detailed quotation process

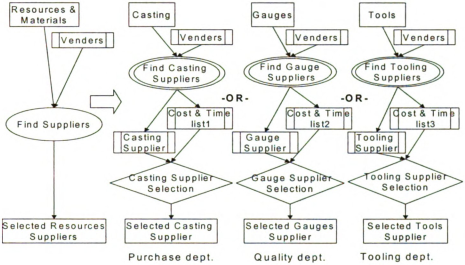


Figure 5. A process for finding suppliers

Find Suppliers – Figure 5 shows the process in which the consumable resources and material suppliers are selected from the list of suppliers. It includes an atomic task called Find Suppliers and a selector called Supplier Selection. A common logical task, Find Suppliers, can be used but specialized based on the input specification as shown in Figure 5. For example, based on the input specification, Gauges, the quality department performs the atomic task, Find Gauge Suppliers, to select a suitable supplier to produce an output specification, Selected Gauges Supplier.

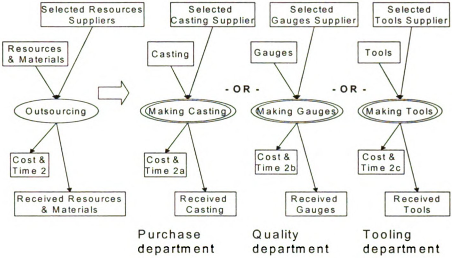


Figure 6. A process for outsourcing

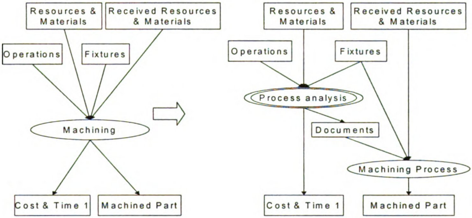


Figure 7. Process flow for machining

Outsourcing process – Outsourcing is a process of purchasing required resources or materials produced or resold by suppliers. In Figure 6, the input specifications for the outsourcing process are Resources & Materials and Selected Resources Suppliers. It is very similar to Find Suppliers in terms of using a common logical task and specializing into a more specific Select Suppliers.

Machining process - As shown in Figure 7, Process Analysis generates Cost & Time related to Physical machining processes and the documents that include CNC programs, process sheets, picture sheets, and audit sheets. Machining includes the machining operations with assigned resources such as machines, fixtures, and other consumable resources. Depending on geometry complexity, tolerance, and machine, the machining process may have many alternatives. Table 1 shows the basic structure of a pulley and its required manufacturing processes. A pulley is shown in Figure 8 with some described features in Table1.

Table 1. Basic features of pulleys

Structure			**Processes**
Components	**Features**		
Wheel	Wheel Flange	Front flange	Facing
		Rear flange	Facing
	Wheel O.D.	Smooth O.D.	Turning
		Stepped O.D.	Turning
	Groove		Grooving
	Chamfer		Turning
Hub	Hub face	Front face	Facing
		Rear face	Facing
	I.D.	Axial hole	Casting, drilling, boring, reaming
		Counter-bore	Counter boring
		Inside cone	Taper boring
		Inside groove	Snap ring grooving
	Hub O.D.	Smooth O.D.	Turning
		Stepped O.D.	Turning
	Chamfer		Boring
Others	Auxiliary hole		Drilling
	Internal thread		Tapping
	Keyway		Broaching
	Part No.		Stamping
	Balance holes		Balancing
	Rib, Boss		Casting

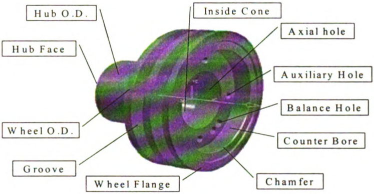


Figure 8. Features of a pulley

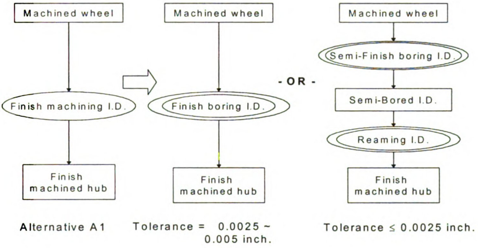


Figure 9. Alternative processes due to tolerance requirement

After reviewing over twenty pulleys, the processes can be classified into two distinct types. The alternative A2 requires a reference plane from the finish machined wheel. The detailed processes show more alternative processes caused by geometric complexity, such as the hole represented in Table 2. The alternative A1 has two more alternative processes depending on the process used to introduce the inner diameter of a pulley: casting or drilling. Figure 9 shows two alternative productions that lead to the attainable tolerance for a specific machining feature: Inner Diameter (I.D.). For a general tolerance (0.0025~0.005inch), finish boring can meet the requirement; however, a better tolerance (≤0.0025 inch) can be achieved by combined Semi-Finish boring and Reaming I.D.

Table 2. Machining process flow of pulley

Alternatives	Tasks	Detailed Alternative Processes	
A1	1. Roughing hub	1. Core drilling hole; 2.Counter boring; 3. Semi-finish boring; 4.Boring chamfer; 5.Facing hub face;	i. Casting hole; ii. Counter boring; iii. Rough boring; iv. Boring chamfer; v. Facing hub face.
	2. Machining wheel	6.Facing flange; 7.Turning flange O.D.; 8.grooving;	
	3. Finishing hub	9. Finish boring;	i. Reaming
	4. Finishing pulley	10. Broach keyway; 11.balancing; 12.stamping.	
A2	1. Roughing wheel	1.turning flange O.D; 2.facing flange; 3.grooving;	
	2. Roughing hub	4.counter boring; 5.boring;	
	3. Finishing wheel	6.facing flange;	
	4. Finishing hub	7.facing hub face; 8.turning hub O.D.; 9.taper boring cone.	
	5. Finishing pulley	10.Drilling holes; 11.Tapping thread; 12. Balancing; 13.Stamping.	

Table 3. Alternative processes due to assigned machine

Alternative 1			Alternative 2		
Setup1	1.Turning flange O.D.	M1	Setup1	1.Turning flange O.D.	M2
	2.Facing front flange			2.Facing front flange	
	3.Facing hub face			3.Facing hub face	
	4.Grooving groove			4.Facing rear flange	
	5.Rough and semi-finish boring I.D.			5.Grooving groove	
	6.Reaming front I.D.			6.Rough boring front I.D.	
Setup2	7.Facing flange			7.Rough back boring rear I.D.	
	8.Facing rear hub face			8.Reaming I.D.	
	9.Facing bottom face				
	10.Reaming rear I.D.				
	11.Drilling auxiliary hole			9.Drilling auxiliary hole	
	12.Tapping thread			10.Tapping thread	

Table 3 illustrates two alternative processes to be chosen depending on the assigned lathe. The rest of the process that was not performed by the lathe was not presented here. The size of the chuck limits a certain machining process. Machine denoted M1 can hold the pulley in a bigger chuck diameter (≤16 inch), which allows all of the features to be finished in one setup. The machine denoted M2 has a smaller chuck diameter (≤12 inch), which forces the machining process to take two setups.

2.2.3 Constraints in Manufacturing

As discussed earlier, the constraints must be evaluated to choose alternative processes. Some constraints are used to pre-evaluate the alternative processes for a task. Other constraints are applied as post-evaluation functions to check the output specification. The post-evaluation is usually required to verify fixture, tool, gauge, and operation sequence before the selected processes are applied on the full-scale production. The pre- and post-evaluation functions are presented according to the entities discussed earlier.

Constraints for Task

The inner diameter is a dimension of the pulley that could be produced by casting or machining (drilling and/or boring). For machining a larger inner diameter, drilling and boring processes are required since the diameter of a drill is limited. With casting process, additional mold material for the hole must be added. The cost comparison between extra mold and the additional machining is important in making a decision. As a general rule, the pre-evaluation used in this case is if the diameter is less than 1 inch, choose machining and, otherwise, choose casting.

Pre-evaluation – In Table 2, the geometric complexity of the casting is evaluated to choose a process flow for the machining process task: Alternative A1 is good for a pulley with a simple geometry, while Alternative A2 is suitable for a pulley with a more complex geometry. Figure 9 shows two alternative processes where the pre-evaluation compares the required tolerance against the tolerance that can be achieved with a given process alternative. Generally, a tolerance of 0.0025~0.005 inch can be produced by finish boring while a better tolerance (less than or equal to 0.0025 inch) can be achieved by combining semi-finish boring and reaming.

Post-Evaluation – A post-evaluation is used to check if the output specifications meet the constraints. The Capability Analysis on Figure 4 runs the test operations with the gauges, fixtures, and cutting tools. The tolerance is evaluated on a part produced as the post-evaluation. When the tolerance cannot be met, iteration may be required to choose another (1) fixture, (2) tool, (3) gauge, and (4) new operation sequence to meet the design requirement. An experienced engineer may require less iteration. If the post-evaluation of Capability Analysis is satisfied, then they are ready for full-scale production.

Constraints for Organization

As shown in Figures 4 and 5, the task of Find Suppliers (casting, gauge, or tooling) finds the suppliers based on their process capability and production scale. Cost and lead-time are two main constraints to select appropriate companies. However, location and credit history (including quality and on-time delivery) are additional constraints sometimes considered by the company. Once the planned processes have been determined, particular departments are assigned to perform the tasks. The basic functions of a department are the main constraint in choosing which department should be responsible for each task. Figures 5 and 6 show the purchasing department performing the tasks of Find Suppliers and Outsourcing that related to casting while quality department performs the tasks related to the gauges.

Constraints for Resource

As discussed earlier, machine specifications such as maximum chuck diameter and maximum power of a machine can lead to the selection of an alternative machining process. In addition, each cutting tool has a specific shape capability and tolerance level, which leads to different operation sequences. Similarly, the assignment of human resources such as the domain expertise of an engineer or the experience level of an operator is an important constraint for choosing certain processes. For the processes represented in Figure 4, a process engineer should be assigned to the task of Operation Analysis, and a quality engineer can be assigned to Gauge Supplier Selection.

Constraints for Making Pulleys

Table 4. Typical process constraints for making a pulley

Entities	Constraints
Task	1. Maximum drill diameter = 1 inch (evaluating drilling or casting I.D.) 2. Extra cost (from extra core mold or additional machining) (evaluating drilling or casting I.D.) 3. Geometric complexity of pulley (evaluating alternative process type A1 or A2 in Table 2) 4. Designed tolerance of I.D. =0.0025 inch (evaluating "finish boring" or "semi-finish boring and reaming") 5. Minimum tolerance of I.D. =0.0025 inch (evaluating turning center or drilling machine) 6. Capability test of tools (gauge, fixture, cutting tool) and operation sequences to meet the design requirement (tolerance, shape) 7. Dimension (I.D., depth, thread, runout, etc.) to match available gauges
Organization	8. Process capability of supplier = {casting, tooling, gauging} 9. Production scale of supplier 10. Bidding cost 11. Bidding lead-time 12. Location of supplier 13. Credit history (including quality and on-time delivery) 14. Department function ={purchasing, tooling, quality, engineering, sales, finance, manufacturing}
Data	15. Material of pulley = {gray cast iron or ductile cast iron} 16. Material of cutting tool = {carbide or ceramic}
Resource	17. Maximum chuck diameter = 16 inch (turning center) 18. Min tolerance = 0.005 inch (turning center) 19. Maximum power = 44 kW (turning center) 20. Shape capability = {O.D., I.D., Groove, flat face, chamfer, thread} (turning center) 21. Process capability = {turning, drilling, facing, grooving, boring, reaming, taper boring) (turning center) 22. Domain expertise of engineer ={process engineer, quality engineer, tooling engineer} 23. Experience level of operator 24. Specification of gauge (size, grade of thread, tolerance of the thread) 25. Specification of cutting tool (shape capability, tolerance level) 26. Others (max turning diameter, Max turning length, Max weight, axis number, etc.)

The entities and constraints for the pulley's production system are summarized in Table 4. The constraints associated with each entity are important to reconfigure processes. The changes in some or all of the four entities may lead to reconfiguring the process. Therefore, related constraints will help identify the part of the process to be modified instead of going through the whole process. Further research to identify the relation among different entities and their constraints are presented in the following chapter.

2.3 Conclusion

This case demonstrates that grammar-based processes models are a feasible method of capturing and representing the processes even for the complex sequence of tasks in an industrial setting. Further research will be required to determine the range of situations where grammar-based models are superior to various alternatives. However, this case study shows that process grammar is a useful way to represent complex tasks and the constraints associated each task are evaluated to choose among alternative processes. We have shown that the interaction among Tasks, Data, Resources, and Organizations generates alternative processes. The explicit graphical representation makes it easier to see each participant's task in relation to the overall process and show important constraints. The ability to handle multiple levels of abstraction provides a natural way to deal with changes in context. Thus, process grammars can facilitate coordination among the departments within an organization as well as among the organizations.

Chapter 3

CONSTRAINT MANAGEMENT

In a collaborative manufacturing environment, a challenging problem for process management is to capture and model the key constraints for reconfiguring the processes. This is an important issue especially in Reconfigurable Manufacturing System (RMS) where the constraints can constantly evolve. The changes of the constraints in RMS emanates from, for example, producing a variety of products, introducing new machines, implementing design changes, etc. To demonstrate this, a case study was carried out at Focus: HOPE, Detroit, Michigan in producing a variety of pulleys, as presented in chapter 2. Numerous constraints affecting the machining and other related processes for producing these pulleys have been collected. This chapter presents a hierarchical approach to capture and model the constraints that are important in reconfiguring processes in the proposed grammatical approach.

3.1 Introduction

Process is one of the most essential concepts in the development of a Reconfigurable Manufacturing System (RMS). However, the theoretical development in the representation and management of processes has not been well established to make a major impact on RMS. The important consequence of the modeling process is that, as new and sometimes unexpected conditions arise during the production, an ideal process may not necessarily be the previous process with another set of parameters. In many situations, alternative processes must be considered and the most suitable process must be selected. Therefore, to implement RMSs effectively, we must be able to capture, represent, and reconfigure the processes in the environment where the constraints and requirements are constantly evolving.

The main goal of a RMS is placed on the dynamical problem of continuously adapting the technological solution at a lower cost [Koren et al. 1999]. An ideal process modeling method must be able to represent the processes and the associated constraints; and, at the same time, it must capture the specific changes in the processes and the constraints that bring about these changes. It is essential that such changes must be introduced systematically and their impact must be clearly understood [Sadiq and Orlowska 2000].

Being able to reconfigure the processes requires capturing the constraints that influence the processes as well as recommencing and re-evaluating the constraints. Chapter 2 demonstrated that a grammar-based approach can accomplish process representation and reconfiguration very effectively. A grammatical representation allows both processes and constraints to be represented in a hierarchy structure. In order to demonstrate the proposed approach, we have captured and represented the machining and other related processes for twenty pulleys through an extensive industrial case study at Focus: HOPE in Detroit, Michigan. Focus: Hope produces well over one hundred different pulleys and we have limited ourselves for convenience to only twenty pulleys. We will show how to reconfigure the process for each pulley and to select and evaluate the necessary constraints to reconfigure the process. This allows us to understand the inner working of the constraints that impose on the processes.

3.2 Process Model Hierarchy

As presented in chapter 2, the proposed grammar-based approach can represent the processes in a hierarchy structure at any level of abstraction. In order to reconfigure the processes, the required constraints must be captured and organized. When a logical task is expanded into detailed tasks, the most suitable process must be selected among the alternative processes by evaluating the necessary constraints. In chapter 2, Figure 3 illustrates the high-level (abstracted) process to manufacture a variety of pulleys at Focus: HOPE. The input/output specifications for each process task also reflect the necessary data flows among tasks. Each task is executed by each department working independently or cooperatively with other departments. The task may include more sub-(or detail) tasks [Zeng et al. 2003]. For example, the logical task called 'Outsourcing' is carried out to purchase the required consumable resources and materials that are produced or resold by suppliers; it includes three atomic tasks: 'Making Casting', 'Making Gauges', and 'Making Tools'.

A process hierarchy helps a participant to understand the overall processes and the detailed processes at an appropriate level of abstraction. With any change in the requirement and constraints, the hierarchy structure can quickly identify the processes that are affected by the change. Figure 10 shows a process hierarchy, in which the processes required for producing a pulley are described in multiple levels. Producing a pulley is the top-level goal, with quotation process, cost and time analysis, outsourcing, and machining in the second level. The process tasks in the third level are the sub-tasks of the second level tasks. The atomic tasks such as cost and time analysis in the second level, or feature analysis, making gauge, find gauge supplier, etc. in the third level cannot be expanded. The logic tasks will have sub-tasks in a lower level. Because of the limit of space, Figure 10 shows a hierarchy up to four levels only.

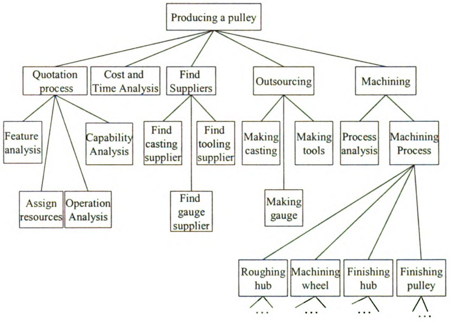


Figure 10. Process Hierarchy in producing a pulley

3.3 Constraints for Process Models

3. 3.1 Categorizations

When representing the processes for producing the pulleys manufactured at Focus: HOPE, an enormous set of constraints are identified and captured. Several categories of the machining and other related process constraints are necessary and thus presented here briefly.

Genesis

The previous chapter shows that the alternative processes are generated from four entities: Task, Data, Resource, and Organization. Considering an alternative process resolves the limitation and/or improves the capability of existing processes. Consequently, the constraints that describe the limitation and capability of each process must be captured in order to reconfigure the processes. They can be categorized by four geneses: task, data, resource, and organization.

Element

The constraints are as well categorized by four elements: feature, process, machine, and production. These elements are identified in our case study, which are typically understood as the key elements in manufacturing. The feature constraints are those that arise directly from the design requirement such as tolerance, geometry, and material. The process constraints arise from the specifications of the process without regard to the individual machine. These kind of constraints, such as the tolerance range of a specific process, are normally presented in handbooks and textbook. The machine constraints arise from the specifications of an individual machine such as horsepower and maximum tolerance that can be achieved. Such constraints can be an independent set of constraints for each machine. The production constraints arise from the constraints related to a production project such as cost, lead-time, etc. In section 3.4, a constraint hierarchy will be presented based on this category.

Obligation

Jones et al. [1996] evaluated the obligation of constraints for assembly planning. As performed in Jones et al. [1996], we have classified the constraints into four categories: requirement, prohibition, optimization, and suggestions. The constraints for machining and other processes have a similar obligation, which are represented as the following:

- ***Requirement***: refers to a constraint that defines the design requirement from the specific features in the blue print.
- ***Prohibition***: refers to a constraint that rules out unsuitable alternative processes for executing a task.
- ***Optimization***: refers to a constraint that selects the best process among the suitable alternative processes to maximize or minimize a scalar function such as cost or tolerance. (MIN and MAX).
- ***Suggestion***: refers to a constraint that helps planners to generate a suitable process plan based on either handbook or their own experience.

3.3.2 Constraint List

The constraints listed below are identified from the case study. A brief definition of each constraint is presented in this section. As discussed in chapter 2, these constraints may be applied when selecting a supplier, choosing a process among many alternatives and so on. The constraints are listed here based on the obligation categories presented above.

<u>**Optimization**</u>

Max-Credit-History: Maximize by selecting a supplier with the best credit history such as quality and on-time delivery.

Min-Cost: Minimize the overall cost for producing a pulley.

Min-Cost-Casting: Minimize the cost of casting by selecting a suitable supplier.

Min-Cost-Fixture: Minimize the cost of fixtures by either selecting a supplier or making them in house.

Min-Cost-Gauge: Minimize the cost of gauge by selecting a suitable supplier.

Min-Cost-Hole: Minimize the cost of producing a hole. The cost may vary depending on the processes used such as drilling hole or casting hole.

Min-Cost-Machining: Minimize the overall cost of machining for a part by planning a suitable machining process.

Min-Cost-Tool: Minimize the cost of tooling.

Min-Distance: Minimize the distance from the location of supplier. It relates to the constraint, Min-Cost.

Min-Setup: Minimize the number of setups for producing a part, which may vary depending on a selected machine.

Min-Time: Minimize the required time to execute a process task.

Prohibition

Prh-Axis-Number: The maximum number of axis in a machine. As the number of axis increases, the flexibility of a machine improves requiring a less number of set-ups.

Prh-Chuck-Diameter: The range of a part diameter that may be chucked into a machine. It prohibits executing certain processes in a particular machine.

Prh-Domain-Expertise: The domain expertise of an engineer. It prohibits some human who can execute a task.

Prh-Experience-Level: The experience level of an operator in operating the machine.

Prh-Function-Dept: The function that may be performed by a department in the company, such as the departments of purchasing, tooling, quality, etc.

Prh-Hole-Diameter: The range of hole diameters that may be accomplished in a machine.

Prh-Horsepower: The maximum horsepower of a selected machine.

Prh-Machine-Type: The type of machine used.

Prh-Material: The types of material processed in the machine.

Prh-Process-Machine: The list of processes that can be run in a machine.

Prh-Process-Supplier: The process capability of a supplier.

Prh-Scale-Supplier: The production capability of a supplier.

Prh-Shape-Type: The shape types of a work piece that may be accomplished in a machine such as flat face, axial hole, chamfer, etc.

Prh-Spindle-Speed: The maximum speed of the spindle of a machine.

Prh-Time-Schedule: The time schedule of a machine available for a part.

Prh-Tolerance: The range of tolerances of features that may be accomplished in a machine.

Prh-Turning-Diameter: The range of external diameters that may be accomplished by turning process in a machine.

Prh-Turning-Length: The range of part lengths that may be accomplished by turning process in a machine.

Prh-Weight: The maximum weight of a part that may be chucked in a machine.

<u>Requirement</u>

Req-Hole-Diameter: Designed diameters of holes on a part.

Req-Material: Material Requirement for a part.

Req-Quantity: Quantity Requirement of a part.

Req-Shape-Type: Particular shape types of a part.

Req-Tolerance: Tolerance requirement for a part.

<u>Suggestion</u>

Sug-Drill-Diameter: Suggest the range of drill diameters for a typical drilling process. It includes Maximum-Drill-Diameter and Minimum-Drill-Diameter.

Sug-Geometry-Complexity: Suggest a certain complex geometry for a part based on the geometry feature and the size of the part.

Sug-Hole-Diameter: Suggest the range of hole diameters that can be accomplished by any process.

Table 5. Classification of Constraints

Constraint Name	Obligation	Element
Max-Credit-History	Optimization	Production
Min-Cost	Optimization	Production
Min-Cost-Casting	Optimization	Production
Min-Cost-Fixture	Optimization	Production
Min-Cost-Gauge	Optimization	Production
Min-Cost-Hole	Optimization	Production
Min-Cost-Machining	Optimization	Production
Min-Cost-Tooling	Optimization	Production
Min-Distance	Optimization	Production
Min-Setup	Optimization	Production
Min-Time	Optimization	Production
Prh-Axis-Number	Prohibition	Machine
Prh-Chuck-Diameter	Prohibition	Machine
Prh-Domain-Expertise	Prohibition	Production
Prh-Experience-Level	Prohibition	Production
Prh-Function-Dept	Prohibition	Production
Prh-Hole-Diameter	Prohibition	Machine
Prh-Horsepower	Prohibition	Machine
Prh-Material	Prohibition	Machine
Prh-Process-Machine	Prohibition	Machine
Prh-Process-Supplier	Prohibition	Production
Prh-Scale-Supplier	Prohibition	Production
Prh-Shape-Type	Prohibition	Machine
Prh-Spindle-Speed	Prohibition	Machine
Prh-Time-Schedule	Prohibition	Machine
Prh-Tolerance	Prohibition	Machine
Prh-Turning-Diameter	Prohibition	Machine
Prh-Turning-Length	Prohibition	Machine
Prh-Weight	Prohibition	Machine
Req-Hole-Diameter	Requirement	Feature
Req-Material	Requirement	Feature
Req-Quantity	Requirement	Production
Req-Shape-Type	Requirement	Feature
Req-Tolerance	Requirement	Feature
Sug-Drill-Diameter	Suggestion	Process
Sug-Geometry-Complexity	Suggestion	Process
Sug-Hole-Diameter	Suggestion	Process
Sug-Prod-Rate	Suggestion	Process
Sug-Tolerance	Suggestion	Process
Sug-Material	Suggestion	Process
Sug-Shape-Type	Suggestion	Process

Sug-Material: Suggest a particular material type.

Sug-Prod-Rate: Suggest that a particular production rate.

Sug-Shape-Type: Suggest a particular shape that may be accomplished by a process.

Sug-Tolerance: Suggest a particular tolerance range of a process.

3.3.3 Classification of Constraints

As discussed above, the constraints can be categorized based on obligation and element. Table 5 shows the constraint list in alphabetical order identified in the case study. With the name of the constraints listed in column one, column two defines the obligation of each constraint. For example, the constraint **Prh-Chuck-Diameter** (the chuck diameter range of a machine), as will be shown later, prohibits a certain process, as an additional set-up may be needed to accomplish a task with a smaller chuck.

Column three defines the element of each constraint. These categories help to identify the constraints that are affected more efficiently in reconfiguring the processes. For example, when considering a new casting supplier, the constraints belongs to the element "production" must be evaluated so that the constraint **Min-Cost-Casting** may be reevaluated to minimize the cost of casting, and the constraints **Prh-Scale-Supplier** and **Req-Quantity** will be applied to choose the best suitable supplier.

3.4 Constraint Hierarchy

Chapter 2 shows that the grammar-based approach demonstrates the benefit of using a hierarchy structure for process reconfiguration. As the processes are abstracted or expanded, the constraints must be transformed accordingly so that they can be evaluated at an appropriated level of abstraction to make a choice among feasible alternative processes.

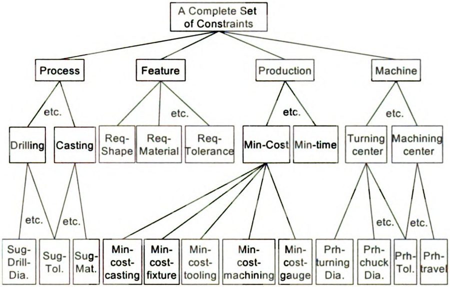


Figure 11. Constraint hierarchy for producing pulleys

To show this, the constraints used in this study are presented and classified based on the obligation and element constraints shown in Table 5. A constraint hierarchy is used to evaluate the constraints effectively. Figure 11 shows the constraint hierarchy for producing a pulley. The complete set of constraints can be subdivided as process, feature, production, and machine. At a specific abstracted level, any constraints at a lower level can be evaluated to reconfigure the processes. In the following sections, we will provide the constraints identified for each of the four elements and how the processes are affected by the constraints.

3.4.1 Production

The cost is an important constraint for an OEM (Original Equipment Manufacturer) to choose a supplier or to determine an appropriate process for a task. The constraint of **Min-Cost** is a measurement of the overall cost for producing a pulley, which includes the costs of machining, casting, tooling, gauge, fixture, etc. The constraint of **Min-Cost** helps an OEM to choose a supplier based on its bids. Focus: HOPE is one of the suppliers bidding for the project. Other possible constraints such as the lead-time, quality, and the distance from a supplier are not considered here for simplicity.

During the macro-level process planning stage, each supplier chooses a particular process for machining, and selects suppliers for casting, tooling, fixture, and gauge. Each department in the company must implement a set of constraints that affects the tasks assigned. For example, the purchasing department uses the constraint of **Min-Cost-Casting** to choose a casting supplier, tooling department uses **Min-Cost-Tooling** to determine the tooling supplier, the quality department uses **Min-Cost-Gauge** to select gauge supplier, and the engineering department uses **Min-Cost-Machining** to choose a suitable process plan for machining the pulley. Therefore, the cost for each process must be summed up as a total cost.

A simple relationship exists among the above constraints. A total cost of a pulley is Sum {**Min-Cost-Casting, Min-Cost-Tooling, Min-Cost-Machining, Min-Cost-Gauge, Min-Cost-Fixture**, etc.}. Thus, if three companies A, B, and C are able to produce the pulley; the constraint, **Min-Cost**, evaluates the total costs submitted by the suppliers in selecting a supplier:

Sum(i) = Sum{**Min-Cost-Casting**(i), **Min-Cost-Tooling**(i), **Min-Cost-Machining**(i), **Min-Cost-Gauge**(i), **Min-Cost-Fixture**(i), etc.}
for company i where i=A, B or C;

The supplier who bid the lowest can be selected by the following constraint and the total cost for the pulley is
Min-Cost = Min{Sum(A), Sum(B), Sum(C)}.

3.4.2 Machine

The constraints (e.g.: the specifications of a particular machine) associated with each type of machines are different. In addition, due to the process capability of each type of machines, alternative processes must be generated according to the type of the assigned machine. Even for the same type of machines, the process capability depends on the status of the machine such as the typical tolerance each machine can achieve. Depending upon the specification, the processes must be reconfigured. For example, the turning center can drill the center hole only, and another milling machine is required to finish the drilling of auxiliary holes on the flange; however, for a machining center that performs both turning and milling processes, the time for changing each setup could be saved.

Based on the assigned machine, the constraint **Prh-Machine-Type** can be implemented for a high-level process. As shown in Figure 11, the constraints, **Prh-Chuck-Diameter** and **Prh-Tolerance**, can be implemented to evaluate the alternative processes for the sub-tasks in a low-level. This shows that a constraint hierarchy can be used to evaluate the alternative processes in an appropriate level related to the process hierarchy in the case study.

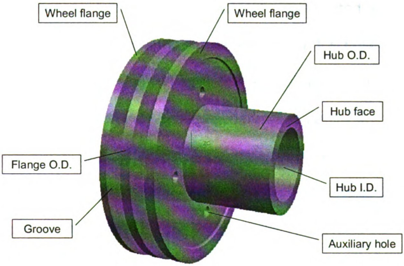
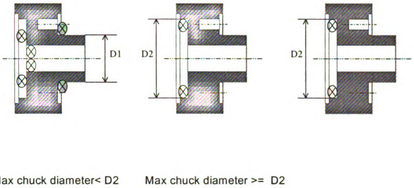


Figure 12. Basic Features of a typical pulley



(a) Machine M1:
Turning Center

(b) Machine M2:
Turning Center

(c) Machine M3:
Machining Center

Figure 13. Alternative Processes depending on the assigned machine

The general features of a pulley are shown in Figure 12. Figure 13 shows the alternative processes for the task, machining, generated for each of three machines assigned to machine the wheel and hub of the pulley with the circular holes. In Figure 13, machine M1 and M2 are turning centers, while M3 is a machining center. For M1 and M2, additional milling center are required to finish all of the features of circular holes. If the machining center is not available, the processes related to a machining center can be disregarded. Other alternative processes will be evaluated by the constraints coming with the turning center, such as **Prh-Chuck-Diameter** and **Prh-Tolerance**.

Table 6 illustrates the alternative processes generated by each of the machines assigned. Alternative 3 is for the machining center in which all features can be done with only one setup. Alternative 1 and alternative 2 are the processes for the turning center. The bigger chuck diameter enables it to finish all the features with fewer setups.

A relationship between machine constraints and feature constraints exists. The prohibition constraints of an assigned machine such as **Prh-Tolerance**, **Prh-Shape-Type** and **Prh-Hole-Diameter** must be related to the feature constraints such as **Req-Tolerance**, **Req-Shape-Type**, and **Req-Hole-Diameter** as follows:

Req-Tolerance $\subseteq$ **Prh-Tolerance**

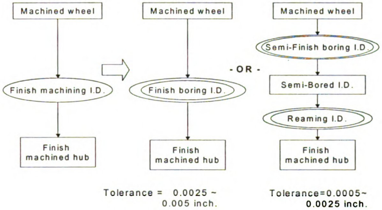
Req-Shape-Type $\subseteq$ **Prh-Shape-Type**

Req-Hole-Diameter $\subseteq$ **Prh-Hole-Diameter**

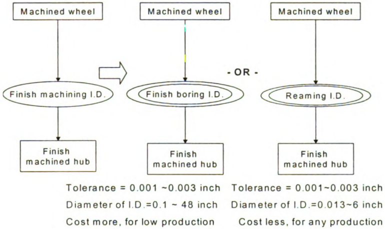
Above relationships represent that if a machine can accomplish a design feature of a part, the design requirement (tolerance, shape-type, or hole-diameter) of the feature will lie in (or belong to) the capability range (tolerance, shape-type, or hole-diameter) of the machine. For example, **Req-Tolerance** represents the tolerances of design features of a part, while **Prh-Tolerance** defines the tolerance range of features that a machine can accomplish. If a designed hole has a tolerance of 0.001 inch and a turning lathe can boring a hole with a smaller tolerance up to 0.0005 inch; since the designed hole tolerance belongs to the tolerance range of the turning lathe, the turning lathe could be used to produce the hole.

Table 6. Alternative processes due to the assigned machine(s)

Alternative 1 (M1 and drilling machine)		Alternative 2 (M2 and drilling machine)		Alternative 3 (M3)	
Setup 1	1.Turning flange O.D.	Setup 1	1.Turning flange O.D.	Setup 1	1.Turning flange O.D.
	2.Facing front flange		2.Facing front flange		2.Facing front flange
	3.Facing hub face		3.Facing hub face		3.Facing hub face
	4. Turning hub O.D.		4.Turning hub O.D.		4.Turning hub O.D.
	5.Grooving groove				
Setup 2	6.Facing flange		5. Facing rear flange		5. Facing rear flange
	7.Facing bottom face		6.Grooving groove		6.Grooving groove
	8. Rough and semi-finish boring I.D.		7. Rough and semi-finish boring I.D.		7. Rough and semi-finish boring I.D.
	9. Reaming I.D.		8.Reaming I.D.		8.Reaming I.D.
Setup3	11.Drilling auxiliary hole	Setup2	9.Drilling auxiliary hole		9.Drilling auxiliary hole
	12.Tapping thread		10.Tapping thread		10.Tapping thread



(a) Cincinnati turning machine



(b) Drilling machine [8]

Figure 14. Change of constraints and alternative processes depending on the assigned machine

3.4.3 Process

Many of the constraints are related to the process capabilities such as the geometry shape (**Sug-Shape-Type**) and dimensional tolerance (**Sug-Tolerance**). When a specific process type is considered, its related constraints may be applied. Drilling and casting are alternative processes for producing the internal diameter for a pulley. The associated constraints for drilling or casting may be applied to evaluate the alternative processes. The constraint **Sug-Drill-Diameter** helps to identify the maximum drill diameter and to determine if the hole can be accomplished directly by drilling. The constraint **Sug-Tolerance** and **Sug-Material** can be applied to choose the specific casting process (e.g.: sand casting or die casting) for producing the hole based on the tolerance requirement (**Req-Tolerance**) of the hole and the material requirement (**Req-Material**) of the pulley.

A relationship exists between the process constraints and the feature constraints. When planning the machining process for the hole of a pulley, some relationships may be described as following:

Req-Hole-Diameter $\subseteq$ **Sug-Hole-Diameter**

Req-Tolerance $\subseteq$ **Sug-Tolerance**

Req-Shape-Type $\subseteq$ **Sug-Shape-Type**

For drilling process, the following relationship, **Req-Hole-Diameter** $\subseteq$ **Sug-Drill-Diameter**, must be considered instead.

These relationships represent that if a process can be chosen to produce a design feature of a part, the design requirement (tolerance, shape-type, or hole-diameter) of the feature will lie in (or belong to) the capability range (tolerance, shape-type, or hole-diameter) of the process.

3.5 Process Reconfiguration with Constraint Hierarchy

Constraint hierarchy provides a useful tool to help to reconfigure the process due to the change of manufacturing systems such as buying a new machine, developing a new process, and installing a new manufacturing system. Only the constraints affected by the change need to be re-evaluated. The hierarchy structure of constraint helps to identify the constraints that are re-evaluated and to reconfigure the processes efficiently.

3.5.1 Machine Assignment

Figure 14 shows how the assignment of a new machine can affect the constraints in choosing a process. At least two alternative processes for the task of Finish Machining Internal Diameter (I.D.) exist. If a turning machine is assigned as in Figure 14 (a), then the constraint **Prh-Tolerance** under the machine element must be used. Each alternative process produces its tolerance for the I.D. However, if a drilling machine is assigned, both alternative processes shown in Figure 14(b) can produce the same tolerance. Therefore, the constraint **Prh-Tolerance** is not enough to decide between the alternatives since no difference can be found. Another constraint in the machine element, **Sug-Hole-**

Diameter, may be used. If the given hole-diameter can be produced with two alternative processes, another constraint in the production element such as **Min-Cost-Machining** has to be evaluated.

Table 7. Constraints associated to the tasks

Tasks	Constraints level		
	Level 2	Level 3	Level 4
Quotation process	Production	Min-Cost, Min-Time	
Find suppliers	Production	Min-Cost	Min-Cost-Casting, Min-Cost-Gauge, Min-Cost-Tool
Machining	Production, feature	Min-Cost, Req-tolerance	Min-Machining-Cost
Machining process	Machine, feature, process	Turning-machine, Req-shape-type, Req-Hole-Diameter	Prh-Process-Machine, Prh-Hole-Diameter, Sug-Drill-Diameter, Sug-Hole-Diameter

3.5.2 Constraints related to Process Hierarchy

Table 7 shows some tasks in the process hierarchy and the related constraints at different levels in the constraint hierarchy. For reconfiguring the process, the constraints at a specific level can be applied on the task at an appropriate level to evaluate the alternative processes. When planning the task "Machining", we may apply the production constraints such as **Min-Machining-Cost** and the feature constraints such as **Req-Tolerance** to choose alternative processes. However, for executing the lower level task "Machining Process", we need to apply the machine constraints such as **Prh-Process-Machine** and **Prh-Hole-Diameter**, feature constraints such as **Req-Shape-Type** and **Req-Hole-Diameter**, and process constraints such as **Sug-Drill-Diameter** and **Sug-Hole-Diameter** to choose a suitable alternative process.

Table 7 illustrates the possible relationship between process hierarchy and the constraint hierarchy shown in Figure 10 and Figure 11. The constraint at a different level in the constraint hierarchy may be associated with the process task at an appropriate level in the process hierarchy. The levels of constraints present the priorities of the constraint to be applied on a process task. The lower is the level (with a higher number), the higher priority has the constraint. The lower-level constraints should be applied first on a process task before applying higher-level constraints on the task. A process task at a higher abstract level could use an upper-level constraint to evaluate the alternative processes. If a constraint is affected by some change, only its associated constraints at upper levels (with a lower number) need to be reevaluated for their associated process tasks. Thus, the constraint hierarchy may help to identify the specific constraints for the process reconfiguration as the change in the manufacturing system affects the process.

3.6 Conclusion

In this paper, the hierarchy structures of both process models and the constraints in a manufacturing environment are presented. The grammar-based approach exhibits the following attractive features: (1) it captures and represents the manufacturing process at any level of abstraction. This will help engineers to understand the overall process and explore more detailed processes, if desired. (2) It provides an effective method to reconfigure the processes with the constraints affected by any change in manufacturing. (3) It constructs a necessary foundation for an open-architecture system that manages the overall process in a manufacturing environment.

Chapter 4

IMPLEMENTATION OF PROCESS SELECTION

In Chapter 3, both processes and constraints are represented in a hierarchy structure and shown the effectiveness of the structure in a real manufacturing environment. The hierarchies represent the relationships among the processes and the constraints in the manufacturing environment. The proposed grammatical approach can not only represent the processes in a hierarchical structure but also capture and model the constraints in a hierarchical structure. The constraint hierarchy may help us to reduce the number of alternative processes and even to select an appropriate alternative process at any level of abstraction. However, a major obstacle in implementing the hierarchies is how to select a suitable process among many alternatives. A decision-making method with the hierarchy structures intact (without getting into more detailed processes) is required for the process selection problems in a complex manufacturing environment.

4.1 Introduction

4.1.1 Decision Making Method for Hierarchies

The Analytic Hierarchy Process (AHP) developed by Saaty [1980] is one of the multi-criteria decision making methods that decomposes a complex problem into a hierarchical order. Three important steps for AHP are (1) structuring the problem as a hierarchy consisting of a goal and subordinate elements (decomposition), (2) making a pair-wise comparison between elements at each level to determine the preferential order of the elements (evaluation), and (3) propagating level-specific, local priorities to global priorities through matrix algebra (synthesis). Subordinate levels of the hierarchy may include objectives, scenarios, events, actions, outcomes, and alternatives. Alternatives to be compared appear at the lowest level of the hierarchy. A decision at a higher level will be made based on the global priorities of alternatives that are calculated through matrix algebra beginning from a lower level. Pair-wise comparisons are made between elements at a particular level with respect to elements in the level above it.

When structuring a hierarchy for manufacturing related problems with the AHP method, the subordinate levels of the hierarchy may include objectives, constraints, and alternatives. These three constituents have been identified in this study. The subordinate elements in the hierarchy could be processes, constraints for evaluating alternatives, machines, organizations, and materials.

The AHP method presented by Saaty [1980] can be described as follows. Given the elements (like constraints) of one level in a hierarchy and one element (like process) of the next higher level, the elements of constraints are compared pair-wise in their strength of influence on the process. Numbers reflecting the result of the comparison are inserted into a matrix to find the eigenvector with the largest eigenvalue. The eigenvector represents the priority ordering of each constraint element on the process, and the eigenvalue is a measure of the consistency of the judgment.

The pairwise comparison between elements helps to determine the priority importance of the elements with respect to one element of the next higher level. The relative importance can be denoted by a_{ij}, the number indicating the strength of element i when compared with element j. The matrix of these elements is denoted A, or

$$A = (a_{ij}) \tag{4.1}$$

The weights ($w_1, \ldots, w_n$) are the measurements of the priority importance of elements ($1, \ldots, n$) with respect to one element of the next higher level. The larger the weight, the more important is the element. Therefore, a_{ij} represents the ratio of the weight of element i to element j. It is known as

$$a_{ij} = w_i/w_j \qquad i, j = 1, \ldots, n \tag{4.2}$$

For the decision-making problems with hierarchies, we want to determine the weights of hierarchy elements at each level. With the matrix consisting of a_{ij}, the estimated weight vector w is found by solving the following eigenvector problem:

$$Aw = \lambda_{max} w \tag{4.3}$$

where the matrix $A=(a_{ij})$, and λ_{max} is the largest eigenvalue of A. In the consistent case, there exists $a_{ik} = a_{ij} \cdot a_{jk}$ for all *i*, *j*, and *k*; then *n* (the order of matrix) is the only non-zero eigenvalue of A, and obviously *n* is the largest eigenvalue, λ_{max}, [Saaty 1980]. Thus, we can use the equation (4.3) to find the eigenvector ***w***. In the inconsistent case, the equation $a_{ik} = a_{ij} \cdot a_{jk}$ may not exist; i.e., if the relative importance of element 1 is greater than that of element 2 and the relative importance of element 2 is greater than that of element 3, then the relation of importance of element 1 need not be greater than that of element 3, a common occurrence in human judgments. Thus, the largest eigenvalue, λ_{max}, of the matrix A is not equal to its order *n*. The largest eigenvalue is the measure of the consistency of the matrix A: the closer the largest (or principal) eigenvalue close to *n*, the more consistent of the matrix A is. Therefore, if the largest eigenvalue closes to *n*, we can still use the equation (4.3) to find the approximate eigenvector *w*. Some concepts are used to evaluate the consistence of the result, as presented later.

The eigenvector, *w,* represents the priority ordering, which can be normalized by making all numbers in the eigenvector to be summed up to unity. Each number is divided by the sum of all number in the eigenvector. In this chapter, the weights are obtained by normalizing the eigenvector of the largest eigenvalue of the evaluated matrix. **Alternative weights** represent the priorities of alternatives with respect to one constraint of the next higher level; **constraint weights** represent the priorities of constraints with respect to one objective of the next higher level; and **global weights** represent the priorities of alternatives with respect to the objective.

4.1.2 Consistency Analysis

There are several concepts used for consistency analysis with the AHP method [Saaty 1980]: *Consistence Index* (C.I.), *Random Index* (R.I.), and *Consistence Ratio* (C.R.). They are represented as following:

- **Consistence Index:** it represents the deviation from consistency, which can be calculated by $(\lambda_{max} - n)/(n-1)$, λ_{max} is the largest eigenvalue of the matrix, and n is the order of the matrix.
- **Random index:** it is the average consistency index of a randomly generated matrix from the scale 1 to 9. Its value varies depending on the matrix order. Table 8 gives the order of the matrix and the average R.I. [Saaty 1980].

Table 8. Random index of the matrix

Matrix order	1	2	3	4	5	6	7	8
Random Index	0	0	0.58	0.90	1.12	1.24	1.32	1.41

- **Consistence Ratio:** it is the ratio of C.I. to average R.I. for the same order matrix, which is calculated by ***C.R. = C.I./R.I.***. For practical problems, the decision matrix is considered to be consistent if has a consistency ratio of 0.10 or less, which means C.R.<0.1.

With the consistence ratio, we can evaluate the result (weight vector) calculated from the matrix of elements. If the matrix is consistent, the weight vector is acceptable, otherwise, the matrix needs to be revised; and the judgment of relative importance between elements needs to be modified.

4.1.3 Application of AHP on Manufacturing Problems

The process selection in a real manufacturing environment is a multi-criteria decision making problem. When evaluating each alternative process, many constraints have objective or subjective values. These constraints are the criteria to decide on an optimum process. As one of multi-criteria decision making approaches, the AHP method uses a ratio scale to quantify relative weights for a given set of criteria, which are represented in a hierarchy structure. Two features differentiate AHP from other decision-making approaches [Akarte et al. 2001]: (1) it provides a comprehensive structure to combine the intuitive objective and subjective values during the decision making process, (2) it can judge the consistency in the decision-making process.

The AHP method has been used on various manufacturing related problems. Valerie and Hu [2002] used AHP for the problem of choosing manufacturing system configurations with consideration of multiple performance criteria: productivity, quality, convertibility, and scalability. Rangone [1996] stated that the AHP framework could effectively compare the performance of manufacturing departments. The overall performances are evaluated in three aspects: quality, flexibility, and environmental compatibility. Luong [1998] combined the AHP and database technology on a decision support system for the selection of computer integrated manufacturing technologies. Tiwari and Banerjee [2001] presented an AHP based decision support system to select the most suitable casting process for a given product. Akarte et al. [2001] also discussed the selection of a casting supplier by identifying the criteria for casting supplier assessment and segregating them in four groups: product development capability, manufacturing capability, quality capability, and cost and delivery. They implemented the AHP method on a prototype web-based system. Chan [2003] further discussed an interactive selection model for supplier selection process by systemizing the earlier steps, such as the determination of buyer-supplier relationships and formation of selection criteria before the implementation of the AHP. Yurdakul and Cogun [2003] developed a multi-attribute selection procedure with AHP for non-traditional machining processes. Abdi et al. [2003] presented a design strategy for reconfigurable manufacturing systems. They applied the AHP model on structuring the decision-making process for the selection of a manufacturing system among feasible alternatives based on the RMS study. The summary of the applications on manufacturing problems is described in Table 9.

Table 9. Application of AHP on manufacturing problems

Groups	Manufacturing problems	Performances		Others
		Criteria	Sub-criteria	
Rangone (1996)	Selection of manufacturing department	• Quality • Flexibility • Environmental compatibility	Conformance rate, inspection costs, rationalization degree, product flexibility, volume flexibility, technology flexibility, solid waste, energy consumption, factory green image	
Luong (1998)	Selection of CIM technologies (such as CAD, GT, CNC, FMS, CAPP, MRP)	• Increased mfg lead time • Increased productivity • Reduced inventory and work in progress • Increased quality (reduced scraps and rework) • Increased flexibility • Increased integration in the company		Combined with database technology (EXCEL); Consider the company characteristics (production type and main function of a company)
Tiwari and Banerjee (2001)	Selection of casting process (such as sand casting, die casting, shell molding)	• Material suitability & flexibility • Geometrical complexity • Dimensional accuracy & surface finish • Cost		
Akarte, Surendra, Ravi, and Rangaraj (2001)	Selection of casting supplier (Web-based)	• Product development capability • Mfg capability • Quality Capability • Cost and time	Maximum casting size, minimum section thickness, casting complexity, software aid; pattern making, sand preparation, molding, core making, melting and pouring; heart treatment, machining, dimensional tolerance, surface roughness, testing facilities; quality certification, quality awards, total casting cost, sample delivery time	Combined with a web-based approach to evaluate the casting supplier.
Valerie and Hu (2002)	Selection of manufacturing system configurations	• Productivity • Quality • Convertibility • Scalability	Expected production, Mean deviation, standard deviation, number of flow-paths, minimum increment, cost/increment	
Chan (2003)	Interactive selection of supplier	(Criteria at different levels) Cost, quality, design capability, technical capability, technological capability, performance history, management capability, degree of cooperation, financial performance, degree of closeness		Before selection, the buyer-supplier relationships need to be determined to form selection criteria
Yurdakul and Cogun (2003)	Selection of non-traditional machining processes (such as AJM, WJM, etc.)	Tolerance, surface finish, surface damage, corner radii, taper, hole diameter, depth/diameter ratio (for cylindrical holes), depth/width ratio (for blind cavities), width of cut, material removal rate		
Abdi and Labib (2003)	Selection of manufacturing systems (DMS, FMS, RMS)	Level 1: planning horizons (long/medium/short term); L2: decision makers (plant manager/shop floor manager/mfg designer); L3: objectives (responsiveness/product cost/product quality/inventory/operator skills); L4: sub-criteria of L3.		A design strategy for RMS is presented.

As shown in Table 9, the criteria used for each manufacturing problem are different. When selecting a suitable process among alternatives, different criteria must be used for each manufacturing process due to the difference in the problems of each process. Table 9 shows the main fields in which AHP could be applied for following manufacturing problems:

- Selection of organizations such as company or internal department
- Selection of resources such as machines or suppliers
- Selection of manufacturing systems such as FMS, RMS, DMS
- Selection of configurations for a specific system
- Selection of processes and CIM technologies

There are two ways of matching machine alternatives for processes:

- Associate each machining process with alternative machines in which the process can be carried on.
- Associate each machine with alternative processes that the machine can carry on.

However, Rebstock and Kaula [2003] presented that there is no single hierarchy for particular problems such as supplier selection and process selection. For example, it is difficult to construct a hierarchy diagram to evaluate hundreds of alternative processes at one level and make a selection with all the criteria needed.

Considering the characteristics of the grammar-based approach, it is possible to decompose a complex process where an engineer has to make many selections among many alternatives into a smaller number of selections at any abstract level [Zeng et al. 2003]. Thus, the AHP method combined with the grammar-based approach becomes a convenient solution for the process selection problem.

In this chapter, we will apply the AHP on the process selection problem for the shop-floor environment. First, a hierarchy model is established with the process constraints and machine constraints, which are used to evaluate alternative processes and machines. The performances of each candidate process/machine are then evaluated. Several case studies using the AHP method will be described in this chapter.

4.2 Multilevel Multiple Criteria Decision Making (MMCDM) Model

The process selection could be a complex problem when selecting both a process and machines. Various constraints are used to evaluate each alternative processes as well as alternative machines. It is difficult to make a selection by considering all alternatives at the same time. In many situations, the selected process does not guarantee that the selected process is the most optimum one.

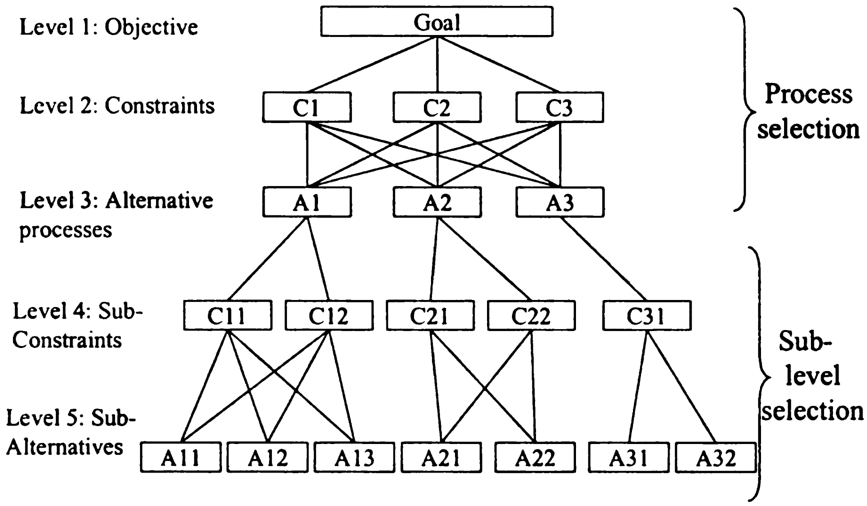


Figure 15. Multilevel Multiple Criteria Decision Making (MMCDM)

Figure 15 shows a multi-level decision model. The main goal is to select a suitable process among alternative processes after evaluating the constraints (or criteria) at level 2. In addition, more selection processes will be required in order to identify suitable machines to carry out the alternative processes, or to choose sub-processes for each alternative process. The machines or sub-processes are the sub-alternatives to be evaluated by the sub-constraints at level 4. Thus, in Figure 15, the decision making model shows the selections at two abstract levels. The first level is the process selection without the details of machines or sub-processes. The second level is a selection, sub-alternative selection, to choose suitable machines or sub-processes with more details involved. More selections at lower levels may be required when other detail information is captured. This model avoids making a selection among many alternatives. It decomposes a complex selection problem as a hierarchy selection problem. Many selections with many alternatives are decomposed into a smaller number of selections at any abstract level with reasonable constraints evaluating reasonable alternatives.

With this multilevel multiple criteria decision making (MMCDM) model, we can use the AHP method and the process/constraint hierarchy to represent a complex selection process as several simple selection processes in the hierarchical order by evaluating quantitative and/or qualitative constraints. The following case studies will describe the detail evaluation.

4.3 A Case Study for Applying MMCDM

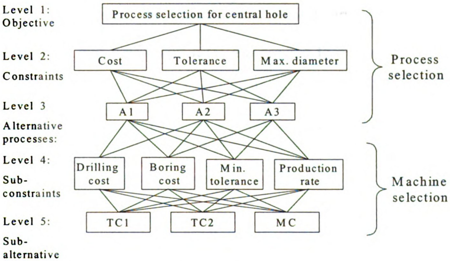


Figure 16. Case study of MMCDM

As shown in Figure 16, a five-level hierarchy shows how to select a process for producing a hole with suitable machines. Level 1 represents the objective. Level 2 represents the process constraints for evaluating alternative processes at level 3. Level 4 contains the machine constraints for evaluating alternative machines at level 5. In order to produce a central hole for a pulley, three alternative processes (A1, A2, and A3) are represented as following:

- **A1 (casting, drilling, and boring):** drilling and boring are used to finish the inner diameter with a casting hole.
- **A2 (cutoff, drilling, and boring):** drilling and boring are required to finish the inner diameter with the blank from the cutoff of a bar stock.
- **A3 (casting, boring):** boring is used to finish the inner diameter with a casting hole.

The constraints at level 2, such as *cost*, *tolerance*, and *maximum diameter* (of the hole), are applied to evaluate the alternative processes. Before choosing the suitable alternative process, a suitable machine should be selected with respect to each alternative process. The constraints at level 4 (drilling cost, boring cost, minimum tolerance, and production rate) are applied to evaluate the alternative machines: two turning centers (TC1 and TC2) and one machining center (MC). The AHP method will be used to select a suitable process for producing the hole with the most suitable machine.

Figure 16 shows a two-level selection model. The low-level selection, called machine selection, chooses a suitable resource (machine) for each alternative process of the next high level. The high-level selection, called the process selection, chooses a suitable alternative process with the selected resource (machine) to achieve the final objective. Therefore, the two-level selection process always selects the best option at each level, which guarantees an acceptable use of the selected process in the shop floor. The selected alternative process at a higher level will use the most suitable machines at a lower level.

4.3.1 Solution Procedure

Step1:

When evaluating the alternatives with objective constraints (i.e. the constraints of cost, tolerance, and production rate), we can obtain the alternative weights of the alternatives by using following rules:

1. If the maximum value is desirable, the alternative weights can be calculated by normalizing the values.
2. If the minimum value is desirable, the alternative weights can be calculated by normalizing the reciprocal of values.

As shown in Tables 10A-10C, both the cost and the tolerance constraints prefer the minimum value, so the alternative weights for them are calculated by normalizing the reciprocal of the values. In Table 10D, the production rate prefers the maximum value, so the alternative weights are calculated by normalizing the values of all machines directly.

Table 10. Relative priorities with respect to objective constraints

Table 10A. Relative priorities with respect to **drilling cost (minimum prefer)**

	Drilling cost ($)	Reciprocal	Alternative weights
TC1	2	0.5	**0.273**
TC2	1	1	**0.545**
MC	3	0.33	**0.182**

Table 10B. Relative priorities with respect to **boring cost (minimum prefer)**

	Boring cost ($)	Reciprocal	Alternative weights
TC1	1	1	**0.545**
TC2	2	0.5	**0.273**
MC	3	0.33	**0.182**

Table 10C. Relative priorities with respect to **tolerance (minimum prefer)**

	tolerance	Reciprocal	Alternative weights
TC1	0.001	1000	**0.25**
TC2	0.001	1000	**0.25**
MC	0.0005	2000	**0.5**

Table 10D. Relative priorities with respect to **production rate (maximum prefer)**

	Production rate (unit/hr)	Alternative weights
TC1	100	**0.143**
TC2	100	**0.143**
MC	500	**0.714**

The alternative weight vectors from above tables are put into a matrix (alternative matrix):

$$M1 := \begin{pmatrix} 0.273 & 0.545 & 0.25 & 0.143 \\ 0.545 & 0.273 & 0.25 & 0.143 \\ 0.182 & 0.182 & 0.5 & 0.714 \end{pmatrix}$$

Tables 10A-10D represent the relative priorities of alternative machines with respect to the different constraints. The alternative weight vectors for the alternative machines with respect to all constraints are put into a matrix, called the **alternative matrix**, for the machines.

Step 2:

The constraints used to evaluate alternative machines may be:

- **Drilling cost**, or **boring cost**: the cost of a process carried out by a machine.
- **Minimum tolerance**: the best tolerance for a feature that can be produced by a machine.

- **Production rate**: the number of the part finished by a machine in a limit time.

The relative importance between constraints is obtained from the judgment of experts. The values related to the judgment can be set based on Table 11. Table 11 presents the scale of relative importance, which was defined by Saaty [1980] for pair-wise comparison. A value within a 1-9 scale is assigned to represent the relative importance between two constraints. With the values obtained from pair-wise comparison among the constraints, we can put them into a matrix, called the **comparison matrix**, to find the eigenvector for the largest eigenvalue of the matrix. The eigenvector will represent the weights of the constraints.

Table 11. Scale of relative importance

Intensity	Definition	Intensity	Definition
1	Equal importance	7	Very strong importance
3	Moderate importance	9	Extreme importance
5	Strong importance	2,4,6,8	Intermediate values

Tables 12A-12C show three comparison matrixes with respect to alternative processes A1, A2, and A3 respectively. For each alternative process, the relative importance among constraints can be different, since the decision maker may have a different opinion to the same constraints. For example, the constraint of the production rate for alternative process A1 has a bigger importance than that of alternative process A2; thus, in the comparison matrix, a bigger value (0.5) is assigned to the production rate for A1 than that (0.33) for A2. Therefore, the three comparison matrixes represent the different relative importance between the constraints with respect to the alternative processes.

The comparison matrix of the same constraints could be different for each alternative process. Because the same constraints may have a different influence on each alternative process, the relative importance and the weights of the constraints for each alternative process are also different. For each alternative process, the weights of the constraints are obtained by normalizing the eigenvector of the largest eigenvalue of the comparison matrix. The weight vectors for the constraints with respect to all alternative processes can be grouped into a matrix, called the **constraint matrix**. In the constraint matrix, if some constraint is not used to evaluate the machines, such as the constraint of drilling cost in Table 12C, it indicates a zero value for the constraint weight of the drilling cost with respect to the alternative process A3.

Table 12. Relative priorities of constraints with respect to alternative processes

Table 12A. Relative priorities of constraints with respect to A1 (C.R.=0)

	Drilling cost	Boring cost	Tolerance	Production rate	Eigenvector (weights)	Constraint weights
Drilling cost	1	1	0.5	2	0.4	**0.2222**
Boring cost	1	1	0.5	2	0.4	**0.2222**
Tolerance	2	2	1	4	0.8	**0.4444**
Production rate	0.5	0.5	0.25	1	0.2	**0.1111**

Table 12B. Relative priorities of constraints with respect to A2 (C.R.=0.156>0.1, inconsistent)

	Drilling cost	Boring cost	Tolerance	Production rate	Eigenvector (weights)	Constraint weights
Drilling cost	1	1	0.25	3	0.351	**0.2042**
Boring cost	1	1	0.25	3	0.351	**0.2042**
Tolerance	4	4	1	2	0.85	**0.4916**
Production rate	0.33	0.33	0.5	1	0.177	**0.1024**

Table 12C. Relative priorities of constraints with respect to A3

	Boring cost	Tolerance	Production rate	Eigenvector (weights)	Constraint weights
Boring cost	1	1	2	0.667	**0.4001**
Tolerance	1	1	2	0.667	**0.4001**
Production rate	0.5	0.5	1	0.333	**0.1998**

The constraint weight vectors from above tables are put into a matrix (constraint matrix):

$$M2 := \begin{pmatrix} 0.2222 & 0.2042 & 0 \\ 0.2222 & 0.2042 & 0.4001 \\ 0.4444 & 0.4916 & 0.4001 \\ 0.1111 & 0.1024 & 0.1998 \end{pmatrix}$$

The consistency of the comparison matrixes can be evaluated using the consistency ratio (C.R.) represented in section 4.1.2. With the largest eigenvalue of the matrix obtained through matrix calculation, the consistency analysis of the matrixes in Tables 12A-12C are shown as the following:

Table 12A: the largest eigenvalue $\lambda_{max} = 4$, the consistency index *C.I. = (λ-n)/(n-1)=(4-4)/(4-1)=0*, and the random index *R.I.=0.9 (matrix order n=4)*; thus the consistency ratio *C.R.=C.I./R.I. = 0 <0.1*; the comparison matrix is consistent.

Table 12B: $\lambda_{max} = 4.422$, *C.I. = 0.141, R.I.=0.9, C.R.= C.I./R.I. = .156 >0.1* Thus the matrix is inconsistent; a new judgment value among all constraints may be required.

Table 12C: $\lambda_{max} = 3$, *so C.I.=0, R.I.=0.58, C.R.=0.* The comparison matrix is consistent.

Step 3:

The matrixes obtained from steps 1-2 are multiplied as the following:

$$M1 := \begin{pmatrix} 0.273 & 0.545 & 0.25 & 0.143 \\ 0.545 & 0.273 & 0.25 & 0.143 \\ 0.182 & 0.182 & 0.5 & 0.714 \end{pmatrix} \qquad M2 := \begin{pmatrix} 0.2222 & 0.2042 & 0 \\ 0.2222 & 0.2042 & 0.4001 \\ 0.4444 & 0.4916 & 0.4001 \\ 0.1111 & 0.1024 & 0.1998 \end{pmatrix}$$

$$M1 \cdot M2 = \begin{pmatrix} 0.309 & 0.305 & 0.347 \\ 0.309 & 0.305 & 0.238 \\ 0.382 & 0.393 & 0.416 \end{pmatrix}$$

The alternative matrix M1 is a 3 by 4 matrix that represents the alternative weights of three alternative machines with respect to four machine constraints. The constraint matrix M2 is a 4 by 4 matrix that represents the constraint weights of four constraints with respect to four alternative processes. Table 13 shows the result obtained from the matrix multiplication. The result represents the global weights (or overall priority) of each machine with respect to alternative processes. As shown in Table 13, the machine center is the best option for all alternative processes A1, A2, and A3, since it has the biggest overall priority: 0.382, 0.393, and 0.416.

Table 13. Global weight of machine with respect to the process

Overall priority	**Process A1**	**Process A2**	**Process A3**
TC1	0.309	0.305	0.347
TC2	0.309	0.305	0.238
MC	**0.382**	**0.393**	**0.416**

Step 4:

As the suitable machines are selected for all alternative processes, another selection procedure similar to that in steps 1-3 is made for the process selection at the next higher level. The data (i.e. actual cost and tolerance) related to the selected machines will be transformed to the higher level for further comparison.

Assuming the casting cost is $4 per unit, Table 14 represents the relative priorities of alternative processes with respect to the different process constraints. The alternative weight vectors for alternative processes with respect to all constraints are grouped into an alternative matrix, M3, for the processes.

Table 14. Attributes of alternatives based on selected sub-alternative

	Cost ($)	Tolerance (inch)	Maximum diameter (inch)
A1	10	0.0005	8
A2	6	0.0005	2
A3	7	0.001	50

Table 14A. Relative priorities with respect to **cost (minimum prefer)**

	Cost	Reciprocal	alternative weights
A1	10	0.1	**0.2439**
A2	6	0.167	**0.4073**
A3	7	0.143	**0.3488**

Table 14C. Relative priorities with respect to **max. diameter (maximum prefer)**

	Max. diameter	Alternative weights
A1	8	**0.1333**
A2	2	**0.0333**
A3	50	**0.8333**

Table 14B. Relative priorities with respect to **tolerance (minimum prefer)**

	Tolerance	Reciprocal	Alternative weights
A1	0.0005	200	**0.4**
A2	0.0005	200	**0.4**
A3	0.001	100	**0.2**

The alternative weight vectors from above tables are put into a matrix (alternative matrix):

$$M3 := \begin{pmatrix} 0.2439 & 0.4 & 0.1333 \\ 0.4073 & 0.4 & 0.0333 \\ 0.3488 & 0.2 & 0.8333 \end{pmatrix}$$

Step 5:

The constraints used here for process selection are *cost*, *tolerance*, and *maximum diameter* of the hole. As shown in Table 15A, the comparison matrix represents the result of pair-wise comparison of the relative importance among constraints. With the constraint weight vector calculated from the comparison matrix, the constraint matrix M4, a 3 by 1 matrix, is obtained. It represents the relative importance of the constraints with respect to the goal. When multiplying M4 by the alternative matrix M3 from left side, the overall priority for each alternative process can be obtained, as shown in Table 15B.

Table 15A. Rrelative priorities with respect to the goal

	Cost	Tolerance	Max. diameter	Eigen vector (weights)	Constraint weights
Cost	1	2	4	0.873	0.5717
Tolerance	0.5	1	2	0.436	0.2855
Max. diameter	0.25	0.5	1	0.218	0.1428

Table 15B. Selection of alternative process for the goal

Alternative	**Global weight**
A1	Priority=0.2439*0.5717+0.4*0.2855+0.1333*0.1428=0.273
A2	Priority=0.4073*0.5717+0.4*0.2855+0.0333*0.1428=0.352
A3	Priority=0.3488*0.5717+0.2*0.2855+0.8333*0.1428= 0.376 (selected)

Thus, the alternative A3 (Casting + Boring) will be selected with the biggest priorities.

The constraint weight vector in Table 15A is put into a matrix (constraint matrix):

$$M4 := \begin{pmatrix} 0.5717 \\ 0.2855 \\ 0.1428 \end{pmatrix}$$

Table 15B shows the result of matrix multiplication M3*M4.

4.4 Modification of Matrix for AHP Method

When applying the AHP method on the process selection problems in a real manufacturing environment, some problems may exist:

a) How can a constraint matrix be constructed if some sub-objectives require only part of the constraints instead of all constraints to evaluate the alternatives?
b) How can an alternative matrix be constructed with respect to the constraints if some constraints exclude some particular alternatives?

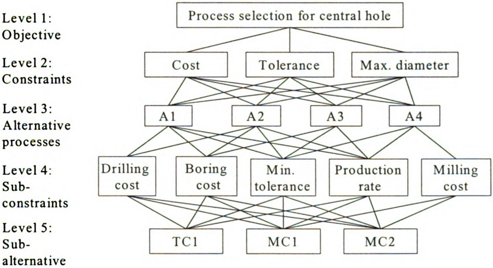
To solve the above problems, we use following methods to construct the matrix or revise the result of the matrix multiplication as needed.

1) For the constraint matrix, if one of the sub-objectives does not use some constraint to evaluate the alternatives, the constraint weight of the constraint with respect to that sub-objective will be assigned zero value in the constraint matrix.
2) For the alternative matrix, if one of the alternatives is excluded by some constraint, the alternative weight of the alternative with respect to the constraint will be assigned zero value in the alternative matrix.
3) For the result of matrix multiplication between the alternative matrix and the constraint matrix, if there exists a zero value in the alternative matrix, assuming $a_{ij}=0$, and at the same time, there exists an item $b_{jk} \neq 0$ in the constraint matrix; the result of the matrix multiplication needs to be revised: the item of the result matrix at the *i*th row and the *k*th column will be changed to zero value. This change means that if an alternative is excluded by a constraint that has a non-zero influence on one objective, the alternative will not have any influence on the same objective.

The application of above rules will be demonstrated with the cases.

4.4.1 Case Study without Matrix Modification

Figure 17 shows a case where a new alternative process A4 and a new constraint of milling cost are introduced comparing it to the case in section 4.3. The process A4 uses casting and milling to produce the center hole of the pulley. The alternative machines are one turning center, TC1, and two machining centers, MC1 and MC2. In Figure 17, the constraints at level 4 are not used to evaluate some alternatives at level 5. Turning center TC1 is excluded by the constraint milling cost, because it cannot carry on the milling process. Thus, a different alternative matrix must be constructed in such situation. The relative priorities in Tables 16A-16E are different from those in Tables 10A-10E.



1. A1: Casting+Drilling+Boring; A2: Cutoff+Drilling+Boring; A3:Casting+Boring; A4:Casting+Milling.
2. Turning center: TC1; Machine Center: MC1 and MC2

Figure 17. Case Study 2

Table 16. Relative priorities with respect to drilling cost, boring cost, tolerance, production rate, and milling cost without matrix modification

Table 16A. Relative priorities with respect to **drilling cost (minimum prefer)**

	Drilling cost ($)	Reciproca l	Alternative weights
TC1	2	0.5	**0.273**
MC1	1	1	**0.545**
MC2	3	0.33	**0.182**

Table 16B. Relative priorities with respect to **boring cost (minimum prefer)**

	Boring cost ($)	Reciprocal	Alternative weights
TC1	1	1	**0.545**
MC1	2	0.5	**0.273**
MC2	3	0.33	**0.182**

Table 16C. Relative priorities with respect to **tolerance (minimum prefer)**

	Tolerance	Reciprocal	Alternative weights
TC1	0.001	1000	**0.25**
MC1	0.001	1000	**0.25**
MC2	0.0005	2000	**0.5**

Table 16D. Relative priorities with respect to **production rate (maximum prefer)**

	Production rate (unit/hr)	Alternative weights
TC1	100	**0.143**
MC1	100	**0.143**
MC2	500	**0.714**

Table 16E. Relative priorities with respect to **milling cost**

	Milling cost ($)	Reciprocal	Alternative weights
MC1	5	**0.2**	**0.667**
MC2	10	**0.1**	**0.333**

For A1, there are four constraint required, assume equal weight for all constraints:

$$M1 := \begin{pmatrix} 0.273 & 0.545 & 0.25 & 0.143 \\ 0.545 & 0.273 & 0.25 & 0.143 \\ 0.182 & 0.182 & 0.5 & 0.714 \end{pmatrix} \quad M2 := \begin{pmatrix} 0.25 \\ 0.25 \\ 0.25 \\ 0.25 \end{pmatrix} \quad M1 \cdot M2 = \begin{pmatrix} 0.303 \\ 0.303 \\ 0.394 \end{pmatrix}$$

For A4, there are three constraints only. Assuming equal weight, then

$$M1 := \begin{pmatrix} 0.333 & 0.167 & 0.667 \\ 0.667 & 0.833 & 0.333 \end{pmatrix} \quad M2 := \begin{pmatrix} 0.33 \\ 0.33 \\ 0.33 \end{pmatrix} \quad M1 \cdot M2 = \begin{pmatrix} 0.385 \\ 0.605 \end{pmatrix}$$

Based on the result of the matrix multiplication, machining center 2 will be selected for A1 and A4 since it has the biggest global weights 0.394 and 0.605 respectively.

4.4.2 Case Study with Matrix Modification

In section 4.4.1, the matrixes are not modified with the rules presented above. The following steps will show how the matrixes are revised based on the real case.

Step 1:

Tables 17A-17E show the relative priorities of alternative machines with respect to different constraints.

Table 17. Relative priorities with respect to drilling cost, boring cost, tolerance, production rate, and milling cost after matrix modification

Table 17A. Relative priorities with respect to **drilling cost (minimum prefer)**

	Drilling cost ($)	Reciprocal	Alternative weights
TC1	2	0.5	**0.273**
TC2	1	1	**0.545**
MC	3	0.33	**0.182**

Table 17B. Relative priorities with respect to **boring cost (minimum prefer)**

	Boring cost ($)	Reciprocal	Alternative weights
TC1	1	1	**0.545**
TC2	2	0.5	**0.273**
MC	3	0.33	**0.182**

Table 17C. Relative priorities with respect to **tolerance (minimum prefer)**

	Tolerance	Reciprocal	Alternative weights
TC1	0.001	1000	**0.25**
TC2	0.001	1000	**0.25**
MC	0.0005	2000	**0.5**

Table 17D. Relative priorities with respect to **production rate (maximum prefer)**

	Production rate (unit/hr)	Alternative weights
TC1	100	**0.143**
TC2	100	**0.143**
MC	50	**0.714**

Table 17E. Relative priorities with respect to **milling cost**

	Milling cost ($)	Reciprocal	Alternative weights
TC1	N/A	**0**	**0**
MC1	5	**0.2**	**0.667**
MC2	10	**0.1**	**0.333**

Based on the alternative weight vectors shown above, the alternative matrix for the machines is obtained as following:

$$M1 := \begin{pmatrix} 0.273 & 0.545 & 0.25 & 0.143 & 0 \\ 0.545 & 0.273 & 0.25 & 0.143 & 0.667 \\ 0.182 & 0.182 & 0.5 & 0.714 & 0.333 \end{pmatrix}$$

Step 2:

Tables 18A-18D show the constraint weights of the constraints with respect to different alternative processes as following:

Table 18. Relative priorities of constraints with respect to alternative processes

Table 18A. Relative priorities of criteria with respect to A1

	Drilling cost	Boring cost	Tolerance	Production rate	Milling cost	Eigenvector (weights)	Constraint weights
Drilling cost	1	1	0.5	2	N/A	0.4	**0.2222**
Boring cost	1	1	0.5	2	N/A	0.4	**0.2222**
Tolerance	2	2	1	4	N/A	0.8	**0.4444**
Production rate	0.5	0.5	0.25	1	N/A	0.2	**0.1111**
Milling cost	N/A	N/A	N/A	N/A	N/A	N/A	**0**

Table 18B. Relative priorities of criteria with respect to A2

	Drilling cost	Boring cost	Tolerance	Production rate	Milling cost	Eigenvector (weights)	Constraint weights
Drilling cost	1	1	0.25	3	N/A	0.324	**0.1900**
Boring cost	1	1	0.25	3	N/A	0.324	**0.1900**
Tolerance	4	4	1	2	N/A	0.868	**0.5091**
Production rate	0.33	0.33	0.5	1	N/A	0.189	**0.1109**
Milling cost	N/A	N/A	N/A	N/A	N/A	N/A	**0**

Table 18C. Relative priorities of criteria with respect to A3

	Drilling cost	Boring cost	Tolerance	Production rate	Milling cost	Eigenvector (weights)	Constraint weights
Drilling cost	N/A	N/A	N/A	N/A	N/A	N/A	**0**
Boring cost	N/A	1	1	2	N/A	0.667	**0.4001**
Tolerance	N/A	1	1	2	N/A	0.667	**0.4001**
Production rate	N/A	0.5	0.5	1	N/A	0.333	**0.1998**
Milling cost	N/A	N/A	N/A	N/A	N/A	N/A	**0**

Table 18D. Relative priorities of criteria with respect to A4

	Drilling cost	Boring cost	Tolerance	Production rate	Milling cost	Eigenvector (weights)	Constraint weights
Drilling cost	N/A	N/A	N/A	N/A	N/A	N/A	**0**
Boring cost	N/A	N/A	N/A	N/A	N/A	N/A	**0**
Tolerance	N/A	N/A	1	1	2	0.667	**0.4001**
Production rate	N/A	N/A	0.5	0.5	1	0.333	**0.1998**
Milling cost	N/A	N/A	1	1	2	0.667	**0.4001**

Based on the constraint weight vectors shown above, the constraint matrix for the machines is obtained as the following:

$$M2 := \begin{pmatrix} 0.2222 & 0.1900 & 0 & 0 \\ 0.2222 & 0.1900 & 0.4001 & 0 \\ 0.4444 & 0.5091 & 0.4001 & 0.4001 \\ 0.1111 & 0.1109 & 0.1998 & 0.1998 \\ 0 & 0 & 0 & 0.4001 \end{pmatrix}$$

Thus, the result of the matrix multiplication between alternative matrix and constraint matrix:

$$M1 \cdot M2 = \begin{pmatrix} 0.309 & 0.299 & 0.347 & 0.129 \\ 0.309 & 0.299 & 0.238 & 0.395 \\ 0.382 & 0.403 & 0.416 & 0.476 \end{pmatrix}$$

Step 3:

The result of matrix multiplication needs to be revised since there exists zero value in alternative matrix and non-zero item in constraint matrix

M1: $a_{15} = 0$; and M2: $b_{54} = 0.4001 \neq 0$

According to the rule, the value of the item in the result of matrix multiplication c_{14} should be changed to zero; the turning center TC1 cannot be chosen for alternative process A4, that is

$$M1 \cdot M2 := \begin{pmatrix} 0.309 & 0.299 & 0.347 & 0 \\ 0.309 & 0.299 & 0.238 & 0.395 \\ 0.382 & 0.403 & 0.416 & 0.476 \end{pmatrix}$$

Thus, the machining center 2 will be selected for the alternative processes A1, A2, A3, and A4 since it has the biggest global weights: 0.382, 0.403, 0.416, and 0.476.

Step 4:

Table 19. Attributes of alternatives based on selected sub-alternative

	Cost ($)	Tolerance (inch)	Maximum diameter (inch)
A1	10	0.0005	8
A2	6	0.0005	2
A3	7	0.001	50
A4	14	0.0005	100

Table 19A. Relative priorities with respect to **cost (minimum prefer)**

	Cost	Reciprocal	Alternative weights
A1	10	0.1	**0.208**
A2	6	0.167	**0.347**
A3	7	0.143	**0.297**
A4	14	0.071	**0.148**

Table 19C. Relative priorities with respect to **max. diameter (maximum prefer)**

	Max. diameter	Alternative weights
A1	8	**0.05**
A2	2	**0.0125**
A3	50	**0.3125**
A4	100	**0.625**

Table 19B. Relative priorities with respect to **tolerance (minimum prefer)**

	Tolerance	Reciprocal	Alternative weights
A1	0.0005	200	**0.286**
A2	0.0005	200	**0.286**
A3	0.001	100	**0.142**
A4	0.0005	200	**0.286**

The alternative matrix for Tables 19A-19C is

$$M3 := \begin{pmatrix} 0.208 & 0.05 & 0.286 \\ 0.347 & 0.0125 & 0.286 \\ 0.297 & 0.3125 & 0.142 \\ 0.148 & 0.625 & 0.286 \end{pmatrix}$$

Tables 19A-19C show the alternative weights of the alternative processes with respect to the different constraints. The constraint matrix for the goal is same as that for case study 1 in section 4.3. Then

$$M4 := \begin{pmatrix} 0.5717 \\ 0.2855 \\ 0.1428 \end{pmatrix} \qquad M3 \cdot M4 = \begin{pmatrix} 0.174 \\ 0.243 \\ 0.279 \\ 0.304 \end{pmatrix}$$

Thus, the alternative process A4 should be selected for producing the hole with the biggest global weight 0.304.

4.5 Selection of Part Family

Present industry is facing a frequently changing market. The order from customers could be various product types and quantities. One problem is that the customer's order may be too small to match the requirement of a minimum order from the supplier. In this case, several parts with similar geometrical shapes or sizes could be grouped into a part family to produce a profitable order for the supplier. Thus, an effective method to identify the suitable part family is required.

Zeng et al. [2003] presented four sets of constraints (production, process, machine, and feature) in a real manufacturing environment. The above case studies show that the process, machine, and production constraints could be applied on the MMCDM model with the AHP method. The feature constraints could also be used to identify a suitable part family with the AHP method.

During the production of the pulleys, a problem emerges because the small order of a particular pulley from the customer cannot meet the minimum order requirement from the casting supplier. It is quite important for the machining company to group different parts into a part family. Within the part family, all parts can be finished with the same casting even though the sizes or geometrical shape may vary a bit for each particular part. In the company, the part family for pulleys may be defined based on their outside diameters since the maximum chuck diameter of the machine limits the part family it can machine. In addition, the inside diameter, weight, and tolerance of a pulley can help to distinguish a part family for a particular pulley; and a suitable machine will be identified to produce the part family.

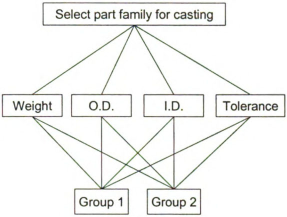


Figure 18. The selection of part family for casting process

Table 20. Two part families of pulleys

	Weight (lb.)	O.D. (inch)	I.D. (inch)	Tolerance (inch)
Group 1	15	15	3	0.001
Group 2	13	14	2	0.005

Figure 18 shows a hierarchy for the selection of a part family. At the constraint level, four constraints (including the *outside diameter (O.D.)*, *inside diameter* (I.D.), *tolerance*, and *weight*) are used to evaluate alternative part families. Group 1 and group 2 are two part families whose characteristics are shown in Table 20. For each part family, only a particular type of casting is ordered from the casting supplier. Once a new pulley is introduced, a suitable part family will be selected for this pulley so that a casting for old pulley could also be used for this new part.

For the identification of the part family, we capture the differences between new pulley and the part family with the constraints of weight, outside diameter, inside diameter, and tolerance. Table 21 represents the difference of the new pulley referred to the two part families. With these, AHP method can be used to select a suitable part family for the given part with the largest overall priority. The solution is similar to that in case study 1, as shown in Table 22A – 22D.

Table 21. The difference of given part refer to the part families

	Weight (lb.)	O.D. (inch)	I.D. (inch)	Tolerance (inch)
Part	12	14	4	0.0005
Difference to group 1	3	2	1	0.0005
Difference to group 2	1	1	2	0.0045

Table 22. Relative priorities of part family with respect to weight, O.D., I.D., and tolerance

Table 22A. Relative priorities of part family with respect to **weight**

	Weight	Reciprocal	Alternative weights
G1	3	0.33	0.25
G2	1	1	0.75

Table 22B. Relative priorities of part family with respect to **O.D.**

	O.D.	Reciprocal	Alternative weights
G1	2	0.5	0.333
G2	1	1	0.667

Table 22C. Relative priorities of part family with respect to **I.D.**

	I.D.	Reciprocal	Alternative weights
G1	1	1	0.667
G2	2	0.5	0.333

Table 22D. Relative priorities of part family with respect to **tolerance**

	Tolerance	Reciprocal	Alternative weights
G1	0.0005	2000	0.9
G2	0.0045	10000/45	0.1

The alternative matrix for above tables is

$$M1 := \begin{pmatrix} 0.25 & 0.333 & 0.667 & 0.9 \\ 0.75 & 0.667 & 0.333 & 0.1 \end{pmatrix}$$

Assuming a distributed weight vector (0.3, 0.3, 0.3, 0.1) for the constraints (weight, O.D., I.D., and tolerance), the result matrix is obtained as the following:

$$M1 := \begin{pmatrix} 0.25 & 0.333 & 0.667 & 0.9 \\ 0.75 & 0.667 & 0.333 & 0.1 \end{pmatrix} \quad M2 := \begin{pmatrix} 0.3 \\ 0.3 \\ 0.3 \\ 0.1 \end{pmatrix} \qquad M1 \cdot M2 = \begin{pmatrix} 0.465 \\ 0.535 \end{pmatrix}$$

Therefore, the part is preferred to be included into group 2 with a bigger weight 0.535.

4.6 Conclusion

This chapter has demonstrated that AHP is an effective tool for evaluating and selecting alternative processes and the related manufacturing resources (such as machines). Combined with process grammar, AHP can be applied on a decision making model – MMCDM, which is set up for the process selection problem in the shop floor environment. It achieves several attractive features (1) the AHP method can be applied on evaluating the alternatives (i.e. processes, machines, and part families) at any level of abstraction. This will help decision makers to understand the overall selection process and select the best alternatives at each level. (2) With process grammar, a complex selection problem could be simplified as hierarchy selection problems that can be solved with AHP method. (3) The hierarchy structure of both processes and constraints represented in the process model makes it easy to obtain a multilevel multiple criteria decision making model for a complex process selection problem. (4) The proposed decision making model could be applied on selecting manufacturing systems, processes, machines, providers, part families, etc. when quantitative and/or qualitative constraints are captured and put into the model.

Chapter 5

CONCLUSION

A methodology to model, design, and reconfigure a process has been described, which will make a production system more flexible and adaptable to a new production. This will reduce design and reconfiguring costs by:

- Representing the processes of a system with a grammar-based approach, and making designer or manager understand the overall processes of the system at any detail level of abstraction.
- Representing the system constraints in hierarchy structure and managing them in process reconfiguration when change arises during the production.
- Describing a method for process selection with the hierarchy structures of both processes and constraints represented above.
- Decomposing a complex decision-making problem as a smaller number of simple selections at any abstract level by combining process grammar and analytic hierarchy process method.

5.1 Contributions

This dissertation presents a grammar-based methodology of process design for Reconfigurable Manufacturing Systems. Specifically, this research makes the following contributions:

- Conducted a case study for the application of process grammar on modeling, designing, and reconfiguring processes in an industrial setting.
- Described a grammar-based approach in capturing and managing the processes in a distributed manufacturing environment.
- Represented the important constraints used to evaluate the alternative processes generated from the entities (task, data, organization, and resource) related to collaborative manufacturing.
- Described the hierarchy structures of processes and constraints that will help to effectively reconfigure processes when change arises during the production.
- Defined the constraint categories and identified the relationships among them when the constraints are used to evaluate the alternative processes at a different abstract level.
- Represented a multilevel multiple criteria decision-making (MMCDM) model using the hierarchy structures of processes and constraints to make the selected process optimum at any abstract level.
- Applied the analytical hierarchy process (AHP) method on the selection of process, machine, and part family and revised the matrix of AHP method for matching the real industrial selection.
- Constructed a foundation for an open-architecture system that manages the overall processes effectively in a distributed manufacturing environment.

5.2 Future Work

To extend this research, it is recommended that the following topics be investigated in the future:

- Mathematical descriptions for quantifying the constraints that are used to evaluate the alternative processes.
- More well-defined relationships among constraints should be captured for constraint transformation between different levels.
- Rules for automatically operating upon the constraints for evaluating the alternative processes at different abstract level.
- Development of software and implementation of the developed methodology in practice.

APPENDICES

APPENDIX A

GLOSSARY

Analytic Hierarchy Process A multi-criteria decision making method that decomposes a complex problem into a hierarchical order. See Chapter 4.

Alternative Matrix A matrix in which each column vector represents the alternative weights of the alternatives with respect to the elements (constraints) of next higher level. See Chapter 4.

Alternative Weight The measurement of relative priorities of alternatives with respect to the constraint that is used to evaluate the alternatives.

Atomic Task A task that cannot be decomposed into a set of subtasks. Atomic tasks are represented using two-concentric oval nodes in the process flow graph.

Comparison Matrix A matrix in which each component value represents the relative importance between the column constraint and the row constraint. See Chapter 4.

Consistence Index (C.I.) The deviation from consistency of a matrix, which is calculated by $(\lambda_{max} - n)/(n-1)$, λ_{max} is the largest eigenvalue of the matrix, and n is the order of the matrix. See Chapter 4.

Consistence Ratio (C.R.) The ratio of consistence index (C.I.) to average random index (R.I.) for the same order matrix, which is calculated by $C.R. = C.I./R.I.$. See Chapter 4.

Constraint A condition that must be satisfied for an alternative (process, resource, or organization) to be considered acceptable. See Chapter 2.

Constraint Hierarchy A hierarchy in which each constraints has an "is a type of" relationship with its ancestors. See Chapter 3.

Constraint Matrix A matrix in which each column vector represents the constraint weights of the constraints with respect to the elements (objectives) of next higher level. See Chapter 4.

Constraint Weight The measurement of relative priorities of constraints with respect to an objective that use all the constraints to evaluate alternatives.

Dedicated Manufacturing System A system designed for producing a specific part at a high volume, which uses typically transfer line technology with fixed tooling and rigid automation. See Chapter 1.

Flexible Manufacturing System A highly automated GT machine cell, consisting of a group of processing stations (usually CNC machine tools), interconnected by an automated material handling and storage system and controlled by an integrated computer system. See Chapter 1.

Global Weight The measurement of relative priorities of alternatives with respect to an objective that use constraints to evaluate the alternatives.

Graph Grammar A mathematical formalism for manipulating symbols representing graph vertices and edges. See Chapter 1.

Group Technology An approach to manufacturing in which similar parts are identified and grouped together in order to take advantage of their similarities in design and production. See Chapter 1.

Hierarchy A series in which each element is graded or ranked. See Chapter 3.

Logical Task A task that can be decomposed into a set of subtasks (logical tasks, atomic tasks, or selectors). Logical tasks are represented using oval nodes in the process flow graph. See Chapter 1.

Methodology A body of practices, procedures, and rules used by those who work in a discipline or engage in an inquiry.

Part Family A collection of parts that are similar either because of geometric shape and size or because similar processing steps are required in their manufacture. See Chapter 1.

Process Design The systematic exploration and determination of the methods by which a process is to be designed, economically and competitively. See Chapter 1.

Process Grammar A proposed formalism for representing, manipulating, and executing sets of acceptable design processes. It provides the mechanism for transforming a high-level process flow graph into progressively more detailed process flow graphs. See Chapter 1.

Process Hierarchy A hierarchy in which each process has an "is a type of" relationship with its ancestors. See Chapter 3.

Process Planning The systematic determination of the methods by which a product is to be manufactured, economically and competitively. See Chapter 4.

Random Index (R.I.) The average consistency index of a randomly generated matrix from the scale 1 to 9. See Chapter 1.

Reconfigurable Manufacturing System A reconfigurable manufacturing system (RMS) is designed for rapid change in the structure of both hardware and software components in order to rapidly adjust to new production method, production capacity, and functionality in response to changes in market or regulatory requirements. See Chapter 1.

Selector A selector selects a specification or a parameter for a task. Selectors are represented using diamond nodes in the process flow graph. See Chapter 1.

Shape Grammar A method to derive designs in the language that it specifies by successive application of shape transformation rules to some evolving shape, starting with an initial shape. See Chapter 1.

Subtask A task component represented by one of the task nodes in a design process grammar in which the component can be a logical task, an atomic task, or a selector. See Chapter 1.

Task A step in a design process or an activity in a production. See Chapter 1.

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