THESIS REPORT
Master's Degree

SYSTEMS RESEARCH CENTER

Supported by the National Science Foundation Engineering Research Center Program (NSFD CD 8803012), the University of Maryland, Harvard University, and Industry

Automated Manufacturability Evaluation for Microwave Modules

by H.J. Rathbun
Advisor: I. Minis

M.S. 92-8

ABSTRACT

Title of Thesis: AUTOMATED MANUFACTURABILITY EVALUATION FOR MICROWAVE MODULES

Name of degree candidate: Howard James Rathbun

Degree and Year: Master of Science, 1992

Thesis directed by: Dr. Ioannis Minis
Assistant Professor
Department of Mechanical Engineering &
Systems Research Center

Current competitive trends in manufacturing require full implementation of concurrent engineering, i.e. the consideration of all relevant aspects of a product's life cycle in the design phase. This research work focuses on the manufacturability evaluation of Microwave Modules (MWM's), providing critical feedback to the designer at the early stages of product development. MWM's are assemblies with both electrical and mechanical manufacturing requirements. In the present context, manufacturability evaluation includes two sequential stages: feasibility assessment and manufacturability rating. The feasibility assessment module relies on a rule-based "rough-cut" process planning system that determines whether a given design can be produced with available equipment, either in a global setting or within a specific

plant. Next, the manufacturability rating module uses an experience-based rating scheme to quantify the difficulty associated with manufacturing the designed product. The concurrent engineering software tool uses Group Technology (GT) codes and detailed information on critical design attributes provided by an existing GT-based design processor.

AUTOMATED MANUFACTURABILITY EVALUATION FOR MICROWAVE MODULES

by

Howard James Rathbun

Thesis submitted to the Faculty of the Graduate School
of The University of Maryland in partial fulfillment
of the requirements for the degree of
Master of Science
1992

Advisory Committee:

Assistant Professor Ioannis Minis, Chairman/Advisor
Associate Professor George Harhalakis Co-Advisor
Assistant Professor Guang-Ming Zhang

DEDICATION

To my parents

ACKNOWLEDGEMENTS

I would like to express my wholehearted thanks to my advisor Dr. Minis, who has spent countless hours in helping me to bring this work to fruition. Also, I would like to thank my co-advisor Dr Harhalakis, for managing our project and providing of his vast manufacturing knowledge. In addition, I would like to thank Dr. Zhang for his help throughout the course of my research.

This research was supported by the Maryland Industrial Partnerships and Westinghouse Manufacturing Systems & Technology Center, under grant #05-4-30520, and by the Systems Research Center under grant #NSFD CD 8803012. I would like to thank Bob Hosier and Jerry Feldstein of Westinghouse MS&TC, as well as Pete Mendecino, Abe Kebede, and John Fisher of Westinghouse BWI for their invaluable help. John Ortiz is also acknowledged for his energetic help in implementing the manufacturability evaluation system. I would also like to thank machinist Russ Wood of the Physics Shop at the University of Maryland for his contributions to the mechanical manufacturability rating tables. Last but not least, I would like to thank Amy Kinsey, both for her rigorous contributions and for tolerating my sense of humor for two years.

I would like to thank my family for their support during the course of my graduate studies. I would also like to thank my friends in the Computer Integrated Manufacturing Lab: Lin, Rakesh, Tom, George, Ashu, Anshu, and Marios. Finally, I would like to thank my friends Jim, Seth, Pip, Colin, Marty, Heidi, Mark, Mark, Craig, Gabby, Wendi, Pam and Mike for helping me to rediscover my wild side.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

Prompted by the competitive pressures of the global market, the U.S. industry has realized the need to employ advanced decision support systems for product design. Responding to this need, industry and academia have made considerable progress towards exploring solutions to the problems posed by simultaneous, or concurrent, engineering. In concurrent engineering, the major concerns corresponding to the entire product life cycle are considered in the design phase. Thus, the product design fulfills not only functional specifications, but also addresses manufacturing, maintenance and service, and disposal issues [Ishii and Mukherjee, 1992]. The research work presented here deals with incorporating manufacturing concerns into the product design phase.

Severe production inefficiencies occur whenever parts that are difficult or even impossible to produce are directed from design to manufacturing. In order to address these difficulties, product manufacturability should be systematically evaluated during both the conceptual and detailed design phases. An effective manufacturability system should perform the following basic tasks: i) determine the design attributes which are impossible to manufacture and the underlying causes of infeasibility; ii) highlight the design features which are difficult to manufacture; iii) suggest design modifications to improve manufacturability; iv) provide the resulting information to the designer during the design phase when changes are the least costly. Basic research studies on concurrent engineering and manufacturability evaluation are reviewed in the following section.

1.1 Background

1.1.1 Concurrent Engineering

The need to include the manufacturing engineer in all phases of the design is discussed in [Tanner, 1985], where some elements that a manufacturability evaluation scheme should include are discussed. Recently, considerable effort has been made in developing computer based concurrent engineering tools which address manufacturing and other product life cycle concerns during the design phase. A system which selects primary and secondary processes as well as materials given the design of a product is presented in [Boothroyd *et al.*, 1992]. Manufacturability and cost evaluation for injection molded parts has been studied in [Poli, 1991]. The resulting system operates without a detailed process plan at both the configuration and parametric design phases, and relies on considerable user input. The problem of bridging the gap between knowledge needed for manufacturability evaluation and design models is addressed in [Chen *et al.*, 1991]. Their work centers around object oriented design representations, and addresses feasibility of manufacture without providing a measure of manufacturing difficulty. A system which provides ratings of a design, based on evaluations from multiple life cycle perspectives, the underlying reasons for them, and suggestions for improving the design is described in [Ishii and Mukherjee, 1992].

1.1.2 Mechanical Manufacturability Evaluation

A system which evaluates mechanical manufacturability based on design features and the corresponding machining processes is given in [Shah *et al.*, 1990]. The system is capable of generating feasible machining operations to produce a particular feature, but provides no measure of manufacturing difficulty. A methodology which compares equipment capabilities to design requirements to assess manufacturability is presented in [Jara-Almonte and Krishnamoorthy, 1991]. This work is based on Nam Suh's axiomatic design approach and bridges the gap between quality and manufacturability evaluation. However, significant knowledge of the processes and machinery capabilities is required. Manufacturability evaluation for a Flexible Machining Center is described in [Courtright, 1988]. Here again, feasibility is studied, but no measure of manufacturing difficulty is provided.

1.1.3 Electrical Manufacturability Evaluation

Much of the manufacturability research in electronics has focused on Printed Circuit Boards (PCB's). The implementation of design rules for designing a manufacturable PCB were presented in [Fox, 1990]. Manufacturability, testability, and quality concerns for PCB's are also presented in [Masyga, 1990]. This work contains a great deal of PCB manufacturing expert knowledge which could be implemented in an expert system for PCB design. A software tool which relies on object oriented storage of knowledge related to PCB manufacturing is described in [Padhy and Dwivedi, 1991]. This system requires detailed knowledge of process information, which is not typically available at the early design stages. Issues associated with fabrication of microwave boards with multiple layers including vias, layer count, layer-to-layer connections, and hole aspect ratio is treated in [Daigle *et al.*, 1991]. Although this work highlights several manufacturability concerns, no software tool has, as yet, been developed. A rating scheme for Hybrid Micro-Assemblies (HMA's) based on manufacturing complexity has been given in [Westinghouse, 1990]. This work provides easily quantifiable measures of manufacturing difficulty based on certain design attributes. Several of the HMA rating measures for this work were adopted directly for the rating of MWM's presented in the current study. However, due to the differences in manufacturing technologies, many attributes which were not accounted for in the HMA rating scheme were included in the proposed MWM rating scheme. The issue of tolerance matching with manufacturing equipment accuracy capabilities by accumulating the inaccuracies associated with each process of Microwave Circuit Board fabrication is treated in [Ogden, 1990]. However, this approach employs Taguchi methods and is more applicable to quality evaluation than manufacturability.

1.1.4 Use of Group Technology in Manufacturability

In [Smart, 1982], a link between Group Technology (GT) and cost was established. The system relied significantly on process planning, and hence an intermediate step between design and cost evaluation was needed. The idea that implementation of GT improves the manufacturability of parts is addressed in [Barash, 1976]. The author claims that using GT intrinsically improves the manufacturability of parts that are designed to match existing part families. Similarly, in [Sule, 1991], implementation of GT for cellular manufacturing is shown to decrease production costs, improving manufacturability without design modifications. A manufacturability rating table for PCB's developed by using expert manufacturing knowledge is discussed in [Reodecha, 1985]. The table is populated with GT-based manufacturability evaluation criteria, thus establishing the link between GT and manufacturability.

1.2 Overview of the Manufacturability Evaluation System

The methodology employed in the current work uses a novel approach to evaluate a part's manufacturability during the detailed engineering design phase. Microwave Modules (MWM's) are chosen as a case study for this methodology. MWM's are primarily surface mounted electronic circuit boards, which operate in the microwave frequency range. The substrate of these circuit boards is an intricate mechanical part which is typically machined in order to achieve the proper mechanical and electrical properties. Thus, in order to assess their manufacturability, both mechanical and electrical manufacturing concerns must be addressed. The manufacturability evaluation system proposed in this research is based on Group Technology (GT) principles [Teicholz and Orr, 1987]. The overall architecture of the concurrent engineering system is shown in Figure 1.

The input to the overall system is a product design information model based on the standard for Product Data Exchange using STEP (PDES) [Bahadur *et al.*, 1991]. The PDES model is intended to capture the complete design information. The mechanical portion of the PDES model uses a Boundary Representation (B-Rep) to describe the shape of the product's shape. The form features are represented as passages, depressions, and transitions, which are subtracted from the B-Rep of the substrate's envelope in a Constructive Solid Geometry (CSG)

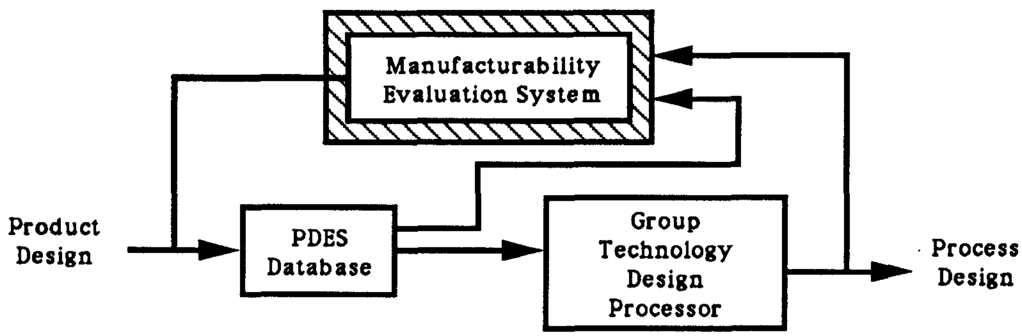

Figure 1. Overall System Architecture

fashion, to create a solid model of the substrate's design. The PDES model also contains information about electrical components and hardware of the MWM, along with plating of the artwork circuitry and/or the substrate layer.

A GT-based design processor described in [Kinsey, 1992] and [Harhalakis *et al.*, 1992] analyzes the PDES model to automatically generate the product's GT code and specific information on the design attributes captured by the code, which is necessary to assess manufacturability. These outputs serve as inputs to the manufacturability evaluation sub-system, which is the subject of the current work.

The manufacturability evaluation methodology operates in two steps as shown in Figure 2. The first step performs feasibility assessment, relying on a rule-based, rough-cut process planning system to determine whether a given design can be produced with available equipment. Various sets of available equipment can be considered, reflecting in-house, subcontractor, or even "world-wide" capabilities. In the second step an experience-based rating scheme is used to quantify the difficulty associated with manufacturing the designed product. Once these Manufacturability Ratings (MR) have been determined, the designer works interactively to analyze the product manufacturability results at several levels of detail. Specific suggestions are provided to improve the part's manufacturability and are related to design attributes. The overall intention of the

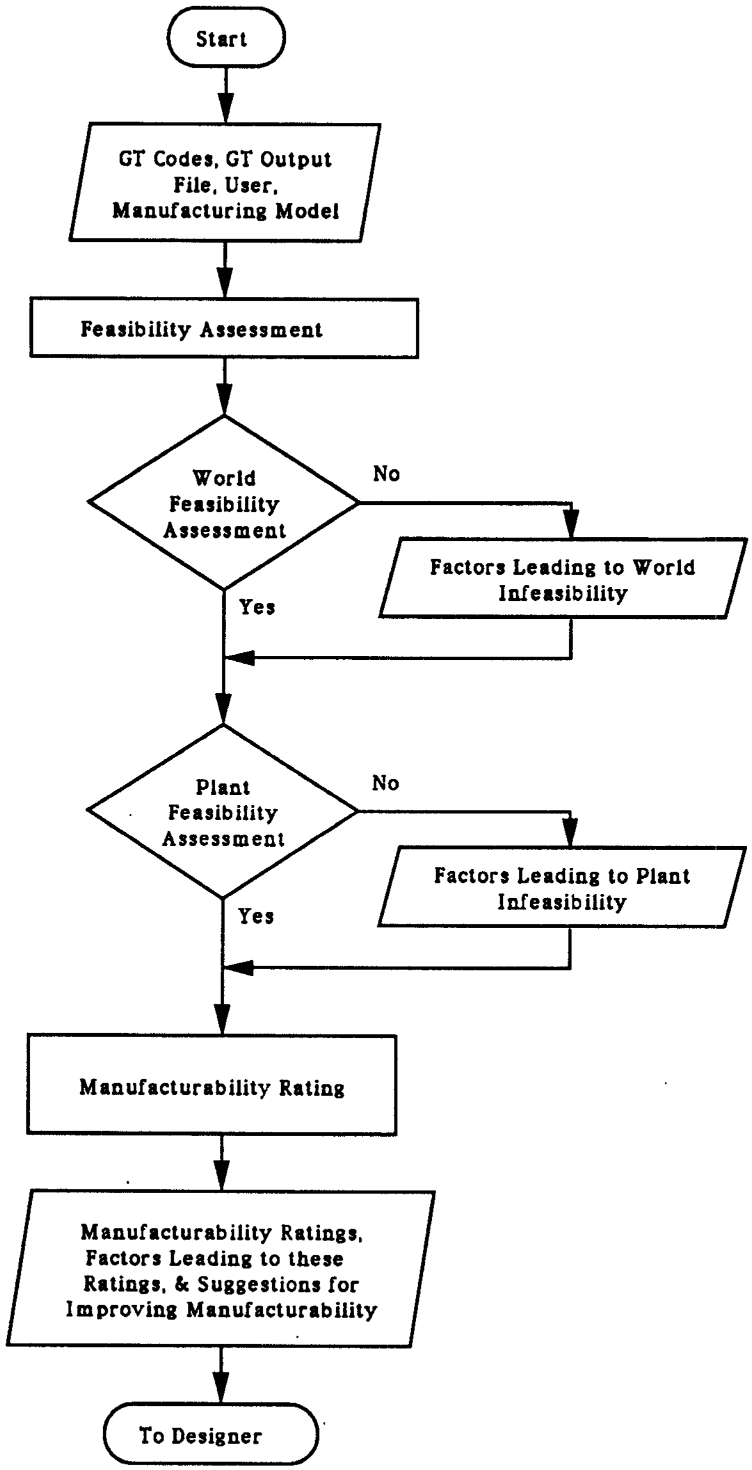

Figure 2. Manufacturability Evaluation System

manufacturability evaluation system is to facilitate prompt design modification iterations, so that the product which is sent to the shop floor is easily manufacturable, thus favorably impacting cycle time and cost.

The research work presented here differs from the others discussed previously in three ways. First, the design information source is a PDES database. Second, the manufacturability evaluation includes both feasibility assessment and quantitative manufacturability ratings. Finally, the system evaluates both mechanical and electrical manufacturability.

This thesis provides the proposed approach for leading to a comprehensive concurrent engineering system. The two major elements of the manufacturability evaluation module are described in detail in Chapters 2 and 3. The software implementation and an industrial application are presented in Chapter 4. Finally, in Chapter 5, conclusions and recommendations for further work are discussed.

CHAPTER 2
FEASIBILITY ASSESSMENT

The first fundamental step of manufacturability evaluation is to determine those design attributes which cannot be manufactured with the equipment available in a given production environment. This determination is facilitated by rules in the form of IF-THEN statements. The latter are used to translate the list of manufacturing requirements from the output of the GT-based design processor into machinery required for the part's manufacture. Since MWM's have both mechanical and electrical manufacturing requirements, two sets of rules had to be developed.

2.1 GT-Based Design Processor

The input to the manufacturability evaluation system is provided by a Group Technology (GT) coding sub-system. GT exploits part similarities to facilitate small batch manufacturing by grouping similar designs to form families that are manufactured by dedicated machine groups, or cells [Teicholz and Orr, 1987]. It is implemented by assigning an alphanumeric string to each part, which represents key part design and manufacturing attributes. Since MWM's have both mechanical and electrical significance, two GT codes are required. The MICLASS

[Organization for Industrial Research, 1986] GT coding scheme was chosen to represent the mechanical attributes and a new coding scheme was developed for the electrical attributes. The latter is described in detail in [Harhalakis *et al.*, 1992]. The GT coding module uses the PDES model to automatically derive the part GT codes, with minimal human intervention. Furthermore, the GT coding software develops two output files: one containing machined feature information, and one containing electrical manufacturing requirement information.

2.2 Mechanical Feasibility

2.2.1 General Description

The objective of the mechanical feasibility assessment module is to determine whether the mechanical attributes of the design can be manufactured with a given set of equipment. The architecture of the mechanical feasibility assessment module is shown in Figure 3. Each mechanical feature of the design requires certain types of machinery for its manufacture. Coupled with other design attributes, such as material and dimensions, the types of machinery capable of producing a feature can be determined using production rules. These rules can be expressed in the form of IF-THEN statements. For example, if the feature is a hole, the part material is non-conductive metallic, and the hole

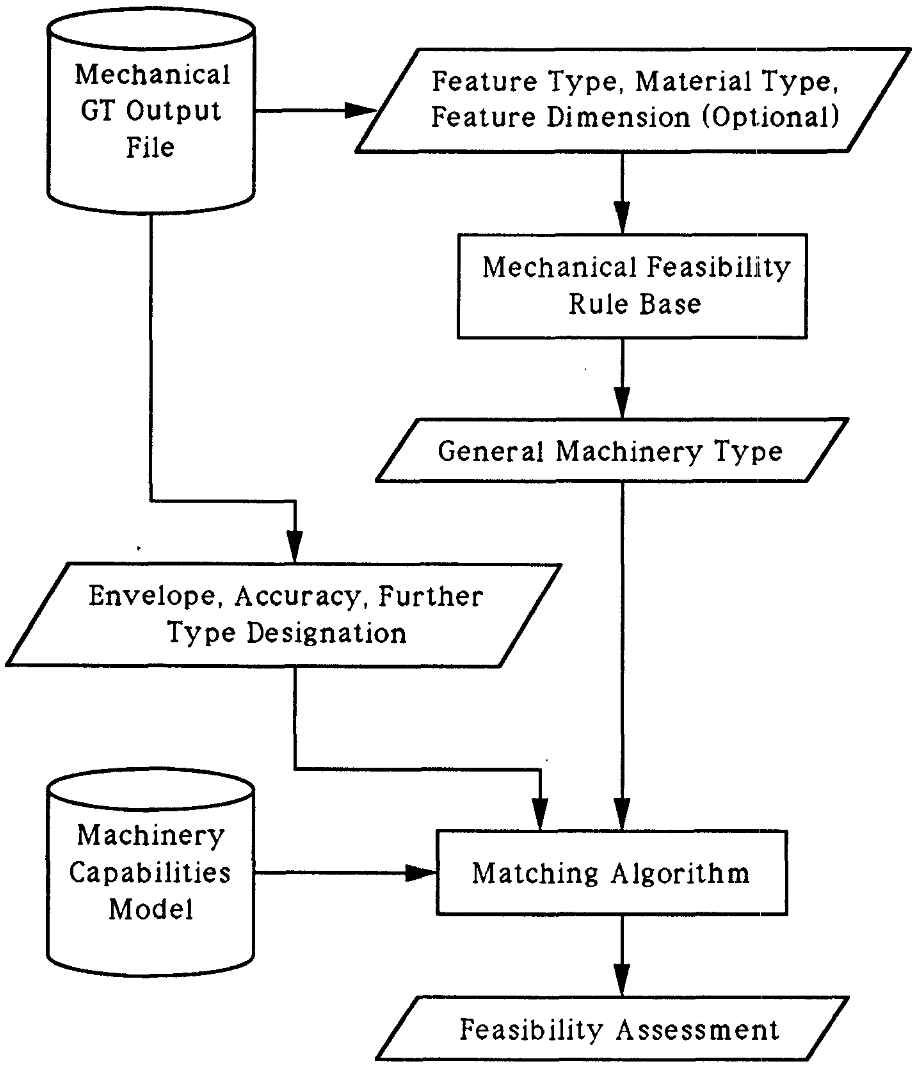

Figure 3. Mechanical Feasibility Architecture

diameter is between 0.002" and 4.0", then the types of machinery capable of producing this feature include both drilling and milling machines. The conglomeration of many such rules forms the Mechanical Rule Base. By incorporating additional design information, the design requirements can be compared to the capabilities of a given production environment. These capabilities are expressed in a format which simplifies the matching algorithm.

2.2.2 Input Mechanical Attributes

The MICLASS GT coding scheme [Organization for Industrial Research (OIR), 1986] classifies machined features for flat parts into eight categories. These include: cutouts, rectangular, radiused, slanted, and complex; holes, perpendicular and non-perpendicular to the part's top surface; flats; slots; and complex cavities. The feature types are classified on the basis of the operations required to manufacture them.

The GT-based design processor extracts the features of the substrate from the PDES database and classifies them into one of the MICLASS feature types. Information on each feature, beyond the attributes described in the GT code, is required for feasibility and manufacturability evaluation. Therefore, the design processor generates, in addition to the GT code, an output file containing feature-specific data. All features have a unique identifier, known as the Implicit Form Feature ID. For cutouts, simply the cutout type is sufficient. For perpendicular holes, the length, diameter, and face location on the substrate envelope are necessary. For non-perpendicular holes, their length, diameter, face location and orientation are required. For Flats, slots and complex cavities, face location and orientation are necessary. Some of this pertinent information is used for manufacturability rating and will be discussed in more detail later.

Material information is also included in the output of the GT processor, since the manufacturing processes for mechanical parts vary widely with different materials. The list of materials provided by OIR in the MICLASS GT coding scheme was not appropriate for MWM's, so a new list of materials was developed [Kinsey, 1992].

2.2.3 Mechanical Rule Base

To translate the feature information into required machinery, a rule base was developed. Each rule has an IF-THEN structure, i.e., it includes a premise and a conclusion in the following format:

IF: {feature type, material type, feature dimension (optional)}
THEN: {general machinery type}.

To develop the rule base, all possible combinations of feature type, material type and feature dimension (where appropriate) were enumerated. The following two examples illustrate the rules for mechanical feasibility:

IF: (Feature = Non_perp_hole) and (material = mwm_substrate)
and (0.002 <= diameter) and (diameter <= 4)
THEN: required_machinery = (Hs_drill_mach, or Hs_mill_mach)

IF: (Feature = Complex_cavity) and (material = mwm_substrate)
THEN: required_machinery = (Hs_mill_mach)

The entire mechanical feasibility rule base is given in Appendix A.

Note that for several of these rules, the conclusion is that it is impossible to manufacture the part with existing technology. This means that there is no machine type which is capable of meeting the design requirement. For example, a rectangular cutout with corner radii less than 0.125 in. cannot be end-milled, since the smallest milling cutter available has a radius of 0.125 in. Furthermore, if the material is soft substrate, the feature cannot be punched due to the material's tendency to tear. The material also prevents the use of Electro-Discharge Machining (EDM) since it is non-conductive. Finally, due to excessive carbon deposit formation, laser beam machining is also not an option. Hence, a rectangular cutout in soft substrate material is impossible to manufacture.

2.2.4 Additional Input Attributes

Given the general machinery type, three more pieces of information are needed to uniquely specify the required machinery: envelope, accuracy, and further type designation. These characteristics correspond to machinery requirements imposed by the part attributes.

2.2.4.1 Substrate Envelope

In this context, the part's envelope is defined by the three dimensions of the smallest rectangular box which physically encloses the part. The part's envelope is included in the MICLASS GT code, in digits 7 through 12 [OIR, 1986]. For example, if digits 7 through 12 are given as 423108, a look-up table in the MICLASS GT coding book indicates that the part's envelope is 6.25x3.5x0.187 in^3.

2.2.4.2 Accuracy

Given the tolerances specified in the design of the mechanical substrate, the required positional accuracy of the machinery is determined and will be compared with the accuracy of available equipment to assess feasibility. A design tolerance indicates the acceptable deviation the actual manufactured part can have from the nominal design specifications to account for unavoidable manufacturing inaccuracies. These tolerances are dictated by the functional relationship of the various components of the design.

There are two main classifications of mechanical tolerances: dimensional and geometric [OIR, 1986]. Dimensional tolerances include diameter, length, and positional tolerances: (i) Diameter tolerances define the acceptable size deviation of outer diameters, inner diameters and hole diameters; (ii) Length tolerances define the acceptable deviation between two surfaces; (iii) Positional tolerances define the acceptable deviation of a surface to a datum or any dimension to a datum. The two sub-categories of geometric tolerance include single and double indicator tolerances. Double indicator tolerances require a datum whereas single indicator tolerances do not. (i) Single indicator tolerances include roundness (circularity), cylindricity, flatness, straightness, and profile. (ii) Double indicator tolerances include concentricity, perpendicularity (squareness), angularity, parallelism, symmetry, true position, and runout. For a complete description of geometric tolerancing, see [Foster, 1982].

A simplified methodology was developed by Courtright, (1988) to translate the design tolerances to equipment accuracy requirements for Vertical Machining Centers (VMC). The VMC's capabilities for three types of geometric tolerances were found to be directly proportional to the VMC's positional accuracy. The tolerance types in [Courtright, 1988] included profile, circularity and flatness. Disregarding inaccuracies due to spindle deflection, it was found that: (i) the tightest profile tolerance achieved cannot be less than twice the positional accuracy, (ii) circularity cannot be less than twice the positional accuracy, and (iii) flatness cannot be less than the positional accuracy. Hence, the tolerance multiplier for profile tolerance is defined to be 2. Similarly, the tolerance multiplier for circularity is 2, and the tolerance multiplier for flatness is 1.

The tolerance multiplier methodology is only applicable to VMC's. Since MWM's are machined using a VMC, the approach taken in [Courtright, 1988] is adopted in the present study for MWM feasibility assessment.

It remains to determine appropriate multipliers for the remaining types of applicable geometric tolerances. This was only possible in some cases. For example, given that straightness can be viewed as a special case of flatness, the associated multiplier is also 1. Furthermore, parallelism controls flatness by default, and hence it has a multiplier of 1. The relevant tolerance multipliers are listed in Table 1.

Table 1.

Mechanical Feasibility Tolerance Multipliers

Tolerance Type	Multiplier
Profile	2
Circularity	2
Flatness	1
Straightness	1
Parallelism	1

From the discussion above, it is apparent that in order to satisfy the design specifications:

$$T_i \geq m_i * P \qquad \text{for all } i$$

where: T_i=ith indicated geometric tolerance

m_i=multiplier for the ith geometric tolerance

P=machinery's positional accuracy

Thus, the required accuracy is given from:

$$P = \min_i \{ \frac{T_i}{m_i} \}$$

For example, assume that an MWM substrate has a profile tolerance of 0.005 in. and a parallelism tolerance of 0.002 in. The multiplier for profile tolerance is 2 and the multiplier for parallelism is 1. We determine P as:

$$P = \min \{ \frac{0.005}{2}, \frac{0.002}{1} \} = 0.002 \text{ in.}$$

Therefore, any machine with a positional accuracy less than or equal to 0.002 in. satisfies the accuracy requirements of this part.

2.2.4.3 Further Type Designation

The further type designation is dependent on the machinery type. If the machinery type is a milling or a drilling machine, then the further type designation is defined as the number of machining axes required to manufacture the feature and is deduced from the feature orientation. If the machinery type is a punch press, then the further type designation is the punching force capacity. The required force, F, is determined by the following approximation:

$$F=\frac{(A+B)}{2}*C*T$$

where: A=longest envelope dimension (length)
B=second longest envelope dimension (width)
C=third longest envelope dimension (thickness)

T=maximum shear strength of the material

2.2.5 Mechanical Equipment Specification Format

To represent the capabilities of a production environment, the individual equipment capabilities were captured in a simple manufacturing model that facilitates feasibility assessment. An example of such a model is shown in Table 2. Each machinery type is expressed in terms of make, model, type, working envelope, positional accuracy, and further type designation. The make and model serve as unique identifiers for the machinery. The type is particular to the manufacture of flat parts, and may be one of: milling machine, high speed milling machine, drilling machine, high speed drilling machine, wire cut Electro-Discharge Machine (EDM), Ram EDM, punch press, and laser beam. Note that not all of these machinery types are relevant in manufacturing the substrates for MWM's.

In this work, the working envelope represents the X, Y, and Z dimensions of the largest part which can be physically fixtured on the machine. This definition, although not conventional, facilitates direct comparison with the product size requirements. As explained before, the further type designation is dependent on the machinery type. If the machinery type is a milling machine or drilling machine, then the further type designation is the number of machining axes required to manufacture the feature and is deduced from the feature orientation. If the machinery type is a punch press, then the further type designation is the punching force capacity.

For example, the Bostomatic 1018 high speed milling machine has a working envelope of 40x17x17 in^3, positional accuracy of 0.0004 in., and 4 machining axes (see Table 2). As a second example, the Baltec PWS610 punch press has a working envelope of 24x12x0.32 in^3, positional accuracy of 0.0015 in., and a punching capacity of 27 tons (see Table 2).

As mentioned in Section 1.3, the feasibility assessment may be performed at two levels: i) against world-wide manufacturing capabilities, and ii) against plant specific capabilities. To simulate a representation of the world's capabilities, information was obtained from several manufacturers for each general machinery type and used in a "world capabilities" file given in Table 2. On the other hand, to illustrate how a particular plant's specific capabilities could be represented, a subset of the "world's capabilities" is listed in Table 3.

2.2.6 Mechanical Equipment Matching Algorithm

The final task of the mechanical feasibility assessment module is to compare the design requirements with the capabilities of the available set of equipment. Recall that for each feature, the following information is determined using the

Table 2.

World Mechanical Capabilities Model

Make	Model	Type	Envel. X	Envel. Y	Envel. Z	Positional Accuracy	Frthr Type
Matsuur	RA-I	Milling_mach	23.6	14.9	18.1	0.0005	3
Matsuur	RA-II	Milling_mach	23.6	14.9	18.5	0.0005	4
Fadal	VMC-20	Milling_mach	20	16	20	0.0004	3
Fadal	VMC-40	Milling_mach	22	16	20	0.0004	4
BostMtc	1018	Hs_mill_mach	40	17	17	0.0004	4
Matsuur	RA-IIID	Hs_mill_mach	200.9	100.3	100.7	0.0004	5
Alzmeta	ABOMAT	Drilling_mach	19.7	15.7	18.3	0.0015	3
Alzmeta	AB4SV	Drilling_mach	22	28	31	0.0015	3
Willis	828	Hs_drill_mach	17.8	17.8	42	0.0015	4
Willis	WB32	Hs_drill_mach	25.5	45	42.2	0.0015	4
Sodick	A350	Wire_cut_e_d_m	21.7	15.5	8.3	0.0002	1
Sodick	BF250	Wire_cut_e_d_m	15.8	11.8	5.5	0.0002	1
Chmer	CM120	Ram_e_d_m	19.7	9.8	8.3	0.0002	1
Chmer	CM240	Ram_e_d_m	19.7	13.8	8.3	0.0002	1
Japax	SDX10NC	Ram_e_d_m	11.8	9.8	2.4	0.0002	1
Wiedman	Centrum	Punch_mach	40	40	0.25	0.002	30
Stripit	SPM500	Punch_mach	39.4	19.7	0.25	0.005	20
Baltec	PWS610	Punch_mach	24	12	0.32	0.0015	27
Trumpf	TLF1000	Lsr_beam_mach	60	120	0.25	0.004	1
Trumpf	TLF1500	Lsr_beam_mach	60	120	0.5	0.004	1

Table 3.

Plant Specific Mechanical Capabilities Model

Make	Model	Type	Envel. X	Envel. Y	Envel. Z	Positional Accuracy	Frthr Type
Matsuur	RA-I	Milling_mach	23.6	14.9	18.1	0.0005	3
BostMtc	1018	Hs_mill_mach	40	17	17	0.0004	4
Alzmeta	AB4SV	Drilling_mach	22	28	31	0.0015	3
Japax	SDX10NC	Ram_e_d_m	11.8	9.8	2.4	0.0002	1
Baltec	PWS610	Punch_mach	24	12	0.315	0.0015	27
Trumpf	TLF1500	Lsr_beam_mach	60	120	0.5	0.004	1

procedure described in Sections 2.2.3 and 2.2.4:

{*general machinery type, required envelope, required positional accuracy, required further type designation*}

In addition, the machinery capabilities are specified as:

{*make, model, general machinery type, envelope, positional accuracy, further type designation*}

The matching algorithm initially searches through the list of available equipment for a general machinery type which matches the required general machinery type. If no match is found, the user is notified. If a type match is found, the algorithm compares the required envelope to the machinery's envelope. A compatible match is made if all three part envelope dimensions are less than or equal to the corresponding machinery envelope dimensions. If no match is found, the user is notified that none of the types of machines available satisfy the part's envelope requirements. If a match is found, the program compares the part's accuracy requirements with the positional accuracies of the qualified machines. As mentioned in Section 2.2.4.2, the machine's positional accuracy must be less than or equal to the required positional accuracy of the part. Finally, the part's required further type designation is compared to further type designations of the machines that are qualified in terms of type, envelope, and accuracy. Any machinery that satisfies the part requirements is provided to the user.

As an example, assume the part's requirements have been determined to be:

Required General Type: High Speed Milling Machine

Required Envelope: 12x10x0.25 in^3

Required Positional Accuracy: 0.0008 in.

Required Further Type Designation: 4

The capabilities of the Bostomatic 1018 high speed milling machine are given as:

Make: Bostomatic

Model: 1018

General Type: High Speed Milling Machine

Working envelope: 40x17x17 in^3

Positional Accuracy: 0.0004 in.

Further Type Designation: 4

Note that further type designation for a milling machine is equal to the number of machining axes. Element by element comparison of the capabilities of the Bostomatic machine to the individual part requirements leads to the conclusion that the Bostomatic 1018 satisfies the part's requirements.

As a second example, assume the part's requirements have been determined to be:

Required General Type: Milling machine

Required Envelope: 12x10x0.25 in^3

Required Positional Accuracy: 0.0002 in.

Required Further Type Designation: 3

The capabilities of the Fadal VMC-20 milling machine are given as:

Make: Fadal

Model: VMC-20

General Type: Milling machine

Working envelope: 20x16x20 in^3

Positional Accuracy: 0.0004 in.

Further Type Designation: 3

The Fadal VMC-20 does not satisfy the part's requirements because the required positional accuracy is less than the VMC-20's positional accuracy.

2.3 Electrical Feasibility

2.3.1 General Description

To address the electrical feasibility of MWM's, an approach comparable to mechanical feasibility assessment was developed. The task here was to develop a methodology which determines if the electrical design attributes of an MWM are satisfied by a given set of equipment. The architecture of the electrical feasibility assessment module is shown in Figure 4. This was accomplished by creating a set of IF-THEN rules which translate the design attributes into machinery requirements. For example, if the design attribute is a surface mounted chip component whose pads are spaced less than or equal to 0.030 in. apart, then robotic placement is required due to the tolerance stringency. The entire set of these rules constitutes the electrical rule base. For some electrical machinery, additional design information is required to assess the design's compatibility. The format of the machinery capabilities specification facilitates the matching algorithm.

2.3.2 Input Electrical Attributes

The electrical GT coding scheme developed and employed in this project [Kinsey, 1992] codifies the existence of various electrical design and manufacturing attributes. These include

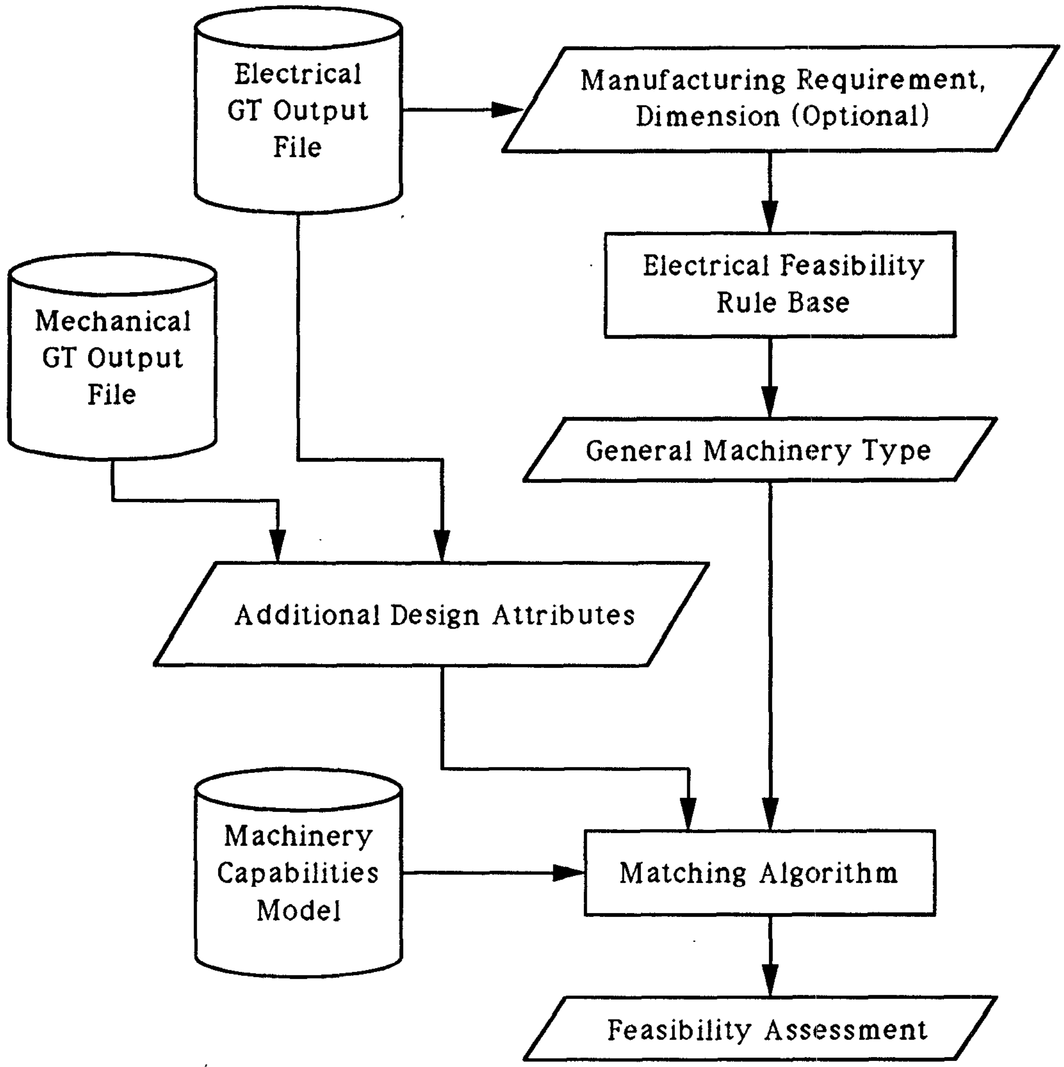

Figure 4. Electrical Feasibility Architecture

electrical components, hardware, artwork etching constraints, artwork platings, and substrate platings [Westinghouse, 1984]. The product's GT code along with the detailed information on the design attributes captured by the code are provided by the GT-based design processor as inputs to the feasibility module.

The component types recognized by the GT processor include chip, die, axial, radial, Double In-line Package (DIP), Single In-line Package (SIP), flatpack, can, and Radio Frequency (RF) . These are the various types of components frequently used in MWM designs. However, for MWM electrical feasibility assessment, these component types can be grouped into two major categories: leaded surface mount and non-leaded surface mount. This is because the leaded components require the extra operation of lead forming. The non-leaded component types include chip and die components, whereas the leaded components include axial, radial, DIP, SIP, flatpack, can, and RF.

The hardware types recognized by the MWM electrical GT code include screws, nuts, bolts, simple adhesives, complex adhesives, adhesive preforms, spacers, standoffs, cups, washers, housings, Field Effect Transistor (FET) mounts, ground pins, non-threaded terminals, threaded terminals, ground screws, wire jumpers, coaxial cables, isolators, solder preforms, ribbon jumpers, hairpins, and Lang couplers.

The artwork dimensions included in the GT processor's output include closest line spacing, smallest line width, artwork etching tolerance, and copper thickness. For artwork and substrate platings, the available information includes material type, plating thickness, and plating tolerance for each plating.

2.3.3 Electrical Feasibility Rule Base

Following an approach similar to that taken in mechanical feasibility assessment, a rule base was developed to translate the design information into required machinery. Each rule has an IF-THEN structure, i.e. a premise and a conclusion in the following format:

IF:{manufacturing requirement, dimension (optional)}
THEN:{machinery type}.

To develop the rule base, all possible manufacturing requirements were enumerated. Manual operation requirements were disregarded. The following two examples illustrate the structure of the electrical feasibility rule base:

IF: (Manuf_req = Chip_Comp_Mount) and (lead_pitch <= 0.03)
THEN: required_machinery = (Robotic_Mounter)

IF: (Manuf_req = Ground_Pin)
THEN: required_machinery = (Insertion_Machine)

The entire electrical feasibility rule base is given in Appendix B.

2.3.4 Additional Electrical Attributes

Additional design information is required to assess the compatibility of the design in question with the available machinery. For artwork etching, etching tolerance is a limiting constraint and will be compared with etching accuracy for photographic enlargement; for artwork and substrate plating, part envelope and plating tolerance are important attributes to be matched with appropriate machine characteristics. For artwork inspection, smallest line width and closest line spacing are constraints. For component placement, envelope, lead pitch, and placement tolerance will be considered. All this information is included in the output of the design processor. Part envelope data are carried by the mechanical GT code.

2.3.5 Electrical Equipment Specification Format

The manufacturing capabilities model provides electrical machinery specifications in a similar fashion as described in Section 2.2.5. The first three equipment attributes are make, model, and type. The remaining attributes depend on the machinery type. For artwork etching equipment, achievable etching tolerance is specified. For artwork and substrate plating baths, maximum part envelope capacity and achievable plating tolerance are included. For artwork inspection equipment, achievable inspection tolerance is given. For component placement, envelope, and placement accuracy are included.

For example, the Optical Gaging Products (OGP) IQ2000 inspection machine has an inspection accuracy of 0.0001 in. Hence, this is defined in the manufacturing model by:

OGP IQ2000 Artwrk_Insp_Eqp 0.0001

The MRSI 501 robotic placement mechanism has a working envelope of 10x8x3 in^3 and a placement accuracy of 0.003 in. The corresponding description is:

MRSI 501 Robotic_Mounter 10 8 3 0.003

An equipment set used in this work to represent "world-wide" capabilities is shown in Table 4. A subset of "world-wide" capabilities employed to represent plant-specific capabilities is given in Table 5.

Table 4.

World Electrical Capabilities Model

Make	Model	Type	Additional Information			
Optibm	X7314	Photo_Enlarger	0.00007			
Colight	9200	Photo_Enlarger	0.00005			
OGP	IQ2000	Artwrk_Insp_Eqp	0.0001			
Epner	E415J	Tin_Plat_Bath	12	10	2	0.00005
Andrson	PL302	Nickl_Plat_Bath	12	10	2	0.00005
Andrson	PL305	Gold_Plat_Bath	12	10	2	0.00005
MRSI	501	Robotic_Mounter	10	8	3	0.003
MRSI	505	Robotic_Mounter	10	8	3	0.0005
TDK	CX6160	Robotic_Mounter	18	15	1	0.0003
Seiko	RT3200	Robotic_Mounter	12	8	4.72	0.0003
MCT	PH-35	Resistive_Tool				
Pace	MBT250	Resistive_Tool				
Vanzeti	ILS7210	Laser_Rflow				
HTC	H432	Vapor_Ph_Rflow				
MCT	6830IR	I_R_Reflow				
TDK	RF4000W	I_R_Reflow				
MCT	6860	Nit_Con_Rflow				
TDK	AF1000	Nit_Con_Rflow				
Elctrvt	500C	Nit_Con_Rflow				
Strckfs	C070	Lead_Form_Eqp				
Strckfs	C060	Rbn_Jpr_Fm_Eqp				
MechApp	APC	Insert_Mach				
MechApp	ASM	Insert_Mach				
Unitek	PGW195	Parall_Gp_Wldr				
Strckfs	C036	Hrpin_Form_Eqp				
TDK	AD1000	Adhsv_Appl_Eqp				
MRSI	170	Adhsv_Appl_Eqp				
MCT	6860	Condct_Cur_Blt				

Table 5.

Plant Specific Electrical Capabilities Model

Make	Model	Type	Additional Information			
Colight	9200	Photo_Enlarger	0.00005			
OGP	IQ2000	Artwrk_Insp_Eqp	0.0001			
Epner	E415J	Tin_Plat_Bath	12	10	2	0.00005
Andrson	PL302	Nickl_Plat_Bath	12	10	2	0.00005
MRSI	501	Robotic_Mounter	10	8	3	0.003
HTC	H432	Vapor_Ph_Rflow				
MCT	6830IR	I_R_Reflow				
Strckfs	C070	Lead_Form_Eqp				
Strckfs	C060	Rbn_Jpr_Fm_Eqp				
MechApp	ASM	Insert_Mach				
Unitek	PGW195	Parall_Gp_Wldr				
MRSI	170	Adhsv_Appl_Eqp				
MCT	6860	Condct_Cur_Blt				

2.3.6 Electrical Equipment Matching Algorithm

The electrical feasibility rule base uses the electrical design attributes provided by the GT-based design processor to generate the machinery type(s) required for the realization of the design. The additional information required to assess the compatibility of the design to specific machinery is also provided by the GT-based design processor. Hence, the following information is on hand:

{*required general machinery type, additional required information*}

The equipment is specified in the capabilities model as:

{*make, model, general machinery type, additional information*}

The matching algorithm uses this information in a straight forward manner. The program first searches through the available equipment types to match the required equipment. If no match is found, the user is notified. If a type match is found, the program compares the remaining design requirements to the machinery's capabilities, if necessary. If the requirement is artwork etching, the machine's achievable artwork etching tolerance must be less than or equal to the part's requirements. For platings, the plating bath's working envelope must be greater than or equal to the part's envelope. In addition, the bath's achievable plating tolerance must be less than or equal to the part's plating tolerance requirements. For artwork inspection, the corresponding equipment accuracy must be less than or equal to the part's artwork inspection requirements. Finally, for component placement, the placement mechanism's working envelope must be greater than or equal to the part's envelope, and the placement accuracy must be less than or equal to the component's placement tolerance requirements.

For the remaining types of manufacturing requirements, only the general equipment type is matched. As is the case in mechanical feasibility, any machinery that passes all feasibility tests is listed in the system's output. Any manufacturing requirement that cannot be satisfied by the production environment under consideration is provided to the user.

As an example, assume that one of the product's requirements has been determined to be:

Required General Type: Robotic_Mounter

Required Envelope: 9x6x0.25 in^3

Required Placement Tolerance: 0.0035 in.

The capabilities of the MRSI 501 robotic placement mechanism are given as:

Make: MRSI

Model: 501

General Type: Robotic_Mounter

Working envelope: 10x8x3 in^3

Placement Tolerance: 0.003 in.

It is apparent that the MRSI 501 satisfies this specific product requirements.

As a second example, assume that one of the product's requirements has been determined to be:

Required General Type: Tin Plating Bath

Required Envelope: 10x6x0.25 in^3

Required Plating Tolerance: 0.00002 in.

The capabilities of the Epner E415J tin plating bath are given as:

Make: Epner

Model: E415J

General Type: Tin Plating Bath

Working envelope: 12x10x2 in^3

Plating Tolerance: 0.00005 in.

Since the Epner E415J tin plating bath's achievable plating tolerance is greater than the part's plating tolerance, it does not satisfy the part's requirements.

2.4 Feasibility Assessment Program Development

The mechanical and electrical feasibility assessment programs are disjoint, having no interdependencies. However, since their underlying methodologies are identical, they can be described simultaneously. The inputs to the feasibility assessment programs include the GT design processor's output, and the manufacturing model containing equipment capabilities. Both are read into active memory for ease of manipulation. The GT processor's output pertains to a specific part, and the manufacturing model pertains to a specific production environment. Both are specified by the user prior to the feasibility assessment.

The system examines the feasibility of each design attribute separately. In mechanical feasibility the attributes are machined features, whereas in electrical feasibility they are the etching, plating and attachment requirements. For each design attribute, the system searches through the rule base for the appropriate rule. This step provides the equipment types required for manufacturing the individual design attribute. Next, the matching algorithm incorporates additional design information and compares the required machinery to the available machinery to assess the design attribute's feasibility.

For each design attribute, an output screen is provided, headed by the part number and the plant name. The name and unique identifier for the design attribute in question is given. For mechanical feasibility, the unique identifier is the Implicit Form Feature ID [Bahadur *et al.*, 1991]. For electrical feasibility, the unique identifier depends on the design attribute. With electrical components, it is the reference designator (Ref. Des.). For hardware, it is the Find-Part Number. Etching and platings are specified by name only. Any available equipment that satisfies the design attribute's requirements is listed by make, model and type. If no equipment in the available set satisfies the design attribute's requirements, then the types of the compatible general equipment (if any) is listed, along with the specific reason(s) for infeasibility. Once all of the design attributes have been exhausted, a final feasibility assessment summary is provided.

CHAPTER 3
MANUFACTURABILITY RATING

A product's manufacturability is quantified by determining its Manufacturability Rating (MR). The MR is a measure of the level of difficulty of manufacturing a part in terms of time and cost. Although the MR does not provide an exact cost estimate, the designer can "zero in" on those design elements which will pose the major difficulties during manufacture. Through successive iterations of design changes and manufacturability evaluations, an easily manufacturable design can be created.

Using MWM's as a case study, this research developed and implemented a rating scheme which relates design attributes to levels of difficulty in manufacturing based on expert knowledge. In addition, the system provides the designer with specific design modification suggestions which will improve the part's manufacturability.

3.1 Manufacturability Rating Methodology

To determine the relative difficulty of manufacturing a given MWM design, a hierarchical weighting approach was taken. The weights are stored in a set of MR tables. Since MWM's have both mechanical and electrical design and manufacturing attributes, two distinct sets of MR tables were developed. Consequently, MWM's have not one, but two MR's.

3.1.1 Global Concern Weighting

The major mechanical and electrical global concerns for MWM manufacture were identified and their relative manufacturing difficulties were assigned weighting factors W_j on a scale of 1 to 10. These weights were provided by manufacturing experts, with higher numbers corresponding to higher degrees of difficulty. Although the weighting factors are fixed at the time of MR calculation, they can be changed to reflect a particular plant's manufacturing capabilities. Since the weights are hard coded in the software program, this process is non-interactive, and would require actual program modification.

3.1.1.1 Mechanical Global Concerns

To identify the major global concerns associated with the mechanical MWM manufacturing requirements, the knowledge and experience of machining experts were solicited. The global mechanical concerns and their relative weighting factors are given in Table 6.

The global concern with the highest weight (10/10) is material machinability. Materials can be difficult to process due

Table 6.

Global Mechanical Manufacturability Concerns for MWM's

Index	Concern	W_j
1	Cutouts	7
2	Perpendicular Holes	3
3	Other Holes	5
4	Flats/ Slots	7
5	Complex Cavities	9
6	Tolerance	9
7	Material Machinability	10
8	Feature Orientation	8

to their intrinsic properties, such as strength, modulus of elasticity, hardness, and ductility. These factors can be combined into one measure of the materials' conduciveness to processing. Tight (small) design tolerances contribute the second highest amount to mechanical MR due to possible added process monitoring requirements. Due to tedious re-fixturing and set-up implications, feature orientations for machined secondary elements may also have a significant impact on manufacturability and is assigned W_j=8.

The remaining overall concerns correspond to form feature types and are weighted according to their processing difficulty. Complex cavities, as defined by the GT coding conventions, are considered to be the most tedious features to manufacture and are assigned W_j=9. On the other hand, perpendicular holes are the simplest to machine, and are assigned a weight W_j=3.

3.1.1.2 Electrical Global Concerns

Experts in the field of MWM fabrication and assembly were interviewed and their knowledge quantified. The global electrical concerns were identified and assigned weighting factors (see Table 7).

Table 7.

Global Electrical Manufacturability Concerns for MWM's

Index	Concern	W_j
1	Artwork Etching	2
2	Artwork Plating	2
3	Substrate Plating	3
4	Silk-Screening (Marking)	1
5	Component Attachment	9
6	Non Soldered Hardware	5
7	Soldered Hardware	6
8	Substrate Cleaning	2
9	Primer Application	3
10	Tuning and Testing	10
11	Inspection	10

Experience has shown that tuning, testing and inspection have a critical impact on electrical manufacturability and hence for both W_j=10. Component attachment through either manual or robotic placement techniques follows in complexity and is assigned W_j=9. Hardware which requires soldering presents, in general, moderate difficulties, and therefore receives W_j=6. Since non soldered hardware does not require the extra operation of soldering, it is assigned W_j=5. Substrate plating and primer application are less difficult operations and hence receive W_j=3. Artwork etching, artwork plating, and substrate cleaning are relatively simple operations, and therefore receive W_j=2. For silk-screening (marking) W_j=1, since it has the least impact on manufacturability.

3.1.2 Sub-Concern Weighting

Each of the global concerns is quantified by second level sub-concerns. For example, the mechanical global concern of Perpendicular Holes can be complicated by i) number of holes, ii) additions (counterbores, countersinks, and threads), iii) differing diameters, iv) highest length to diameter ratio, and v) different locations with respect to the product envelope (see Appendix E). The complete MR table for Perpendicular Holes is given in Table 8. As a second example, the artwork etching sub-concerns include line spacing, line width, etching tolerance, and copper thickness (see Table 9). Realizing that each second-level concern contributes by a different amount to the global concerns, each is assigned a weighting factor. The weight for the ith subconcern within the jth global concern is given by S_{ij}. For perpendicular holes, the most important attribute is the highest ratio of length to diameter, and hence the resulting weight S_{42}=10. The number of

Table 8.

Perpendicular Holes Manufacturability Rating Table

$W_2=3$

Number of Holes	Additions (Thrds.,Cbores, Csinks, etc.)	Different Diameters	Ratio of Length to Diameter (Highest Ratio)	Location
Weight=2	Weight=6	Weight=8	Weight=10	Weight=9
No Holes =0	No Additions =0	No Holes=0	No Holes=0	No Holes=0
1 - 10 =1	1 Type of Addition=3	1 Diameter=1	L/D<1=2	All in from same side=1
11 - 100 =5	2 Types of Additions=7	2-5 Diameters =5	1<=L/D<2=5	Holes on two sides=10
>100 =10	>=3 Types of Additions=10	>5 Diameters =10	L/D>=2=10	

(S_{i2} → weight row; A_{i2} → rating rows)

Table 9.

Artwork Etching Manufacturability Rating Table

$W_1=3$

Line Spacing (Thousandths, Closest)	Line Width (Thousandths, Smallest)	Artwork Tolerance (Thousandths)	Copper Thickness (oz/sq in)
Weight=10	Weight=10	Weight=8	Weight=5
>0.1=1	>0.1=1	>0.01=1	<1=10
0.1-0.01=2	0.1-0.01=2	0.01-0.001=2	1-2=2
<0.01=10	<0.01=10	<0.001-0.0005=4	>2=10
		<0.0005=10	

(S_{i1} → weight row; A_{i1} → rating rows) part faces (locations) on which perpendicular holes lie is also very important, and hence $S_{52}=9$ (see Table 8).

Finally, the evaluation criteria for the second-level concerns were enumerated and weighted by the factors A_{ij}. For example, in Table 8, if the highest length to diameter ratio for perpendicular holes is less than one, then $A_{42}=2$. If the highest length to diameter ratio for perpendicular holes is between 1 and 2, then $A_{42}=5$. The entire set of mechanical and electrical MR tables are given in Appendices C and D, respectively.

The methodology presented here is an extension of that presented in [Reodecha, 1985]. The fundamental ambiguity in the Reodecha methodology is that there is conflicting design information in the evaluation criteria. Hence, the MR calculated in this manner is imprecise. In developing the MWM manufacturability rating scheme, the evaluation criteria were separated to be mutually exclusive.

3.1.3 MR Calculation

Once the MR tables were developed, a mathematical formulation was required to derive the part's MR using the weights in the tables. The MR is calculated as follows:

$$MR=\sum_{j=1}^{k} W_j\left[\sum_{i=1}^{n(j)}(S_{ij})(A_{ij})\right] \qquad (4.1)$$

Where: W_j=Overall weight for global concern j (first level)

S_{ij}=Weight for second level concern i within global concern j

A_{ij}=Weight for specific evaluation criterion i within global concern j

k=Total number of global concerns

n(j)=Total number of second level concerns within global concern j

3.2 MR Normalization

Direct application of equation 4.1 to derive the mechanical and electrical MR provides values which are unrealistic and biased. To obtain proper results, scaling of the W_j's and S_{ij}'s is required. Both mechanical and electrical manufacturability ratings were scaled from 0 and 100 with higher values corresponding to higher values of manufacturing complexity. This was accomplished through proper scaling of the W_j's. All W_j's are scaled by the same factor C, which is given by:

$$C=\frac{100}{\sum_{j=1}^{k} W_j} \qquad (4.2)$$

where: C=Scaling factor

k=Total number of global concerns

W_j=Unscaled weight for global concern j

In order to avoid the bias of MR towards overall concerns with many quantifying individual concerns, regardless of the W_j, appropriate normalizations were also required. This was done through scaling the subconcern weights S_{ij}'s. The scaling factor F for the subconcern weights S_{ij}'s for the jth subconcern is given by:

$$F_j = \frac{1}{10 * \sum_{i=1}^{n(j)} (S_{ij})} \qquad (4.3)$$

where: F_j=Scaling factor

n(j)=Total number of second level concerns within global concern j

S_{ij}=Unscaled weight for second level concern i within global concern j

3.3 Manufacturability Rating Program Development

Having fully developed the MR methodology, tables and normalizations, the algorithm that determines the MR values for a given design includes two major steps: i) translation of design attributes into numerical manufacturability ratings and ii) interactive presentation of the results to the user. Although the mechanical MR procedure relies entirely on the output of the GT-based design processor, the electrical MR procedure requires some additional input from the user.

3.3.1 Translation of the Design Attributes to MR's

The procedures which translate the output of the design processor and the necessary user input to MR's are straightforward. For each sub-concern of the global concerns, the applicable evaluation criteria is determined and the associated A_{ij} value is assigned. For example, in deriving the mechanical MR, the number of different hole diameters is determined from the GT processor's output and the appropriate sub-concern within the global concern holes is weighted. If the part has 3 different diameters for Perpendicular Holes, A_{32}=5 (see Table 8). Having determined all A_{ij} values the following equation is used to derive the MR values:

$$MR=\sum_{j=1}^{k} W_{js}\left[\sum_{i=1}^{n(j)} (S_{ijs})(A_{ij})\right] \qquad (4.4)$$

Where: W_{js}=Scaled overall weight for global concern j (first level)

S_{ijs}=Scaled weight for second level concern i within global concern j

A_{ij}=Weight for specific evaluation criterion i within global concern j

k=Total number of global concerns

n(j)=Total number of second level concerns within global concern j

3.3.2 Interactive Presentation of MR Results

The manufacturability rating program lists the overall manufacturability concerns for the part being analyzed from the highest to the lowest rating values. The designer may review any overall concern, examine the corresponding second level sub-concerns and the design attribute(s) causing the particular rating. Along with this information, recommendations for design modifications are provided which may improve the part's MR (if possible). These recommendations are based on the manufacturability tables themselves, and point toward lower values of A_{ij}. For an example of the presentation of the MR results to the user, see Chapter 4.

CHAPTER 4
SOFTWARE IMPLEMENTATION AND EXAMPLES

4.1 Software Architecture

The architecture of the software which performs the MWM manufacturability evaluation is illustrated in Figure 5. First, the user is prompted to choose between assigning GT codes and manufacturability evaluation. To execute the GT-based design processor for a part, it is assumed that the PDES model of the part under consideration is already in place. The development and implementation of the GT-based design processor is described in [Kinsey, 1992]. The highlighted sections pertain to the programs outlined here. Both mechanical and electrical feasibility assessment as well as manufacturability rating operate on the output of the GT-based design processor. It is assumed that the user will assess the part's feasibility before proceeding to manufacturability. However, feasibility assessment can be bypassed entirely if the user desires. Both feasibility assessment programs advise the user to initially assess feasibility using the "world-wide" capabilities model. If the part is found to be infeasible with the world's capabilities, the feasibility assessment programs store the "world-infeasible" attributes of the design in a separate text file. To provide system flexibility, the "world-infeasible" attributes are not considered during manufacturability

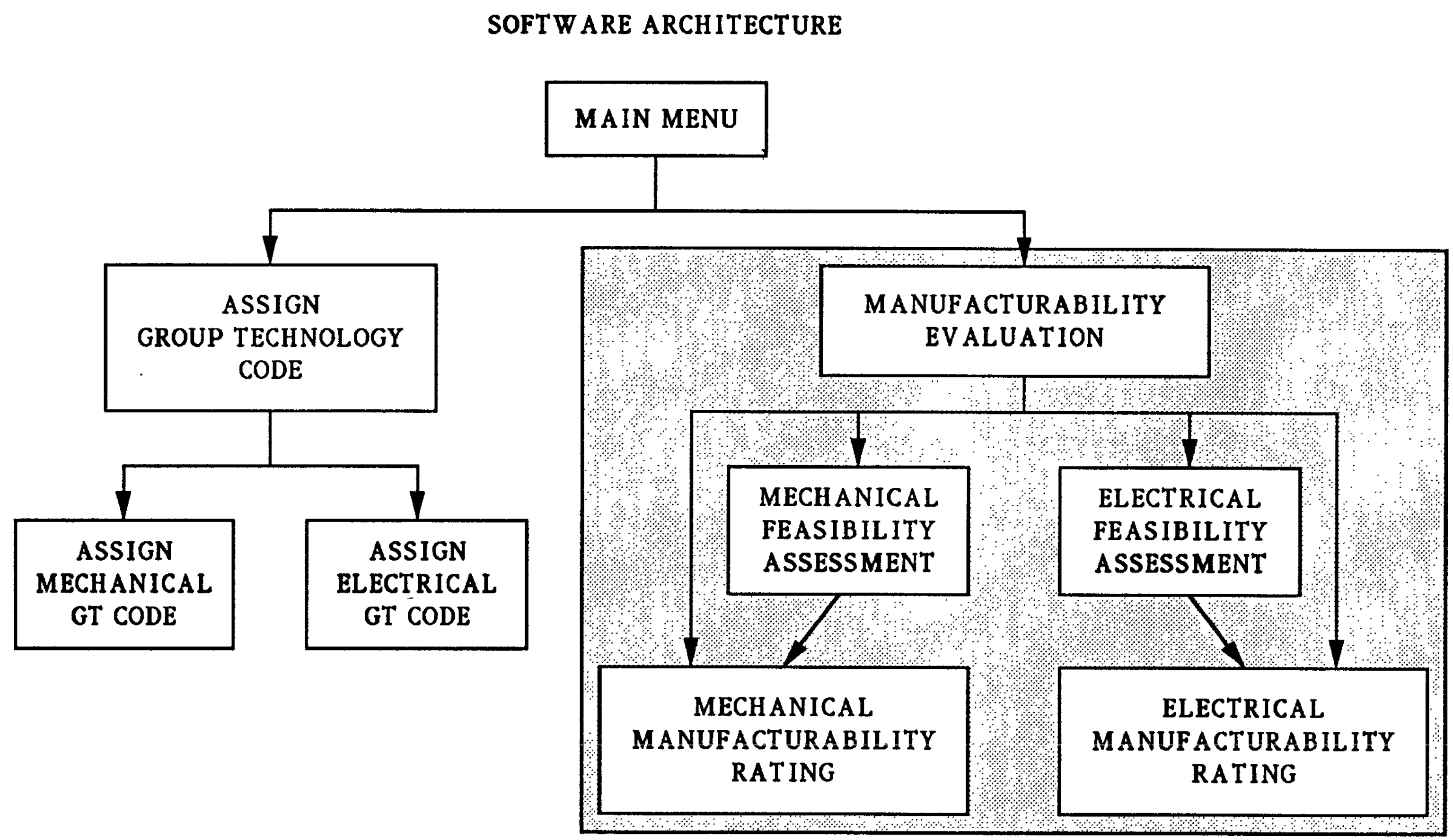

Figure 5. Software Architecture

rating. For detailed information on running the system modules, see [Computer Integrated Manufacturing Lab, 1992].

The concurrent engineering software tool has been implemented on a DEC VAX mainframe at Westinghouse Manufacturing Systems and Technology Center in Columbia, Maryland. The PDES model resides in an ORACLE relational database environment [Bahadur *et al.*, 1991]. The GT coding program uses Pro-C to process information from the PDES database and the user to generate the GT codes and output files [Kinsey, 1992]. The manufacturability evaluation program is implemented in standard VAX C.

4.2 Example

The following example is used to illustrate the four procedures of the manufacturability evaluation system, highlighting the important aspects of each. The mechanical portion of the example part is shown in Figure 6 (reprinted from [Kinsey, 1992]).

The first step is to assess the part's mechanical feasibility using the world-wide capabilities model (see Table 2, Chapter 2). Once the user has specified the manufacturing environment, the program accesses the information from the output of the GT-based design processor. The format of this output is provided in [Kinsey, 1992]. Subsequently, the program parses through each feature to

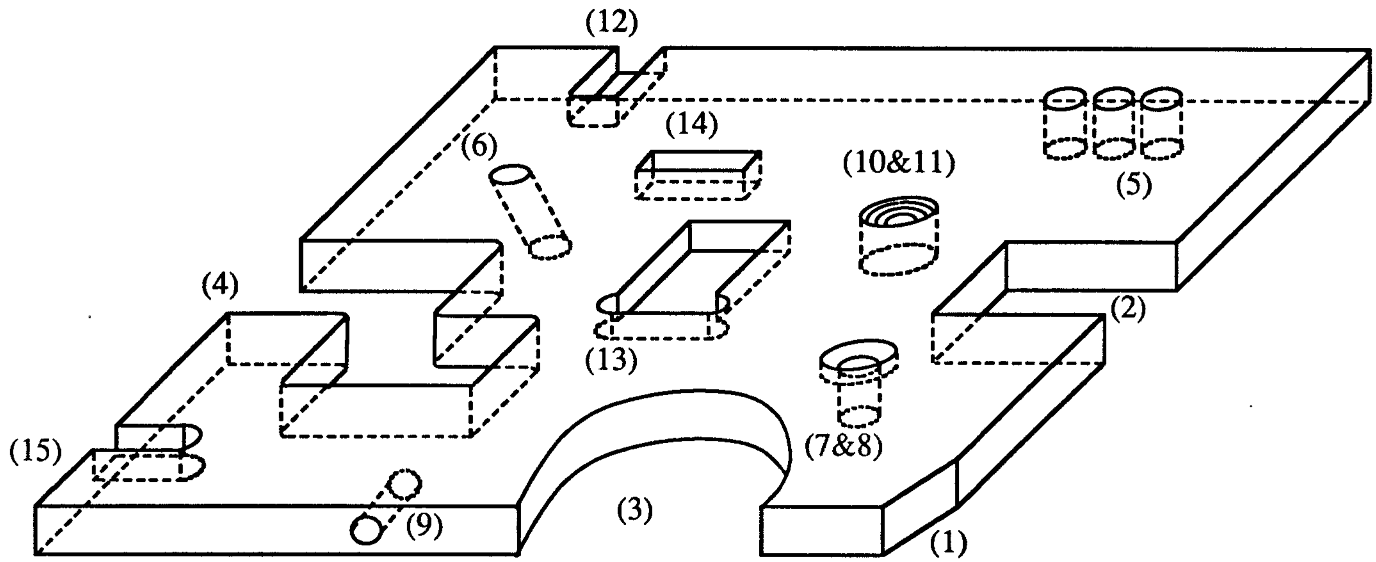

Figure 6. Mechanical Sample Part

determine feasibility. Two sample output screens are shown in Figure 7. Note that the rectangular cutout (feature 2 in Figure 6) is considered infeasible. This is because there is no equipment capable of producing a rectangular cutout in soft substrate material (see also Section 2.2.3). The output screen is headed by the part number and the plant name. Any available machinery that satisfies the design attribute's requirements are listed by make, model and type. In the case of the slanted cutout (feature 1 in Figure 6), these include the Bostomatic 1018 and the Matsuura RA-IIID high speed milling machines. If no machine in the available set satisfies the design attribute's requirements, then the types of equipment (if any) that correspond to the requirements are listed, along with the reason(s) that renders them infeasible in this particular case.

Once all of the design attributes have been exhausted, a final feasibility assessment is provided. If all design attributes were found to be feasible, then the final assessment is feasible. If some design attributes were found to be infeasible, then the final assessment is infeasible and the infeasible attributes are listed. For the example part, since feature 2 is considered infeasible, the final assessment is that the part is infeasible. Since the part was considered infeasible within the world-wide capabilities model, feature 2 is stored separately and disregarded in the mechanical manufacturability rating program. The same procedure can be executed using a particular plant capabilities model.

```
Part Number : 97942-SAMPLE

Plant       : Worldmech

Manuf. Req.     Available Equip.                          Unavailable Equip.
                Make    Model    Type                     Type
--------------- ----------------------------------------- ---------------
Slanted_cutout
Imp FF ID:1
                Bostmtc 1018     Hs_mill_mach
                OR
                Matsuur RA-IIID  Hs_mill_mach
```

```
Part Number : 97942-SAMPLE

Plant       : Worldmech

Manuf. Req.     Available Equip.                          Unavailable Equip.
                Make    Model    Type                     Type
--------------- ----------------------------------------- ---------------
Rect_cutout
Imp FF ID:2


Impossible to machine with existing technology.

Hit Return to continue.
```

Figure 7. Sample Mechanical Feasibility Screens

Similarly, the part's electrical feasibility is assessed using the "world-wide" capabilities model. The program accesses the appropriate information from the output of the GT-based design processor. Next, the program parses through each of the part's manufacturing requirements to assess electrical feasibility. Two sample outputs of the part's electrical feasibility are given in Figure 8. The first manufacturing requirement, exposing of the artwork, is satisfied by the Optibeam X7314 and the Colight 9200 photographic enlargers. The surface mounting of the leaded component Q7 is satisfied by the MRSI 501, MRSI 505, TDK CX6160, and Seiko RT3200 robotic placement mechanisms.

The mechanical manufacturability program accesses the output of the design processor and calculates the mechanical MR as described in Chapter 3. The overall results of the mechanical manufacturability rating are given in Figure 9. If the user chooses to investigate the contribution of Material Chemistry to mechanical manufacturability, the underlying design attribute leading to the specific rating is given (Figure 10). In this case, the material contribution is Polyimide/6061 Aluminum, and has poor machinability. Recommendations for material selection which would improve the part's manufacturability are also given.

Finally, the part's electrical manufacturability ratings are determined. In addition to the output of the GT-based design processor, some additional information is required from the user to calculate the part's electrical MR. The overall results of the

```
Part Number : 97942-SAMPLE

Plant       : Worldelec

Manuf. Req.     Available Equip.                                Unavailable Equip.
                Make     Model    Type                          Type
--------------- ----------------------------------------------- ---------------
Expose_Artwork
                Optibm   X7314    Photo_Enlarger
                OR
                Colight  9200     Photo_Enlarger
```

```
Part Number : 97942-SAMPLE

Plant       : Worldelec

Manuf. Req.     Available Equip.                                Unavailable Equip.
                Make     Model    Type                          Type
--------------- ----------------------------------------------- ---------------
SM_Ld_Cmp_Mnt
Ref Des: Q7
                MRSI     501      Robotic_Mounter
                OR
                MRSI     505      Robotic_Mounter
                OR
                TDK      CX6160   Robotic_Mounter
                OR
                Seiko    RT3200   Robotic_Mounter
```

Figure 8. Sample Electrical Feasibility Screens

```
Manufacturability Rating for Part 97942-SAMPLE
 :  52.83 / 100

Contributions to MR :                          Rating
1 .  Material Chemistry                         13.79
2 .  Tolerances                                 12.41
3 .  Machined Feature Orientations               9.66
4 .  Cutouts                                     6.93
5 .  Flats and Slots                             5.13
6 .  Holes Not Perpendicular to AB Plane         3.60
7 .  Holes Perpendicular to AB Plane             1.32
8 .  Complex Cavities                            0.00

Enter the contribution number you wish to examine (1-8)
(to quit type 'q') :
```

Figure 9. Mechanical Manufacturability Overall Ratings

```
Material: Polyimide / 6061 Aluminum has Poor Machinability.

Material(s) with better machinability include:
   PTFE
   PTFE / 6061 Aluminum
   PTFE / Brass
   PTFE / 5083 Aluminum
   Polyimide

Hit Return to continue.
```

Figure 10. Material Contribution to MR and Design Modification Suggestion

electrical MR program are given in Figure 11. A sub-concern of the Tuning and Testing global concern is Voltage (see Appendix D). The results for investigation of the contribution of Voltage under Tuning and Testing are given in Figure 12. Note how both the design attribute and modification suggestions are given.

```
Manufacturability Rating for Part 97942-SAMPLE
 :  52.73 / 100

Contributions to MR:                          Rating
1.   Tuning and Testing                        12.96
2.   Component Attachment                      10.78
3.   Inspection                                 8.92
4.   Substrate Plating                          4.72
5.   Artwork Etching                            3.77
6.   Primer Application                         3.40
7.   Artwork Plating                            2.74
8.   Substrate Cleaning                         2.73
9.   Silk Screening                             1.89
10.  Soldered Hardware                          0.58
11.  Non Soldered Hardware                      0.25

Input the contribution number you wish to examine (1-11)
(or 'q' to quit) and hit return :
```

Figure 11. Electrical Manufacturability Overall Ratings

```
Voltage :
10 uV  <= Minimum Voltage < 1 mV

To lower the Manufacturability Rating,
increase the Minimum Voltage.

Hit Return to continue.
```

Figure 12. Voltage Contribution to MR and
Design Modification Suggestion

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

Due to increasing competition in the marketplace, manufacturing firms have sought ways to gain a competitive edge. Traditional manufacturing methods are rapidly giving way to newer, concurrent engineering trends. The entire production function is developing into a collaborative effort by all parties involved in the product's life cycle from preliminary conception to disposal.

This research illustrates one aspect of life cycle engineering by incorporating manufacturing concerns into the design phase with the goal of producing easily manufacturable designs, using Microwave Modules (MWM's) as a case study. The concurrent engineering system presented here has three main entities. The first is a Product Data Exchange specification using STEP (PDES) database. The PDES model is intended to capture complete design information for a manufactured part. Second, a Group Technology (GT) based design processor analyzes the PDES database and generates a mechanical and an electrical GT code, and two output files containing detailed information on the design attributes captured by the code. The third system component is the manufacturability evaluation programs.

Manufacturability evaluation is divided into two sub-problems. The first consists of assessing the part's feasibility with available equipment and the second of rating the part's manufacturability. The feasibility assessment programs generate the equipment required to produce the mechanical and electrical attributes of the design, then compare them to the machinery available in a particular production environment. The Manufacturability Ratings (MR) are generated to give a measure of the relative difficulty of producing the part. The design attributes leading to specific ratings are provided to the designer along with design modification suggestions to improve the part's manufacturability.

5.1 Conclusions

As a result of the research work presented here, several conclusions can be drawn. The overall system architecture has shown that GT principles can ease manufacturability evaluation. The GT-based design processor filters design attributes from the PDES database into a finite number of groups. For example, all machined features for flat parts can be classified in to the eight MICLASS feature types. Thus, feasibility and manufacturability methodologies can be applied to the design attribute groups rather than trying to account for all possible design attribute types. Also, in some cases, digits of the GT code could be translated directly into manufacturability rating values.

Previous manufacturability research efforts have dealt with either feasibility assessment or manufacturability rating. This research has established the need for both tools in an effective manufacturability evaluation system. The reasoning for this is intuitively obvious. If a design is infeasible for manufacture in a given environment, then a finite manufacturability rating within that environment is meaningless.

In developing the feasibility assessment methodology, the need arose for a manufacturing model to describe the characteristics of a particular set of equipment. This was accomplished by developing a format in which equipment capabilities were numerically expressed, facilitating straightforward comparison of the design requirements with the equipment capabilities.

Finally, the incorporation of expert knowledge in the manufacturability evaluation methodology was demonstrated. In feasibility assessment, this involved development of the mechanical and electrical "rough-cut" process planning rule bases. For manufacturability rating, the weightings provided by MWM manufacturing experts were based on years of collective experience. The feasibility rule bases and the manufacturability rating tables were based on the experience of manufacturing experts from Westinghouse Electric Corporation Electronic Systems

Group and the University of Maryland, College Park. Hence, the rules and tables are somewhat biased to the capabilities of these facilities.

5.2 Recommendations For Further Work

5.2.1 Overall System

Through the course of this research work, a number of points for future work have been revealed. Since the overall system approach was developed in a generic fashion, the same methodology could be applied to include more general types of manufactured products than MWM's. In addition, evaluation of the design from multiple life cycle perspectives would make the system all inclusive. For example, a similar rating scheme could be applied for marketability and disposability. Also, if the system were directly interfaced with a solid modelling CAD package, the manufacturability evaluation feedback could be immediately acted upon.

5.2.2 Feasibility Assessment

The rules in the feasibility assessment rule base are experienced based. Hence, they could easily be implemented in new user friendly Artificial Intelligence software packages such as

Level 5 or Nexpert Object. This would also facilitate efficient rule base modification.

Design attributes and manufacturing capabilities associated with manual operations were omitted due to ambiguities in representation. This problem would need to be overcome for products which are labor intensive.

Feasibility assessment could be used as a basis for subcontracting. Weighting factors for the performance of various vendors could be employed to support these decisions. In addition, having the capabilities of multiple factories in working memory would provide immediate subcontracting options.

Finally, incorporation of other limiting aspects for feasibility would make the system more accurate. For example, in the electronics industry, sequentiality and timing of operations can be critical to the feasibility of product designs.

5.2.3 Manufacturability Rating

Several possibilities for improvements to the MR programs exist as well. The user should have the ability to interactively modify the weighting factors to reflect the capabilities of a particular plant. Currently, this would require modification of the actual program source code. Also, giving the user an indication of how much impact a particular design modification would have on the MR would be helpful. For example, suppose the design modification is to increase an artwork plating tolerance. Quantitative measures of how much the MR would decrease if the tolerance were increased could be provided. Finally, determining the variance of the manufacturability ratings within a large product population would provide the designer a measure of significance that will aid in assessing the differences between manufacturability rating values.

Appendix A

Mechanical Feasibility Rule Base

IF ((feature = Rect_cutout) and (material = conductive_metallic))
THEN required_machinery = (Punch_mach, Lsr_beam_mach,
Ram_e_d_m, Wire_cut_e_d_m)

IF ((feature = Rect_cutout) and (material =
nonconductive_metallic))
THEN required_machinery = (Punch_mach, Lsr_beam_mach)

IF ((feature = Rect_cutout) and (material = mwm_substrate))
THEN Impossible to machine with existing technology.

IF ((feature = Slanted_cutout) and (material = mwm_substrate))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Slanted_cutout) and (material =
nonconductive_metallic))
THEN required_machinery = (Punch_mach, Lsr_beam_mach,
Milling_mach, Hs_mill_mach)

IF ((feature = Slanted_cutout) and (material =
conductive_metallic))

THEN required_machinery = (Punch_mach, Lsr_beam_mach, Milling_mach, Ram_e_d_m, Wire_cut_e_d_m, Hs_mill_mach)

IF ((feature = Radius_cutout) and (material = mwm_substrate))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Radius_cutout) and (material = nonconductive_metallic))
THEN required_machinery = (Punch_mach, Lsr_beam_mach, Milling_mach, Hs_mill_mach)

IF ((feature = Radius_cutout) and (material = conductive_metallic))
THEN required_machinery = (Punch_mach, Lsr_beam_mach, Milling_mach, Ram_e_d_m, Wire_cut_e_d_m, Hs_mill_mach)

IF ((feature = Compl_cutout) and (material = mwm_substrate))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Compl_cutout) and (material = nonconductive_metallic))
THEN required_machinery = (Punch_mach, Lsr_beam_mach, Milling_mach, Hs_mill_mach)

IF ((feature = Compl_cutout) and (material = conductive_metallic))
THEN required_machinery = (Punch_mach, Lsr_beam_mach,
    Ram_e_d_m, Wire_cut_e_d_m)

IF ((feature = Perp_hole) and (material = mwm_substrate) and
    (diameter < 0.002))
THEN Impossible to machine with existing technology.

IF ((feature = Perp_hole) and (material = mwm_substrate) and
    (diameter >= 0.002))
THEN required_machinery = (Hs_drill_mach, Hs_mill_mach)

IF ((feature = Perp_hole) and (material = conductive_metallic) and
    (diameter < 0.002))
THEN required_machinery = (Ram_e_d_m)

IF ((feature = Perp_hole) and (material = nonconductive_metallic)
    and (diameter < 0.002))
THEN Impossible to machine with existing technology.

IF ((feature = Perp_hole) and (material = conductive_metallic) and
    ((0.002 <= diameter) and (diameter <= 4)))
THEN required_machinery = (Drilling_mach, Ram_e_d_m,
    Milling_mach, Hs_drill_mach, Hs_mill_mach)

IF ((feature = Perp_hole) and (material = nonconductive_metallic)
and ((0.002 <= diameter) and (diameter <= 4)))
THEN required_machinery = (Drilling_mach, Milling_mach,
Hs_drill_mach, Hs_mill_mach)

IF ((feature = Perp_hole) and (material = nonconductive_metallic)
and (diameter > 4))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Perp_hole) and (material = conductive_metallic) and
(diameter > 4))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material = mwm_substrate)
and (diameter < 0.002))
THEN Impossible to machine with existing technology.

IF ((feature = Non_perp_hole) and (material = mwm_substrate)
and ((0.002 <= diameter) and (diameter <= 4)) and
(orientation = perpendicular_to_ac))
THEN required_machinery = (Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material = mwm_substrate)
and ((0.002 <= diameter) and (diameter <= 4)) and
(orientation = perpendicular_to_bc))
THEN required_machinery = (Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material = mwm_substrate)
and ((0.002 <= diameter) and (diameter <= 4)) and
(orientation = skewed_to_one_plane))
THEN required_machinery = (Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material = mwm_substrate)
and ((0.002 <= diameter) and (diameter <= 4)) and
(orientation = skewed_to_more_than_one_plane))
THEN required_machinery = (Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
conductive_metallic) and (diameter < 0.002))
THEN required_machinery = (Ram_e_d_m)

IF ((feature = Non_perp_hole) and (material =
nonconductive_metallic) and (diameter < 0.002))
THEN Impossible to machine with existing technology.

IF ((feature = Non_perp_hole) and (material = conductive_metallic) and ((0.002 <= diameter) and (diameter <= 4)) and (orientation = perpendicular_to_ac))

THEN required_machinery = (Drilling_mach, Ram_e_d_m, Milling_mach, Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material = conductive_metallic) and ((0.002 <= diameter) and (diameter <= 4)) and (orientation = perpendicular_to_bc))

THEN required_machinery = (Drilling_mach, Ram_e_d_m, Milling_mach, Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material = conductive_metallic) and ((0.002 <= diameter) and (diameter <= 4)) and (orientation = skewed_to_one_plane))

THEN required_machinery = (Drilling_mach, Milling_mach, Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material = conductive_metallic) and ((0.002 <= diameter) and (diameter <= 4)) and (orientation = skewed_to_more_than_one_plane))

THEN required_machinery = (Drilling_mach, Milling_mach, Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
nonconductive_metallic) and
((0.002 <= diameter) and (diameter <= 4)) and (orientation =
perpendicular_to_ac))
THEN required_machinery = (Drilling_mach, Milling_mach,
Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
nonconductive_metallic) and ((0.002 <= diameter) and
(diameter <= 4)) and (orientation = perpendicular_to_bc))
THEN required_machinery = (Drilling_mach, Milling_mach,
Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
nonconductive_metallic) and
((0.002 <= diameter) and (diameter <= 4)) and
(orientation = skewed_to_one_plane))
THEN required_machinery = (Drilling_mach, Milling_mach,
Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
nonconductive_metallic) and ((0.002 <= diameter) and
(diameter <= 4)) and (orientation =
skewed_to_more_than_one_plane))

THEN required_machinery = (Drilling_mach, Milling_mach,
    Hs_drill_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
    conductive_metallic) and
    (diameter > 4) and (orientation = skewed_to_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
    nonconductive_metallic) and (diameter > 4) and (orientation
    = skewed_to_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
    conductive_metallic) and (diameter > 4) and (orientation =
    skewed_to_more_than_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Non_perp_hole) and (material =
    nonconductive_metallic) and
    (diameter > 4) and (orientation =
    skewed_to_more_than_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Flat_slot) and (material = mwm_substrate) and
((orientation = perpendicular_to_ab) or (orientation = perpendicular_to_bc) or (orientation = perpendicular_to_ac)))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Flat_slot) and (material = mwm_substrate) and
(orientation = skewed_to_one_plane))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Flat_slot) and (material = mwm_substrate) and
(orientation = skewed_to_more_than_one_plane))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Flat_slot) and (material = nonconductive_metallic)
and ((orientation = perpendicular_to_ab) or (orientation = perpendicular_to_bc) or (orientation = perpendicular_to_ac)))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Flat_slot) and (material = nonconductive_metallic)
and (orientation = skewed_to_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Flat_slot) and (material = nonconductive_metallic)
and (orientation = skewed_to_more_than_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Flat_slot) and (material = conductive_metallic) and
((orientation = perpendicular_to_ab) or (orientation =
perpendicular_to_bc) or (orientation =
perpendicular_to_ac)))
THEN required_machinery = (Milling_mach, Ram_e_d_m,
Hs_mill_mach)

IF ((feature = Flat_slot) and (material = conductive_metallic) and
(orientation = skewed_to_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Flat_slot) and (material = conductive_metallic) and
(orientation = skewed_to_more_than_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Complex_cavity) and (material = mwm_substrate)
and ((orientation = perpendicular_to_ab) or (orientation =
perpendicular_to_bc) or (orientation =
perpendicular_to_ac)))
THEN required_machinery = (Hs_mill_mach)

```
IF ((feature = Complex_cavity) and (material = mwm_substrate)
      and (orientation = skewed_to_one_plane))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Complex_cavity) and (material = mwm_substrate)
      and (orientation = skewed_to_more_than_one_plane))
THEN required_machinery = (Hs_mill_mach)

IF ((feature = Complex_cavity) and (material =
      nonconductive_metallic) and ((orientation =
      perpendicular_to_ab) or (orientation = perpendicular_to_bc)
      or (orientation = perpendicular_to_ac)) )
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Complex_cavity) and (material =
      nonconductive_metallic) and (orientation =
      skewed_to_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Complex_cavity) and (material =
      nonconductive_metallic) and (orientation =
      skewed_to_more_than_one_plane))
THEN required_machinery = (Milling_mach, Hs_mill_mach)
```

IF ((feature = Complex_cavity) and (material = conductive_metallic) and ((orientation = perpendicular_to_ab) or (orientation = perpendicular_to_bc) or (orientation = perpendicular_to_ac)))

THEN required_machinery = (Milling_mach, Ram_e_d_m, Hs_mill_mach)

IF ((feature = Complex_cavity) and (material = conductive_metallic) and (orientation = skewed_to_one_plane))

THEN required_machinery = (Milling_mach, Hs_mill_mach)

IF ((feature = Flat_slot) and (material = conductive_metallic) and (orientation = skewed_to_more_than_one_plane))

THEN required_machinery = (Milling_mach, Ram_e_d_m, Hs_mill_mach)

Appendix B

Electrical Feasibility Rule Base

IF (Man_req = Expose_Artwork)
THEN required_machinery = (Photo_Enlarger)

IF (Man_req = Artwk_Tin_Plat)
THEN required_machinery = (Tin_Plat_Bath)

IF (Man_req = Artwk_Nkl_Plat)
THEN required_machinery = (Nickl_Plat_Bath)

IF (Man_req = Artwk_Gld_Plat)
THEN required_machinery = (Gold_Plat_Bath)

IF (Man_req = Artwk_Inspct)
THEN required_machinery = (Artwrk_Insp_Eqp)

IF (Man_req = Subst_Tin_Plat)
THEN required_machinery = (Tin_Plat_Bath)

IF (Man_req = Subst_Nkl_Plat)
THEN required_machinery = (Nickl_Plat_Bath)

IF (Man_req = Subst_Gld_Plat)

THEN required_machinery = (Gold_Plat_Bath)

IF ((Man_req = Chip_Comp_Mnt) and (lead_pitch > 0.03))
THEN required_machinery = (Robotic_Mounter)

IF ((Man_req = Chip_Comp_Mnt) and (lead_pitch <= 0.03))
THEN required_machinery = (Robotic_Mounter)

IF (Man_req = Chip_Comp_Sldr)
THEN required_machinery = (Resistive_Tool, Laser_Rflow,
Vapor_Ph_Rflow, I_R_Reflow, Nit_Con_Rflow)

IF (Man_req = SM_Ld_Cmp_Frm)
THEN required_machinery = (Lead_Form_Eqp)

IF ((Man_req = SM_Ld_Cmp_Mnt) and (lead_pitch <= 0.03))
THEN required_machinery = (Robotic_Mounter)

IF ((Man_req = SM_Ld_Cmp_Mnt) and (lead_pitch > 0.03))
THEN required_machinery = (Robotic_Mounter)

IF (Man_req = SM_Ld_Cmp_Sldr)
THEN required_machinery = (Resistive_Tool, Laser_Rflow,
Vapor_Ph_Rflow, I_R_Reflow, Nit_Con_Rflow)

IF (Man_req = Gnd_Pin_Insrtn)
THEN required_machinery = (Insert_Mach)

IF (Man_req = Rbn_Jpr_Form)
THEN required_machinery = (Rbn_Jpr_Fm_Eqp)

IF (Man_req = Lang_Coupler)
THEN required_machinery = (Parall_Gp_Wldr)

IF (Man_req = Adhsv_Preform)
THEN required_machinery = (Condct_Cur_Blt)

IF (Man_req = Solder_Preform)
THEN required_machinery = (Nit_Con_Rflow)

IF (Man_req = Non_Thrd_Term)
THEN required_machinery = (Insert_Mach)

IF (Man_req = Hairpin_Conn)
THEN required_machinery = (Hrpin_Form_Eqp)

IF (Man_req = Smpl_Adhsv_Appl)
THEN required_machinery = (Adhsv_Appl_Eqp)

IF (Man_req = Cplx_Adhsv_Appl)

THEN required_machinery = (Adhsv_Appl_Eqp)

IF (Man_req = Cplx_Adhsv_Cur)
THEN required_machinery = (Condct_Cur_Blt)

Appendix C

Mechanical Manufacturability Rating Tables

Concern: Cutouts

Overall Weight:7

Different Cutout Types	# of Complex Cutouts	# of Simple Cutouts
Weight=9	Weight=10	Weight=4
No Cutouts=0	No Cutouts=0	No Cutouts=0
1 Type of Simple Cutouts=2	1-10 Complex Cutouts=3	1-10 Simple Cutouts=3
2 Types of Simp. Cutouts=4	11-100 Complex Cutouts=6	11-100 Simple Cutouts=6
3 Types of Simp. Cutouts=6	>100 Complex Cutouts=10	>100 Simple Cutouts=10
Only Complex Cutouts=9		
Compl. & Simple Cutouts=10		

Concern: Perpendicular Holes

Overall Weight=3

Number of Holes	Additions (Thrds.,Cbores, Csinks, etc.).	Different Diameters	Ratio of Length to Diameter (Highest Ratio)	Location
Weight=2	Weight=6	Weight=8	Weight=10	Weight=9
No Holes =0	No Additions =0	No Holes=0	No Holes=0	No Holes=0
1 - 10 =1	1 Type of Addition=3	1 Diameter=1	L/D<1=2	All in from same side=1
11 - 100 =5	2 Types of Additions=7	2-5 Diameters =5	1<=L/D<2=5	Holes on two sides=10
>100 =10	>=3 Types of Additions=10	>5 Diameters =10	L/D>=2=10	

Concern: Non Perpendicular Holes

Overall Weight=5

Number of Holes	Additions (Thrds.,Cbores, Csinks, etc.)	Different Diameters	Ratio of Length to Diameter (Highest Ratio)	Location
Weight=2	Weight=6	Weight=8	Weight=10	Weight=9
No Holes =0	No Additions =0	No Holes=0	No Holes=0	No Holes=0
1 - 10 =1	1 Type of Addition=3	1 Diameter=1	L/D<1=2	All in from same side=1
11 - 100 =5	2 Types of Additions=7	2-5 Diameters =5	1<=L/D<2=5	Holes on two sides=4
>100 =10	>=3 Types of Additions=10	>5 Diameters =10	L/D>=2=10	Holes on three sides=7
				Holes on more than three sides=10

Concern: Flats / Slots

Overall Weight:7

Number of Flats/Slots	Location
Weight=2	Weight=6
None=0	No Flats/Slots =0
1 -10=5	All in from same side=1
>10=10	F/S on two sides=4
	F/S on three sides=7
	F/S on more than 3 sides=10

Concern: Complex Cavities

Overall Weight:9

Number of Complex Cavities	Feature Location
Weight=2	Weight=6
No CC's=0	No CC's=0
1=1	All in from same side=1
2-3=3	CC's on two sides=4
3-10=6	CC's on three sides=7
>10=10	CC's on more than three sides =10

Concern: Tolerance

Overall Weight:9

Tolerance
Weight=10
None=0
1 Type of Dim. Tolerance=2
2 Types of Dim. Tolerance=4
3 Types of Dim. Tolerance=6
Type A Geom. Tolerance=8
Type B Geom. Tolerance=10

Concern: Material Chemistry

Overall Weight:10

Material Machinability
Weight=10
E=1 "Excellent"
G=2 "Good"
F=5 "Fair"
P=8 "Poor"
D=10 "Difficult"

Concern: Orientation

Overall Weight:8

Orientations
Weight=10
No Machined Elements=0
All MSE's perpendicular to one plane =1
MSE's perp. to more than one plane=4
MSE's skewed to one plane=7
MSE's skewed to more than one plane=10

Appendix D

Electrical Manufacturability Rating Tables

Concern: Artwork Etching

Overall Weight=2

Line Spacing (Thousandths) (Closest)	Line Width (Thousandths) (Smallest)	Artwork Tolerance (Thousandths)	Copper Thickness (oz/sq. in.)
Weight=10	Weight=10	Weight=8	Weight=5
>0.1=1	>0.1=1	>0.01=1	<1=10
0.1-0.01=2	0.1-0.01=2	0.01-0.001=2	1-2=2
<0.01=10	<0.01=10	<0.001-0.0005 =4	>2=10
		<0.0005=10	

Concern: Artwork Plating

Overall Weight=2

Line Spacing (Thousandths) (Closest)	Line Width (Smallest) (Thousandths)	Artwork Tolerance (Thousandths)	Number of Platings
Weight=10	Weight=10	Weight=8	Weight=5
>0.1=1	>0.1=1	>0.01=1	0=0
0.1-0.01=2	0.1-0.01=2	0.01-0.001=2	1=3
<0.01=10	<0.01=10	<0.001-0.0005 =4	2=6
		<0.0005=10	>2=10

Artwork Plating (Continued)

Thickness of Plating (oz/sq. in.)	Plating Tolerance	Masking Requirements	Waste Treatment	Safety
Weight=5	Weight=5	Weight=10	Weight=10	Weight=10
<1=10	>0.001=0	none=0	none=0	no concerns=0
1 - 2 =2	0.001-0.0005 =5	1=3	acid/base=5	lead, or tin, or copper=5
>2=10	<0.0005=10	2=6	heavy metal =10	arsenic, or cadmium, or mercury=10
		>2=10		

Concern: Substrate Plating

Overall Weight=3

Number of Platings	Thickness of Plating (oz/sq. in.)	Plating Tolerance	Masking Requirements
Weight=5	Weight=5	Weight=5	Weight=10
0=0	<1=10	>0.001=0	0=0
1=3	1 - 2=2	0.001-0.0005 =5	1=3
2=6	>2=10	<0.0005=10	2=6
>2=10			>2=10

Concern: Substrate Plating (Continued)

Waste Treatment	Safety
Weight=10	Weight=10
none=0	no concern =0
acid/base=5	lead, or tin, or copper=5
heavy metal =10	arsenic,CuCN, cadmium, or mercury=10

Concern: Silk-Screening (Marking)

Overall Weight=1

Silk Screening (Marking)
Weight=10
No=0
Yes=10

Concern: Component Attachment

Overall Weight=9

# of Leads to be Formed per Cmpnt (Wrst Cse)	# of Types of Adhesive Curing	Total # of Leads to be Pre-tinned	Placement Accuracy (Worst Case)	Soldering Technique	Number of Components
Weight=10	Weight=5	Weight=5	Weight=10	Weight=5	Weight=10
<=2=1	0=0	<=2=2	>0.1=1	Isolated Reflow =10	0=0
3-6=4	1=2	3-6=6	0.01,<=0.1=4	Bulk Reflow =5	1-3=1
7-20=6	2=4	>6=10	0.005,<=0.01 =8		4-12=2
>20=10	>=3=10		<0.005=10		13-28=3
					29-50=4
					51-78=5
					79-112=6
					113-153=7
					154-200=8
					>200=9

Concern: Component Attachment (Continued)

Orientations	Patterns
Weight=8	Weight=7
No Components=0	No Components =0
Components at 1 Orientation=1	Grid Pattern=3
Components at 2 Orientations=4	Random Pattern=10
Components at 3 Orientations=7	
Components at Random Orient. =10	

Concern: Non Soldered Hardware

Overall Weight=5

# of Nuts, Bolts, etc.	# of Simple Adhesives	# of Complex Adhesives	# of Supports	# of Other types of hrdwr
Weight=4	Weight=6	Weight=10	Weight=4	Weight=6
None=0	None=0	None=0	None=0	None=0
1-10=1	1=3	1=5	1-10=1	1-10=3
11-40=3	2=6	2=7	>10=10	>10=10
41-80=6	>2=10	>2=10		
>80=10				

Concern: Soldered Hardware

Overall Weight=6

# of Grnd Pins,Non-Thrd Termin.	# of Grnd Scrws, Thrd Termin's, etc	# of Wire Jmprs, Coax Cables	# of Ribbon Jmprs,Hair-pins, etc.	# of Lang Couplers	# of Types of Other H'ware
Weight=7	Weight=4	Weight=10	Weight=8	Weight=10	Weight=6
None=0	None=0	None=0	None=0	None=0	None=0
1-10=1	1-20=4	1-3=1	1-6=2	1-2=3	1-10=3
11-20=3	21-50=6	4-8=3	7-16=4	3-4=6	>10=10
21-40=6	>50=10	9-20=5	17-25=6	>4=10	
>40=10		>20=10	>25=10		

Concern: Substrate Cleaning

Overall Weight=2

Number of Chemicals	Outgassing Requirements
Weight=10	Weight=8
0-1=1	yes=10
2-3=5	no=0
>3=10	

Concern: Primer Application

Overall Weight=3

Number of Primer Applications
Weight=10
0=0
1=3
2=6
Greater than or equal to 3=10

Concern: Tuning and Testing

Overall Weight=10

# of Types of Tuning	Software Complexity	Test Expense	Timing	Bandwidth
Weight=10	Weight=8	Weight=9	Weight=4	Weight=6
No tuning=0	none=0	low=1	Not Significant=0	Not Significant=0
1 type=2	low=2	medium=4	DC-100mS=1	Less than 100kHz=1
2 types=4	medium=5	high=10	10mS-100mS =2	100kHz-1MHz =2
3 or more=10	high=10		10mS-1uS=3	1MHz-10MHz =3
			1uS-100nS=4	10MHz-100 MHz=4
			100nS-10nS=5	100MHz-3 GHz=6
			10nS-1nS=8	3GHz-6GHz =8
			Less than 1 nS=10	Greater than 6GHz=10

Concern: Tuning and Testing (Continued)

Current	Operating Frequency	Gain & Sensitivity	Voltage	Power Den. (W/sq. in.)
Weight=10	Weight=8	Weight=9	Weight=10	Weight=3
<100uA or >=30A=10	Not Significant=0	Not Significant=0	<10uV or >=1000V=10	1=1
100uA - 1mA or 20A-30A=8	<1MHz=1	<10dB=1	10uV-1mV or 500V-1000V=8	2-3=2
1mA-10mA or 10A-20A=4	1MHz-100 MHz=2	10dB-20dB=3	1mV-10mV or 100V-500V=4	3-4=3
10mA-0.1A or 1A-10A=2	100MHz-500 MHz=3	20dB-54dB=4	10mV-0.1V or 50V-100V=3	4-5=4
0.1A-1A=1	500MHz-2 GHz=6	54dB-60dB=6	0.1V-50V=1	5-6=5
	>=2 GHz=10	>=60dB=10		Greater than 6=10

Concern: Inspection

Overall Weight=10

Number of Components & Hardware	Lead Pitch	Soldering Technique
Weight=8	Weight=10	Weight=4
1-10=0	>.1=0	Isolated=5
11-50=2	.1-.05=2	Bulk=10
51-100=6	.05-.02=4	
>100=10	<.02=10	

Appendix E
Feature Location

One key factor that plays a critical role in mechanical manufacturability rating is feature location with respect to the face of the part envelope. The mechanical manufacturability tables in Appendix D show that location is a sub-concern of holes, flats, slots, and complex cavities. It is noted however, that the MICLASS GT code does not capture feature location. Therefore, location must be determined through direct interaction with the PDES database. An appropriate routine was incorporated into the GT-based design processor specifically for this purpose.

Each feature in the PDES database is located and oriented with respect to the part's envelope by an Axis 2 Placement [Bahadur *et al.*, 1991]. The latter is a local coordinate system comprising of the coordinates of the local origin and the local x and z directions. Since an Axis 2 Placement is a right handed coordinate system, the local y axis is implied. Assume that the part has a rectangular solid envelope whose sides are parallel to the global coordinate system in which the part is defined. Then the plane surfaces which contain the six part faces are given by:

$$(x_{min}, y, z)$$
$$(x_{max}, y, z)$$

(x, y_{min}, z)

(x, y_{max}, z)

(x, y, z_{min})

(x, y, z_{max})

The feature's location is determined through comparison of the Axis 2 Placement x coordinate to x_{min} and x_{max}, the y coordinate to y_{min} and y_{max}, and the z coordinate to z_{min} and z_{max}. The matching values give the feature location. For example, in Figure 13, features 1 and 2 are considered to be on the top face, because their Axis 2 Placement z coordinates match z_{max}. Feature 3 is on the front face because its Axis 2 Placement y coordinate matches y_{min}. Feature 4 is a rectangular cutout which passes completely through the part and therefore its location is not considered.

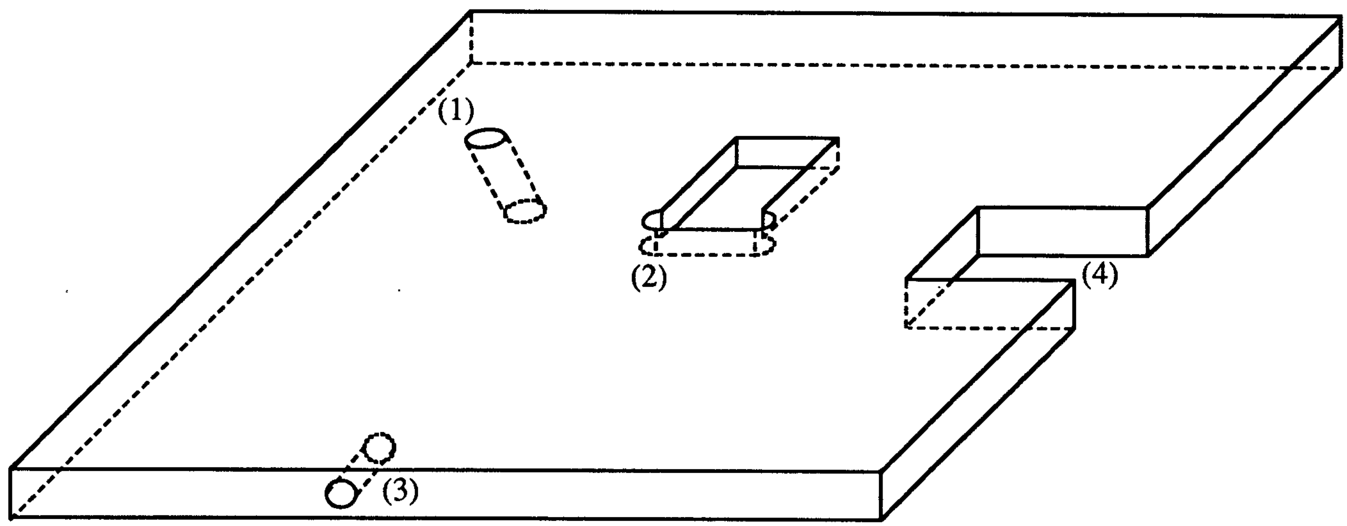

Figure 13. Sample Form Features on a Flat Part

REFERENCES

Bahadur, S., Harhalakis, G., Hosier, R., Minis, I., 1991, "A PDES Model for Microwave Modules", Proceedings of the ASME International Computers in Engineering Conference, Sante Clara, CA.

Barash, M. M., 1976, "Group Technology Considerations in Planning Manufacturing Systems", Transactions of SME CAD / CAM IV Conference.

Boothroyd, G., Dewhurst, P., Knight, W. A., 1992, "Selection of Materials and Processes for Component Parts", Proceedings of the 1992 NSF Design and Manufacturing Systems Conference, Atlanta, GA.

Chen, Y. M., Miller, R. A., Vemuri, K. R., 1991, "On Implementing an Integrated Design-Manufacturability Assessment Environment", ASME Computers in Engineering.

Computer Integrated Manufacturing Laboratory, 1992 "Microwave Module Group Technology Coding and Manufacturability Evaluation Program User's Manual", Department of Mechanical Engineering and Systems Research Center, University of Maryland, College Park.

Courtright, M.J., 1988, "Manufacturability Analysis for a Flexible Manufacturing Cell", M.S. Thesis, University of Maryland, College Park.

Daigle, R. C., Bull, G. W., Doyle, D. J., 1991, "Multi-Layer Microwave Boards, Manufacturability & Design Issues", Microwave Hybrids Circuits Conference.

Foster, L. W., 1982, Geo-Metrics II, Addison - Wesley Publishing Company, Inc., Reading, Massachusetts.

Fox, G., 1990, "PCB Design for Manufacturability", Circuit Design, Vol. 7 no. 6.

Harhalakis, G., Minis, I., Kinsey, A., 1992, "Automated Group Technology Code Generation Using PDES," submitted for consideration in Rensselaer's Third International Conference On Computer Integrated Manufacturing.

Ishii, K., and Mukherjee, S., 1992, "Compatibility-based Life-cycle Design", Proceedings of the 1992 NSF Design and Manufacturing Systems Conference, Atlanta, GA.

Jara-Almonte, C.C., and Krishnamoorthy, S., 1991, "Evaluation of the Manufacturability of Machined Components Using Axiomatic Design Principles", Proceedings of the 1991 NSF Design and Manufacturing Systems Grantees Conference, Austin, TX.

Kinsey, A.J., 1992, "Automated Generation of Group Technology Codes From A PDES Product Information Model", M.S. Thesis, Department of Mechanical Engineering, University of Maryland, College Park.

Masyga, J., 1990, "Teamwork Design for PWB Manufacturability", Circuit Design, Vol. 7 no. 6.

Ogden, C., 1990, "The Impact of Process Capability on the Manufacturability of Microwave Circuit Boards", Microwave Journal.

Organization for Industrial Research, 1986, OIR Multi-M, Code Book and Conventions, Waltham MA.

Padhy, S.K., and Dwivedi, S.N., 1991, "PWBMA - An Object - Oriented Knowledge - Base System For Manufacturability of Printed Circuit Boards", Proceedings of the ASME International Computers in Engineering Conference, Sante Clara, CA.

Poli, C., and Rajagopalan, S., 1991, "Design for Injection Molding and Die casting: A Knowledge-Based Approach", ASME Computers in Engineering.

Reodecha, M., 1985, A Classification And Coding System For CAD/CAM Applications In The Electronics Industry, PhD. Dissertation, North Carolina State University, Raleigh, N.C.

Shah, J.J., and Hsiao, D.W.-C., Robinson, R., 1990, "A Framework for Manufacturability evaluation in the Machining Domain", Proceedings of NSF Design and Manufacturing Systems Conference.

Smart, H. G., 1982, "Least Cost Estimating with Group Technology", Journal of Manufacturing Systems, Vol. 1 no. 1.

Sule, D. R., 1991, "Machine Capacity Planning in Group Technology", International Journal of Production Research, Vol. 29 no. 9.

Tanner, J. P., 1985, Manufacturing Engineering, Marcel Dekker, Inc., New York, New York.

Teicholz, E., Orr, J., 1987, Computer Integrated Manufacturing Handbook, McGraw-Hill Inc., New York, New York.

Westinghouse Electric Corporation, 1984, Final Report: Manufacturing Methods and Technology AN / SPS - 40 Power Amplifier Module.

Westinghouse Electric Corporation, 1990, Hybrid Complexity Factor - Concurrent Engineering.