# A DECISION SUPPORT SYSTEM METHODOLOGY FOR THE SELECTION OF RAPID PROTOTYPING TECHNOLOGIES FOR INVESTMENT-CAST GAS TURBINE PARTS

by

ANGELA GALLAGHER
B.S. Purdue University, 1994

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Major Professor: Christopher D. Geiger

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# ABSTRACT

In the power generation sector, more specifically, the gas turbine industry, competition has forced the lead time-to-market for product advancements to be more important than ever. For design engineers, this means that product design iterations and final product development must be completed within both critical time windows and budgetary constraints. Therefore, two areas that have received significant attention in the research and in practice are: (1) rapid prototyping technology development, and (2) rapid prototyping technology selection.

Rapid prototyping technology selection is the focus of this research. In practice, selecting the rapid prototyping method that is acceptable for a specific design application is a daunting task. With technological advancements in both rapid prototyping and conventional machining methods, it is difficult for both a novice design engineer as well as an experienced design engineer to decide not only what rapid prototyping method could be applicable, but also if a rapid prototyping method would even be advantageous over a more conventional machining method and where in the manufacturing process any of these processes would be utilized.

This research proposes an expert system that assists a design engineer through the decision process relating to the investment casting of a superalloy gas turbine engine component. Investment casting is a well-known technique for the production of many superalloy gas turbine parts such as gas turbine blades and vanes. In fact, investment-cast turbine blades remain the state of the art in gas turbine blade design. The proposed automated expert system allows the engineer to effectively assess rapid prototyping opportunities for desired gas turbine blade application. The system serves as a starting point in presenting an engineer with commercially-available state-of-the-art rapid prototyping options, brief explanations of each option and the advantages and disadvantages of each option. It is not intended to suggest an optimal solution as there is not only one unique answer. For instance, cost and time factors vary depending upon the individual needs of a company at any particular time as well as existing strategic partnerships with particular foundries and vendors.

The performance of the proposed expert system is assessed using two real-world case studies. The first case study shows how the expert system can advise the design engineer when suggesting rapid manufacturing in place of investment casting. The second case study shows how rapid prototyping can be used for creating part patterns for use within the investment casting process. The results from these case studies are telling in that their implementations potentially result in an 82 to 94% reduction in design decision lead time and a 92 to 97% cost savings.

I would like to dedicate this research to my family, my source of encouragement.

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# CHAPTER 1:
# INTRODUCTION

## 1.1 Motivation of This Work

As competition has forced the lead time-to-market for product advancements within the gas turbine (GT) industry to be more important than ever, rapid prototyping (RP) technologies have received significant attention. However, RP technologies are dynamic and require frequent monitoring if one desires to be kept up-to-date. In addition, an engineer must not only know which RP processes can be appropriately utilized for a particular application, but must also understand how those processes fit into the manufacturing process.

This is of particular interest in the design of gas turbine engine parts. The current industry practice when designing GT parts is to rely on in-house manufacturing engineers or on established relationships with foundries to suggest appropriate RP options. Yet, this practice can be faulty when the manufacturing engineers are not kept up-to-date with their RP knowledge and/or the consulted foundry only presents options that they can accommodate. Hence, there is a need for a decision support system (DSS) that can assist GT design engineers in selecting the most feasible RP technology within the appropriate step in the manufacturing process for GT parts. This research is carried out in order to design such a DSS to be used by GT design engineers who do not have an extensive knowledge of RP but would like to utilize RP to facilitate their design iterations.

The purpose of the system developed in this research effort is to assist GT design engineers in not only understanding the basic principles of the investment casting (IC) process, which is necessary in the production of turbine and combustion parts requiring superalloy properties, but also to provide an overview of pertinent RP processes and show where these methods can be utilized within the IC process to enable faster and low-cost design iterations. Investment casting is the primary focus in this research because IC is a well-known technique for the production of many superalloy gas turbine parts such as blades and vanes (Dierksmeier and Ruppel, 2003) and an investment-cast turbine blade remains the state-of-the-art in gas turbine blades (Shelmet Precision Casting, 2009). The primary purpose of this DSS is not to present a specific course of action to the GT design engineer, but, rather, to present the engineer a set of design options from which the engineer can choose that which is best depending upon his/her budgetary and time specifications. Such a DSS can be utilized by GT original equipment manufacturers (OEMs) such as Siemens Energy Inc., General Electric (GE) and Mitsubishi.

## 1.2 Expected Contributions of This Research Investigation

The findings of this research effort contribute significantly not only to the GT industrial practice, but also to the research community. When used during product development, RP can potentially offer substantial savings in terms of time and cost. It is suggested that RP can potentially reduce design costs by 70% and lead time by 90% (Waterman and Dickens, 1994). However, if a design engineer does not select and utilize the most appropriate RP method, these benefits are not fully realized. In practice, selecting an appropriate RP method is challenging for several reasons. First, there is a large number of RP processes and secondary indirect rapid tooling processes available with new technologies being introduced each year. Furthermore, a designer must be knowledgeable of the selection criteria such as time, cost, complexity, accuracy, etc. Therefore, the findings presented in this research investigation can serve as a valuable assistant to the design engineer in selecting the most appropriate technology and/or process. However, it is important to note that the knowledge base on which the DSS is based must be updated regularly with the latest RP technologies. In addition, gas turbine manufacturers such as Siemens Energy, Inc. and GE can adapt this research to their particular needs concerning strategic alliances with specific RP vendors. Strategic alliances between companies and vendors create exclusive RP opportunities.

For the research community, a novel approach is presented to show the importance of not only mapping specific manufacturing processes to appropriate RP applications, but also suggesting rapid manufacturing (RM) opportunities that allow a more traditional manufacturing process to be bypassed entirely when applicable. Furthermore, an approach addressing RP options applicable to intricate cores is a necessary feature for an expert system geared towards gas turbine parts. This approach can be further utilized as the foundation for other industries and manufacturing processes other than IC.

## 1.3 Organization of the Remainder of This Thesis Document

This thesis is organized as follows. Chapter 2 presents an overview of RP, RT, and RM and then explains such processes that are pertinent to gas turbine part design and manufacturing that typically require investment casting. This chapter further presents an overview of gas turbines, describes the IC process, and then presents an overview of how RP, RT, and RM fit within the investment casting process of gas turbine parts. Readers that are familiar with rapid technologies can proceed directly to Chapter 3.

Chapter 3 presents a literature review of existing RP/RT/RM-based decision support tools, compares these tools, and presents an explanation of why the research presented in this document is needed.  Based on the results from the review of the open literature, it is found that there are limitations with the existing tools as these tools do not address cores, GT material issues, and the possibilities of replacing investment casting with RM with respect to concerns relative to investment-cast GT parts. Chapter 4 introduces the proposed methodology behind the creation of the decision support system, which is based on the principles of expert system design, designed to address these limitations. Chapter 5 describes an implementation of the proposed expert system logic. Validate of the proposed decision support system involves two case studies, which are presented in Chapter 6. Chapter 7 concludes this research and outlines directions for further research in this area.

# CHAPTER 2:
# OVERVIEW OF RAPID TECHNOLOGIES

## 2.1 Introduction

The purpose of this chapter is to briefly summarize the rapid technologies and processes including those that support existing rapid prototyping methodologies. In this summary, definitions and illustrations are provided. This chapter concludes with an overview of gas turbine engines and the components of gas turbines that are suitable for rapid production using investment casting. Readers familiar with rapid technologies and gas turbine engine design may proceed directly to Chapter 3, where a review of the current literature relevant to rapid technologies application to gas turbine part design, development and manufacture is given.

## 2.2 Definitions of Existing Rapid Technologies

The term Rapid Prototyping (RP) has been defined, in both research and practice, many ways to describe prototyping processes, as shown in Figure 2.1. For instance, some industries use the term RP when the process is completed more rapidly now than previously. However, for the purpose of this research, RP are defined as technologies and processes that use and implement CAD data to create parts through an additive process. That is, RP is a technique that creates parts a layer at a time without machining, molding, or casting.

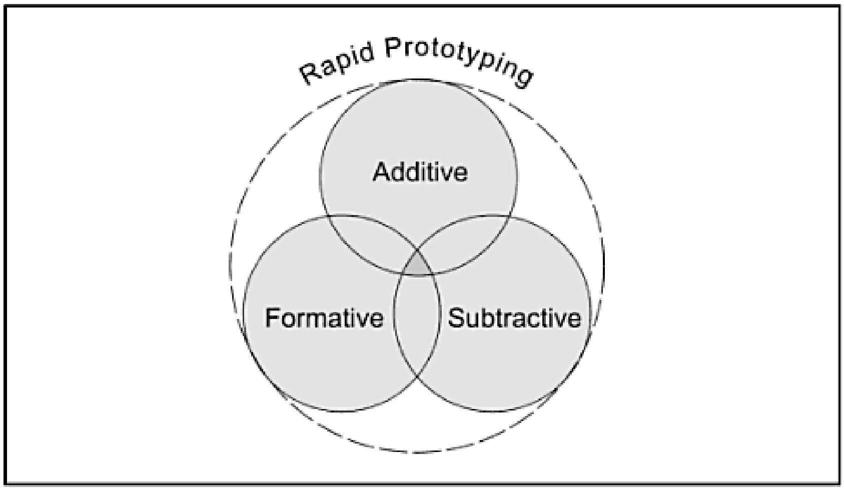


Figure 2.1. Overview of rapid prototyping (obtained from Grimm (2004)).

There are also several definitions for rapid tooling and rapid manufacturing. In this research, the definitions provided by Grimm (2004), a well-known and well-cited authority in RP, are used. Rapid tooling (RT) is the "…production of tools, molds, or dies, directly or indirectly, from a rapid prototyping technology" (Grimm, 2004). Rapid manufacturing (RM) is defined as the "…production of end-use parts, directly or indirectly, from a rapid prototyping technology" (Grimm, 2004).

To further define RT and RM, two additional characteristics of these processes are provided: (1) direct processes and (2) indirect processes. Direct processes "…produce the actual tool (or tool insert) … on the rapid prototyping system" (Grimm, 2004). Indirect processes are processes in which "…there is a secondary process between the output of the rapid prototyping system and the final tool…" (Grimm, 2004). In other words, a direct process actually makes the tool or part, and an indirect process offers a way to create an inverse of the part, which is especially useful when a temporary tool is needed for a short production run.

## 2.3 Description of Direct Rapid Processes

### 2.3.1 Stereolithography (SL or SLA®)

Stereolithography (SL), developed by 3D Systems, Inc. is currently referred to as SLA®, which is a registered trademark of 3D Systems, Inc. SL builds highly accurate three dimensional (3D) parts by using 3D CAD data and an ultraviolet point laser to photo-cure a liquid resin into solid cross-sections, layer by layer (3D Systems, 2009). After the part is created in the SL machine, it is removed and placed in a post-curing chamber for final photo-curing. After the part is cured, further finishing can be done depending on the desired application. An overview of the SL process is shown in Figure 2.2.

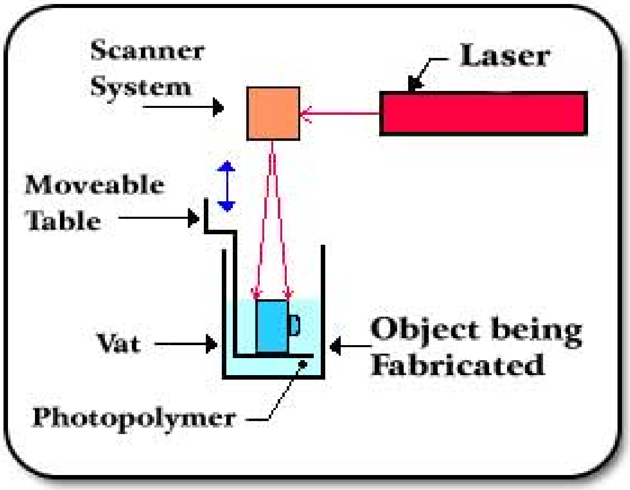


Figure 2.2. Illustration of the SL process (obtained from LAE Technologies (2005)).

### 2.3.2 Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS)

Selective Laser Sintering (SLS), developed by the DTM Corporation, is now owned by 3D Systems (Grimm, 2004). SLS uses 3D CAD data and an SLS machine to create 3D objects from powdered materials. An SLS machine has two powder magazines on either side of the fabrication area. There is a roller that transfers powder from one magazine to the build area with one layer of thickness. Heat from a laser beam steered by a scanning system sinters the powder together. The platform then descends a layer thickness and the process repeats until the part is completed. Excess powder is then brushed away and manual finishing is performed. An illustration of the SLS process is shown in Figure 2.3.

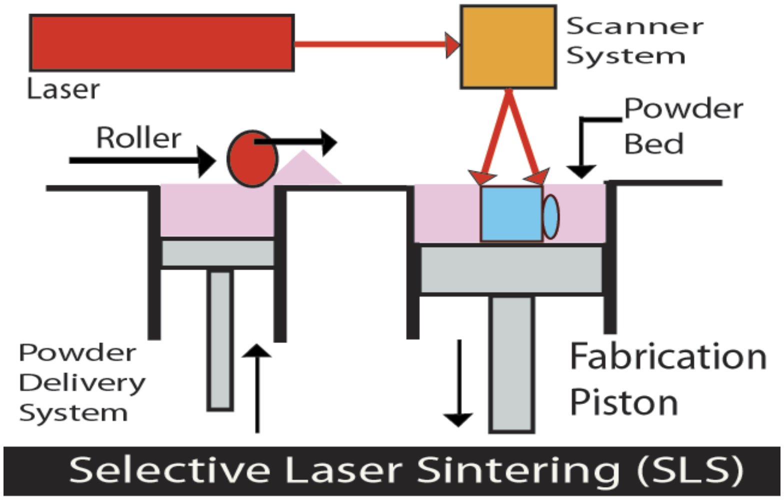


Figure 2.3. Illustration of the SLS process (obtained from Martello Co. (2009)).

Direct Metal Laser Sintering (DMLS) is similar to SLS with the notable difference being that a wider variety of metals can be used with DMLS, including super-alloys (Harbec Plastics, Inc., 2009). Current gas turbine materials that can be used with DMLS include 17-4, 15-5, and Cobalt Chrome. Forthcoming gas turbine materials include Inco 718, Inco 625, Hast-X, and Ti64. Harbec Plastics, Inc. (2009) suggests that implementing DMLS can be advantageous when:

- tolerances on investment castings are not extremely tight;
- investment-cast parts have multiple post-machining requirements for final completion; and/or

- short lead times are required.

### 2.3.3 Selective Laser Melting (SLM)

Selective Laser Melting (SLM) refers to the direct route of SLS when the powder completely melts. However, this complete melting can lead to deformation (Kruth et al., 2004). SLM can currently accommodate parts up to 250x250x250mm (10x10x10"). Figure 2.4 shows a vane segment in a nickel-based alloy that was generated by SLM and in the finished-machined condition.

Figure 2.4. Vane segment in a nickel-base alloy as generated by SLM (left) and in the finished-machined condition (right) (obtained from Richter (2008)).

### 2.3.4 Tomo Lithographic Molding (TOMO™)

Mikro Systems (MIKRO), Inc. has developed a breakthrough manufacturing technology called Tomo Lithographic Molding (TOMO™). This process includes making a master tool using lithographically-derived layers and stack lamination methods. This tooling approach and their proprietary metal powder slurry compositions allow high resolution sintered metal products using low-pressure molding methods (MIKRO Systems, 2009). Figure 2.5 illustrates the basic TOMO™ process.

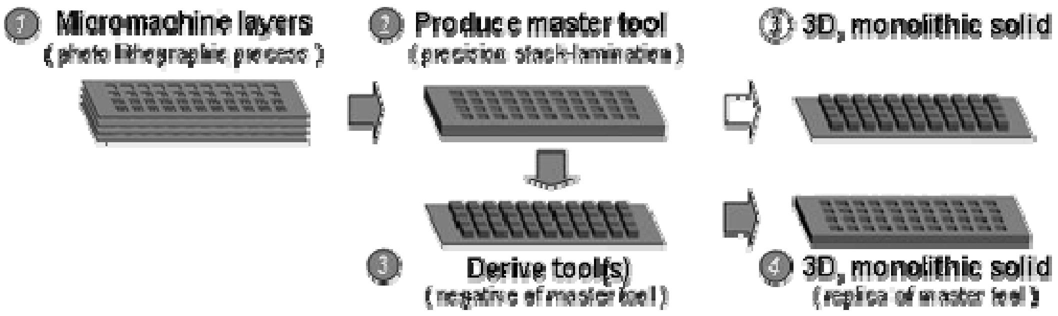


Figure 2.5. Illustration of the TOMO™ process (obtained from MIKRO Systems (2009)).

### 2.3.5 Fused Deposition Modeling (FDM)

Developed by Stratasys, Inc., the Fused Deposition Modeling (FDM) process extrudes a plastic or wax material through a nozzle that traces the geometry in an additive manner until the part is completely formed. The nozzle contains heaters that keep the plastic slightly above its melting point so that it flows through the nozzle, hardens, and forms the layer. After a layer is built, the platform lowers, and the extrusion nozzle deposits another layer. A range of materials are available including, but not limited to, acrylonitrile butadiene styrene plastic resin and investment casting wax (Grimm, 2004). Figure 2.6 is an illustration of the FDM process.

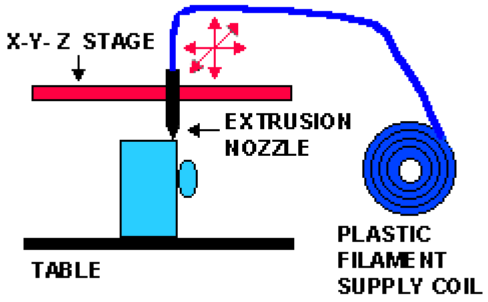


Figure 2.6. Illustration of the FDM process (obtained from Castle Island Co. (2008)).

### 2.3.6 Laser Engineered Net Shaping (LENS®)

Laser Engineered Net Shaping™ (LENS®), developed at Sandia National Laboratories, is a process that builds on the SLS process with some exceptions (Hofmeister et al., 1999). With LENS®, there are four nozzles that direct metal powder at a moveable central point as a laser beam heats the point. Guided by CAD data, these nozzles and laser work together to construct a 3D, high-density model layer by layer. An illustration of the LENS® process is shown in Figure 2.7. LENS® and Laser Engineered Net Shaping ™ are registered trademarks of Sandia National Laboratories and Sandia Corporation. Optomec, Inc. is commercializing the technology as Direct Metal Deposition System™, or DMDS™.

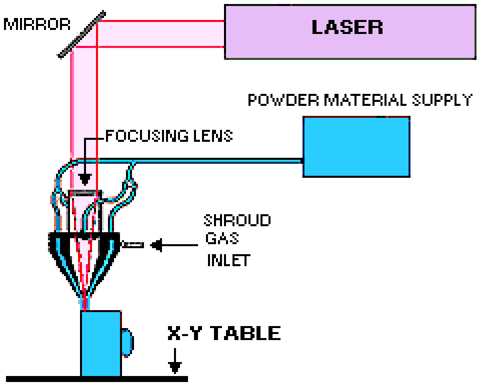


Figure 2.7. An illustration of the LENS® process (obtained from Castle Island Co. (2008)).

### 2.3.7 Direct Shell Production Casting

Direct Shell Production Casting (DSPC), developed at the Massachusetts Institute of Technology and is licensed to Soligen Inc. for metal casting (Mondal, 2004). The DSPC process works by a print head moving over Alumina powder and depositing colloidal silica binder to hold it together. The next layer of powder is applied and this process is repeated layer by layer until the shell is completely produced. Then, the shell is fired before casting (Cheah, 2005).

### 2.4 Indirect Rapid Tooling Processes that Utilize RP-Generated Patterns

Even though the properties of the materials that can be utilized in RP processes have continuously been improving, there still exists the need to obtain a part formed using RP in a different material. For instance, a more permanent tool may be desired for use in short prototype runs or production runs, and specific materials are generally required in most tool fabrication processes. Consequently, numerous indirect processes have been developed that “transfer” RP-generated patterns into parts composed of a different material. By transfer, it is meant that an inverse of the part is created to be used as a tool to create the part in a different material. However, only a few of these developments are common and commercially available today. Table 2.1 presents a comparison table for these indirect processes. Cost information is not included in this table as costs can vary widely depending upon the vendor and the part. However, the processes are presented in the chart in approximately increasing order of cost. Regardless of the indirect process used, the RP-generated pattern must first undergo finishing procedures and the accuracy of the indirect process is ultimately limited by the precision of the pattern after finishing (Grenda, 2007).

Table 2.1. Comparison of indirect tooling processes (Grenda (2007)).

| **Indirect Tooling Process** | **Lead Time** | **Tolerance** | **Part Quantity** | **Injectable Moldable Materials** | **Strengths** | **Weaknesses** |
|---|---|---|---|---|---|---|
| RTV Silicone Rubber Mold | 1-2 weeks | 0.005 with 0.020 walls | < 50 | Urethanes, epoxies, acrylics | Least expensive mold | Tool life, accuracy (better for simple parts), limited materials |
| Aluminum-Filled Epoxy Tooling | 4-6 weeks | 0.002 in/in | 50 -1000 | Thermoplastics | Least expensive for true thermoplastics | Long cycle times, tool life, accuracy (better for simple parts) |
| Spray Metal Tooling | ~ 4 weeks | 0.002 in/in | 50 -1000 | Thermoplastics | Can handle large parts | Tool life, accuracy (better for simple parts), poor for narrow slots |
| Cast Kirksite Tooling | 3-6 weeks | 0.003 in/in | 50 -1000 | Thermoplastics | Complex shapes | Deep slots are difficult, rough surface finish |

### 2.4.1 RTV/Silicone Rubber Tooling

Room Temperature Vulcanization (RTV) tooling, also known as silicone rubber tooling, is the cheapest option for rapid tooling and is used to create urethane, epoxy, or silicone rubber parts. The process includes making a master pattern, generally created by RP, pouring silicone rubber room temperature vulcanizing (RTV) molding compound around the pattern (often under vacuum), and then filling the mold with thermoset materials. Once the rubber has solidified, the pattern is removed and the mold is ready. Figure 2.8 illustrates this process. Although RTV/silicone rubber tooling provides fast and inexpensive molds, tool life limitations restrict production numbers to usually less than 50 parts per tool (Wohlers, 2006).

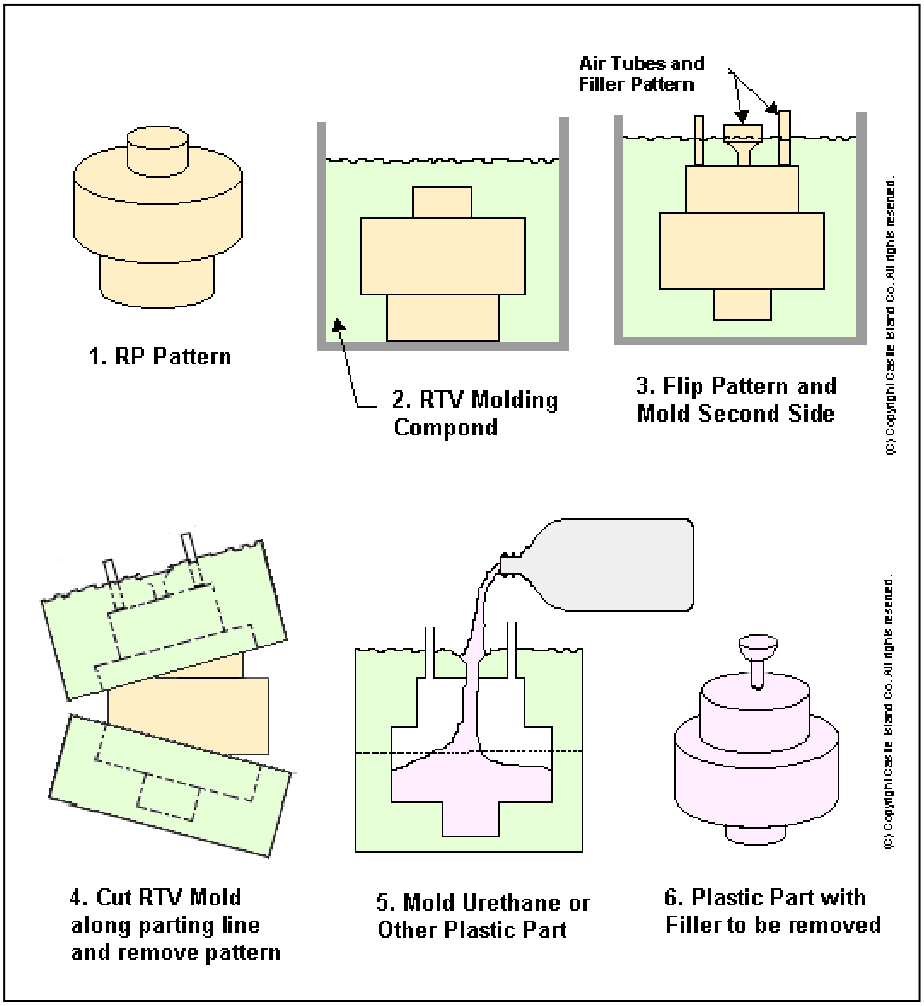


Figure 2.8. Illustration of the RTV/Silicone Rubber Tooling Process (obtained from Castle Island (2005)).

### 2.4.2 Aluminum-filled Epoxy Tooling

Aluminum-filled epoxy tooling is similar in concept to RTV/silicone rubber tooling, yet it is more expensive as aluminum-filled epoxy is used instead of silicone rubber. Grenda (2007) suggests that aluminum-filled epoxy tooling is a reasonable choice for short prototype runs that require a thermoplastic and the tool life ranges from 50 to 1,000 parts depending upon the requirements.

### 2.4.3 Spray Metal Tooling

The first step of the spray metal tooling process is arc-spraying a thin zinc/aluminum alloy coating to an SLA® pattern or a model made from wood or metal. The alloy solidifies into the desired shape and adheres to the pattern. Then, this shell is reinforced with an aluminum-filled epoxy resin. The finished mold can create parts from virtually any production material, and the tool life is similar to aluminum-filled epoxy tooling, but the spray metal tooling method can accommodate larger parts (Engineers Handbook, 2006).

### 2.4.4 Cast Aluminum and Zinc Kirksite Tooling

Cast aluminum and zinc kirksite tooling begins with a master pattern typically created by SLA®. Then, using RTV/silicone rubber tooling as described above, a cavity is produced around the model. Next, the silicone cavity is filled with ceramic and, after drying, it is covered with either a molten aluminum- or zinc-based alloy. This type of tooling is advantageous for more complex geometries, but it is, in general, less accurate and more expensive than aluminum-filled epoxy or spray metal tooling (Grenda, 2007).

## 2.5 RP versus Computer Numerical Control (CNC) Machining

As noted in Section 2.2, RP is viewed as an additive process and thus does not included Computer Numerical Control (CNC) machining, a subtractive process. While this thesis primarily focuses on RP methods, technologies, and applications, it is not intended to suggest that RP is the single best solution for all applications. On the contrary, the best solution can only be determined when there exists an understanding of the advantages and disadvantages of both RP and CNC machining.

Prototype development has changed dramatically in the last 15 years which makes the selection process between RP and CNC machining increasingly difficult (Wohlers and Grimm, 2009). It is only after considering all of the factors of time, quality, and cost when an engineer can make an informed decision as to the best technology for a particular application. Table 2.2 compares CNC machining to rapid prototyping according to several important attributes.

A summary of a number of direct and indirect RP processes have been described as well as a general comparison of RP with CNC machining has been provided. The design of many components within the turbine and combustion sections of a gas turbine engine can benefit greatly from utilization of this knowledge. Next, a brief overview of a gas turbine engine design and operation is given, followed by a discussion of the application of the investment casting process on gas turbine engine component design.

Table 2.2. Comparison of CNC machining and rapid prototyping (summarized from Wohlers and Grimm (2009)).

| **Attribute** | **CNC Machining** | **Rapid Prototyping** |
|---|---|---|
| Materials | Almost unlimited. | Limited, yet there have been advancements in RP materials, which now include metals, plastics, ceramics and composites. |
| Maximum Part Size | Large enough to handle large gantry systems, yet size is only limited by the capacity of the machine tools. | Build envelopes can be large, such as 24 x 36 x 20 in. (600 x 900 x 500 mm), yet if a part is large for the envelope, it can be built in sections and then adhered together. However, size has an impact on the time factor. |
| Part Complexity | As the part's complexity increases, the number of tool changes increases, which adds time and cost. | A benefit of RP is the ability to produce parts with complex features with little impact on time/cost. |
| Accuracy | Typically 0.0125 to 0.125 mm (0.0005 to 0.005 in) | 0.125 to 0.75 mm (0.005 to 0.030 in) is the typical range of an RP system. |
| Surface Finish | $R_a$ 20 to 200 in. (0.5 to 5 microns) | $R_a$ 100 to 600 in. (2.5 to 15 microns) |
| Lead Time | Many jobs have a longer lead time than those done in RP except for simple designs. | In general, RP has a shorter lead time. |

## 2.6 Overview of Gas Turbine Design and Operation

Gas turbines are rotary engines that extract energy from the flow of combustion gas. As shown in Figure 2.9, a gas turbine mainly consists of a compressor to compress the incoming air, a combustion chamber where fuel is mixed with air and combusted, and a turbine element where energy is extracted.

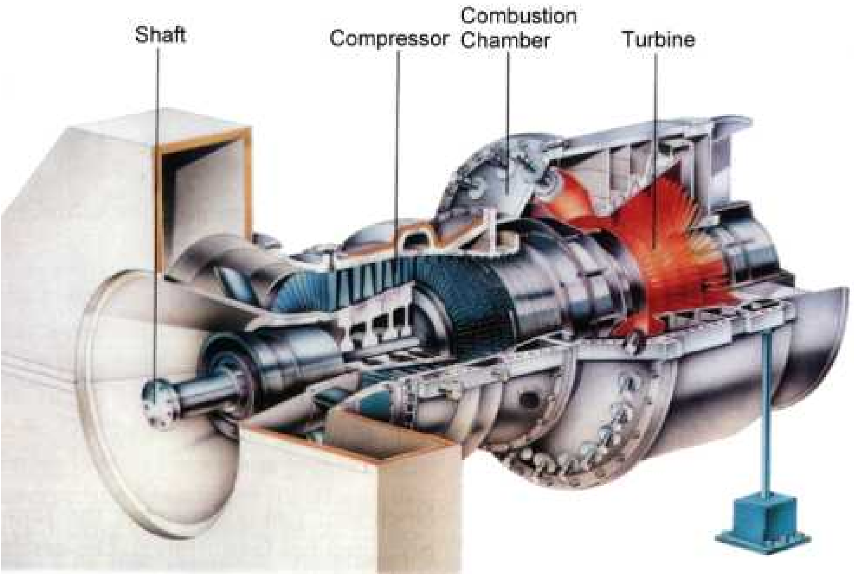


Figure 2.9. An illustration of a gas turbine engine (obtained from EnergyTech (2009)).

Gas turbines have complex parts within the turbine and combustion sections in which part temperatures reach levels much higher than the part melting points. These high temperatures are possible through the application of part coatings and the use of intricate internal cores within the parts. Such high temperatures require exotic materials, and these materials favor investment casting (Lessiter, 2002). By definition, exotic means unusual or different. In the case of many gas turbine parts, these materials are superalloys.

## 2.7 Overview of Investment Casting

Investment casting (IC), one of the oldest manufacturing processes, can produce intricate shapes with a high degree of accuracy. Metals that are candidates for IC cannot be processed by traditional manufacturing techniques. IC is a well-known technique for the production of many superalloy gas turbine parts such as blades and vanes (Dierksmeier and Ruppel, 2003), and an investment-cast turbine blade remains the state-of-the-art in gas turbine blades (Shelmet Precision Casting, 2009). The IC process steps include the following:

1. *Design*: The IC process begins with a CAD drawing that describes the casting's shape, size, finish requirements, and acceptance criteria.
2. *Creating the Die*: Using the CAD data, a tool or wax die, which is the inverse of the part, is created. A wax pattern is created by injecting a specially-designed wax into the empty cavity of the die and then removing the wax pattern from the tooling. Dies are usually constructed from metal sections that slide apart in order to easily remove the hardened wax pattern. Ceramic cores can be used to create hollow and/or complex inner geometric sections within castings. These cores are placed inside the pattern dies before the wax injection and stay there during the casting. Figure 2.10 shows a wax pattern being removed from its tooling. The wax pattern can also be created directly via rapid prototyping.

Figure 2.10. A wax pattern removal from its tooling (obtained from PCC Structurals (2009)).

3. *Wax Pattern Assembly*: Many castings are created as one-piece patterns. However, large or complex castings require the creation of waxes in sections, which are then wax-welded together. Risers and gates are implemented to form pathways for the molten metal to flow through the ceramic mold during casting, allowing the mold to fill rapidly and completely before the metal solidifies. Figure 2.11 shows an example of a wax pattern assembly.

Figure 2.11. A wax pattern assembly for a stator. (obtained from PCC Structurals (2009)).

4. *Creation of a Ceramic Mold*: The ceramic mold, or investment, is produced by first dipping the completed pattern into a ceramic slurry mixture. Any excess slurry is then allowed time to drain before it is stuccoed with a fine grain sand and then allowed time to harden. This process is repeated until the mold reaches its desired thickness. After the investment is dry, it is then heated to melt the wax, leaving a hollow shell that is ready to be filled with an alloy (see Figure 2.12).

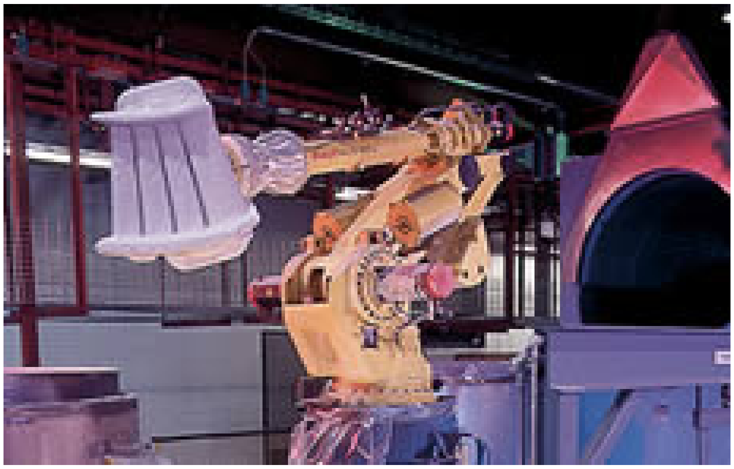


Figure 2.12. A robot dips a multi-stage vane segment at PCC Structurals' Deer Creek facility (obtained from PCC Structurals (2009)).

5. *Casting*: At casting, the mold is preheated in a furnace and a molten metal is then poured into the gating system of the mold which fills the mold cavity to form a raw casting. The molten metal is then allowed to cool and solidify into the shape of the final casting.

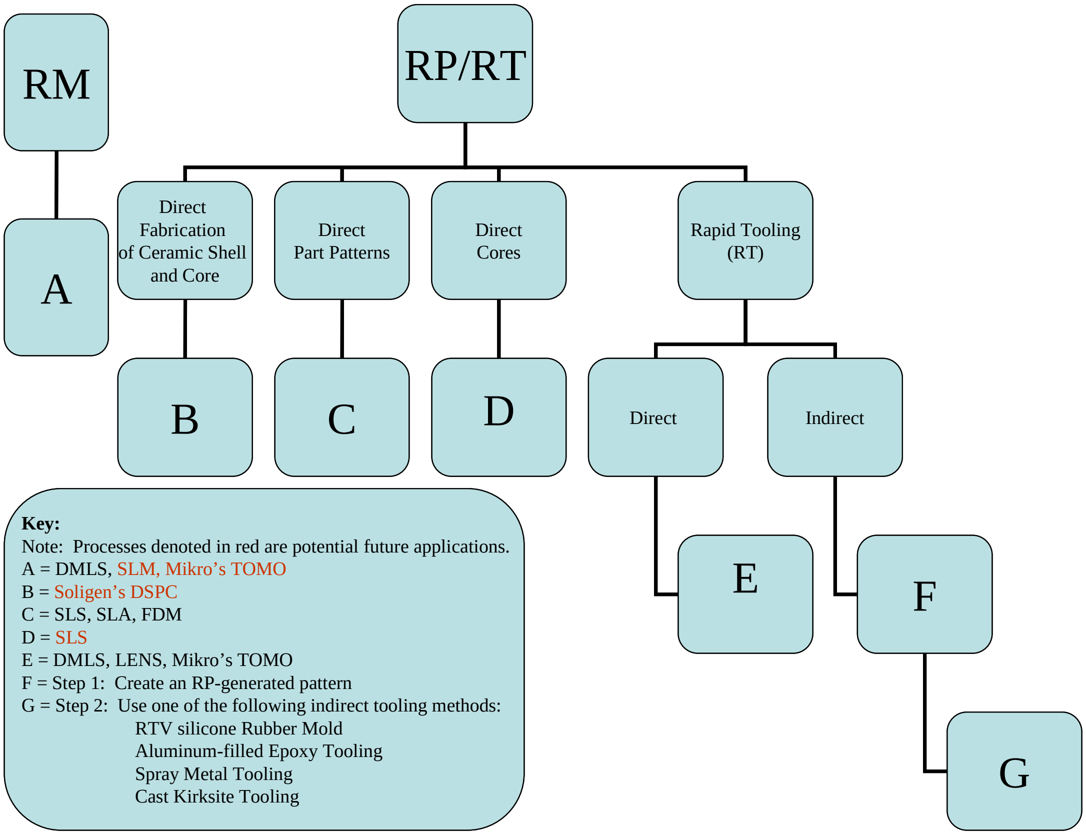
6. *Ceramic Shell Removal and Final Processing*: After casting, the shell, gates, risers, and any ceramic cores are removed via mechanical methods such as hammering and vibrating, along with water blast techniques and chemical leaching. The casting is then subjected to finishing operations such as grinding to remove signs of the casting process, particularly where the gates were located. Figure 2.13 shows an investment-cast hollow turbine blade before the ceramic cores are removed, and Figure 2.14 shows the same casting with the cores removed.

Figure 2.13. An investment-cast hollow turbine blade with cores (obtained from Wu et al. (2009)).

Figure 2.14. An investment-cast hollow turbine blade with cores removed (obtained from Wu et al. (2009)).

## 2.8 Overview of RP/RM/RT within IC of GT parts

Figure 2.15 shows an overview of how rapid manufacturing, rapid prototyping, and rapid tooling can be utilized within the investment casting process. Note that processes denoted in red are potential future applications based on the review of the current literature and interviews with subject matter experts. Steps F and G are for creating indirect tooling for short prototype or production runs, if desired. Steps A-G will be elaborated on in Chapter 4 of this thesis.



**Key:**
Note: Processes denoted in red are potential future applications.
A = DMLS, SLM, Mikro's TOMO
B = Soligen's DSPC
C = SLS, SLA, FDM
D = SLS
E = DMLS, LENS, Mikro's TOMO
F = Step 1: Create an RP-generated pattern
G = Step 2: Use one of the following indirect tooling methods:
RTV silicone Rubber Mold
Aluminum-filled Epoxy Tooling
Spray Metal Tooling
Cast Kirksite Tooling

Figure 2.15. Overview of RM/RP/RT for IC of GT parts.

## 2.9 Summary

This chapter presents an overview of existing rapid technologies. In particular, descriptions of direct and indirect processes are given along with a comparison of RP versus CNC machining. Overviews of gas turbines and investment casting are also presented. Then, it is shown how and where these processes can work together. The next chapter presents a literature review of the existing RP tools that were researched within the creation of this thesis and discusses the gap that is filled by the research within this thesis.

# CHAPTER 3:
# LITERATURE REVIEW

## 3.1 Introduction

This chapter reviews nine existing RP selection tools and compares the capabilities of each. These tools are chosen in the search of an expert product development tool for choosing the most appropriate RP process for gas turbine designs that are traditionally manufactured via investment casting. A summary table of direct comparisons is presented and an explanation is brought forth as to the novelty and usefulness of the decision support tool presented in this research investigation.

## 3.2 Existing Rapid Prototyping Selection Tools for GT Part Design

### 3.2.1 Selection Tools Using Mathematical Decision Theory

Rao and Padmanabhan (2007) propose an RP process selection index for ranking RP technologies for fabricating a part. Their work involves assigning quantitative or qualitative values to a list of attributes such as material properties, build envelope, part size, etc. Any qualitative values are converted into quantitative values via fuzzy logic and then each criterion is weighted. An index value is computed based on the information that is provided by the user and the RP technology with the highest index value is suggested as the best RP option for the user's particular needs. The major drawback to this methodology is that it requires the user to answer several questions regarding RP selection criteria and does not permit omitted data. A user not familiar with RP or is asked questions beyond the scope of investment-cast GT parts would most likely be unable to provide all of the required data.

Byun and Lee (2005) present a methodology for choosing the most appropriate RP method using a modified TOPSIS method that analyzes quantitative and qualitative data. The major drawback to this methodology is that the user must input a large number of criteria to complete a decision matrix and does not allow for any missing data.

Lan, Ding, and Hong (2005) propose to select the best RP method by running a user's inputs through an "expert system and fuzzy synthetic evaluation" that ranks the RP alternatives. However, some of the criteria that the user is expected to input such as scan speed and overhead time are complex issues that are not likely to be known by a design engineer who is unfamiliar with RP.

### 3.2.2 Selection Tools Considering Minimal Factors

Campbell and Bernie (1996) develop a decision support system for RP that is an expandable and easy-to-use database that yields useful information in assisting a design engineer in making the best use of RP. The proposed methodology considers queries such as build envelope, material properties and multiple feature tolerances and allowed for relaxation of ranges in the cases in which no RP suggestion is made. The drawback of this methodology is that the user must input "the model dimensions and required tolerances for each feature in the part" which would not only be tedious for the designer, but would also render the system useless for extremely complex designs.

Cheah et al. (2005) review the application of rapid prototyping and tooling techniques (RP&T) for the investment casting manufacturing process. The RP&T processes are examined with respect to concepts, strengths, and weaknesses (Cheah et al., 2005). However, since the publishing of the work of Cheah et al. (2005), there have been material breakthroughs that outdate many of the techniques mentioned in this work. For instance, the authors suggest an applicable alternative to direct pattern fabrication for IC is by Laminated Object Manufacturing (LOM), and LOM-based patterns are more useful in the conventional sand casting rather than IC (Mondal, 2004). Furthermore, the proposed research by the authors is not tailored to the GT industry and therefore, does not suggest options particular to specific GT industry-based materials and applications. In particular, this work does not discuss the possibility of creating parts directly using RM or of the RP processes and options applicable to cores if the part has complex inner core geometries.

Masood and Soo (2002) propose an RP technology selection approach that incorporates 39 commercially-available RP systems available from 21 RP manufacturers. Although their purpose is to create a selection tool for the purchase of a machine that supports an RP technology, it provides insight into an approach for an RP selection process as the authors consider accuracy, build envelope, surface finish, and end application.

### 3.2.3 Higher End Selection Decision Support Systems

IVF Industrial Research and Development Corporation (n.d.) propose a web-based RP selection program that is called “RP Selector, A Tool for the Choice of Process Chains Based on RP/FFF for Prototypes and Small Series Production” uses the term Free Form Fabrication (FFF) as a collective name for the commercially-available additive methods that are commonly referred to as Rapid Prototyping. The authors are unknown, but this project is funded through the IVF Industrial Research and Development Corporation. This decision support tool first asks the user to choose between four categories: (1) visualization design model, (2) visualization design & assembly model,

(3) plastic functional prototype, or (4) metal functional prototype. The user is then presented with questions about the part in terms of size, quantity, and material. Depending upon the user input, the tool then presents an output table which compares various available options in terms of lead time, accuracy, quality, and relative cost. Most of the selection criteria are presented in the output table. The disadvantage of this method is that it can only make estimates for the RP method. An advantage to this method is that it can visually present the user with a way to quickly see the tradeoffs that need to be considered if their design does not meet all the requirements of a particular RP process. A demonstration of this DSS currently exists on the internet at http://extra.ivf.se/rp-selector/Demo-selector/index.htm.

Palmer (2009) develops an expert system that selects the most appropriate Additive fabrication process and material option to “create physical reproductions of any part .... based on as many or as few input fields the user may be able to complete”. This system only addresses direct RP processes and does not include indirect RT processes. Therefore, with respect to a specialized tool for GT IC parts, the system would only be effective in creating a part or core pattern via RP.

Pal and Ravi (2007) provide an approach for selecting a suitable rapid tooling process for sand and investment casting. The authors compile a database of RT capabilities and calculate overall compatibility indices. A case study of a body casting is used to validate their approach. Pal and Ravi (2007) do not discuss the possibility of creating parts directly using RM or of the processes applicable to core issues which are commonplace when developing gas turbine components.

### 3.3 Summary

Table 3.1 compares the attributes of existing expert system methodologies for rapid technology selection. From Table 3.1, it is evident that there are existing RP tools that have successfully developed for RP selection within the metal casting industry; however, there is an opportunity for further research in this area in that none of the existing decision support tools for RP technology selection encompass all the information a GT design engineer should know with regards to RP. For example, most existing tools ignore the concept that, with advances in materials and methodology, it is now possible to bypass the IC process altogether via RM processes such as DMLS and possibly SLM and TOMO™. For instance, an outdated tool may advise a design engineer that a certain RP process should be used for an IC pattern, when, in fact, the part could be made directly by DMLS.

Table 3.1. Summary of existing research that apply RP technology to investment casting.

| | **Direct RP processes for IC** | **Indirect RP processes for IC** | **IC** | **Sand Casting** | **Cores** | **RM** | **CNC** |
|---|---|---|---|---|---|---|---|
| Palmer (2009) | ✓ | | | | | | |
| Pal and Ravi (2007) | ✓ | ✓ | ✓ | ✓ | | | |
| Cheah et al. (2005) | ✓ | ✓ | ✓ | | | | |
| Rao and Padmanabhan (2007) | ✓ | | | | | | |
| Byun and Lee (2005) | ✓ | | | | | | |
| Campbell and Bernie (1996) | ✓ | | | | | | |
| Masood and Soo (2002) | ✓ | | | | | | |
| Lan, Ding, and Hong (2005) | ✓ | ✓ | | | | ✓ | |
| IVF Industrial Research & Development Corp. (no date) | ✓ | ✓ | ✓ | ✓ | | | |

Another limitation of existing RP tools is that there is no clear guide for an engineer to apply rapid prototyping technologies to the investment casting manufacturing process. Also, there is no mention of how RP can be implemented for core patterns or inserts for tooling.

Furthermore, past research and existing interactive tools often compare a large number of feasible RP processes for an application. The number of feasible RP processes can be reduced if the scope is limited to using RP to create parts used as consumable patterns for the investment casting of GT parts or to bypass the investment casting process and create GT parts directly using RM. Furthermore, with the advancements in build style and materials, there have been significant improvements in the overall quality of RP patterns used for IC, which allows for the elimination of inferior techniques from consideration. Therefore, there is a need to eliminate infeasible RP options for engineers in the GT industry so their task of using RP in the process of investment-cast GT part design iterations is simplified. When choices are presented simpler, the differences between the choices can be better understood, allowing for a selection to be based on an educated understanding rather than on marketing tactics or biased and, perhaps, outdated information. Also, none of the existing RP decision support tools give the user any idea as to the point in which another perhaps more conventional method such as Computer Numerical Control (CNC) machining may become more feasible than RP. The goal of this thesis is to capture these features in one comprehensive decision support framework using proven decision theoretic concepts.

# CHAPTER 4:
# PROPOSED METHODOLOGY –
# A RAPID PROTOTYPING EXPERT SYSTEM

## 4.1 Overview

The proposed methodology is based upon a collection of assumptions and knowledge gathered from the author reviewing the open research literature as well as interviewing practicing gas turbine design and manufacturing engineers. The author also visited existing foundries and rapid prototyping service bureaus that either utilize RP within their investment casting process or directly create end use parts via rapid manufacturing. The proposed methodology utilizes an expert system approach that uses a set of expert-based if-then rules to give guidance to the user (i.e., a gas turbine design engineer) as to the most applicable processes suited for his/her particular needs.

## 4.2 Proposed Methodology Assumptions

This section presents the proposed expert system user assumptions followed by the technology selection criteria assumptions.

- The expert system user is a GT engineer who has limited knowledge of RP technologies and yet, at least initially, would like to utilize a rapid prototyping technology for his/her particular application.
- The user can utilize RP service bureaus and is not limited in which RP process he/she can select for a particular application.
- Until an RP service bureau is obtained by the user, specific lead times are generally unknown and only a range of lead times can be given. However, the lead time ranges are deterministic and known a priori with certainty.

- The costs are deterministic and known a priori with certainty. The proposed methodology does not specifically address cost since many variables affect cost such as the RP service bureau, multiple part orders, RP service bureau price negotiations, etc.

## 4.3 Proposed Expert System Rule-Based Logic

An overview of the proposed expert system RP technology selection criteria and expert rule-based logic is presented in Figure 4.1.

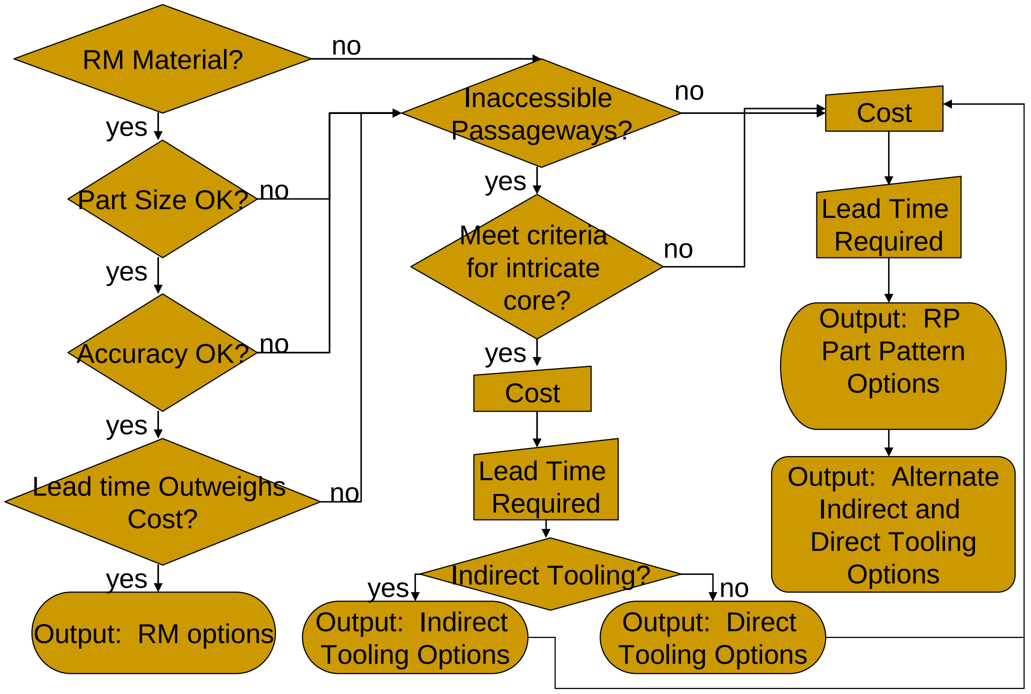


Figure 4.1. Overview of proposed rapid prototyping selection expert system logic.

### 4.3.1 Material

Regarding the box labeled “RM Material?” in Figure 4.1, the first concern in RP technology selection is the desired material of the final part. The reasoning behind this is to determine if the part can be made directly via RM, bypassing the IC process. This step should not address materials and processes that could be utilized for localized areas, repairs, or inserts for tooling. If the GT part cannot be created via a material currently supported by RM, the user is then directed to the IC series of questions. If the part's material is one that can currently be utilized by RM, then the part may be able to be created via RM depending upon the part size and accuracy desired, and the user is then directed to the series of question related to the final part's size.

### 4.3.2 Part Size

If the final part can be made from one of the material choices that are currently supported by RM, the next concern in RP technology selection is part size. It must now be determined if the part size is within the current build size platform of RM. Although larger parts can be separately created and then welded together, this adds time and cost that should be taken into consideration. The user will be made aware of this issue via an information window within the tool. If it is determined that the part's size is too large, the user will then be guided to the IC route. If the part's size is acceptable for RM, the required accuracy of the part will need to be determined before proceeding to feasible RM options.

### 4.3.3 Accuracy

The next concern in RP technology selection is the required accuracy of the part. If the required accuracy is not supported by current RM processes, the user is notified and directed to the IC process. If the required accuracy of the part is compatible with RM processes, the user then must decide if part design cost outweighs part lead time or if the part lead time outweighs part design cost. If lead time outweighs cost, then the user is presented with a comparison table of current and applicable RM options. If cost outweighs lead time, then the user is directed to proceed with the IC process.

### 4.3.4 Inaccessible Passageways

If the final part cannot be made directly via RM and should be made via IC, the next issue to consider is whether or not the part needs to have a complex core. It is not clear when a separately-formed core is needed since the means of determining that is proprietary to individual foundries. However, there are some general guidelines that an engineer can use to estimate if a complex core will need to be created. The first issue is ascertain if the part has inaccessible passageways or hollow bodies or cavities. If the part does not have any of these, a complex core is not needed and the user proceeds to determining an RP process for creating a part pattern. If the part does have any inaccessible passageways or hollow bodies or cavities of any kind, it is necessary to determine if the passageway meets the criteria for a complex core.

### 4.3.5 Length to Width Ratio

The next question addresses the length to width ratio of the hollow section. This information will determine if the part does not need a complex core in which the user can proceed to making a part pattern or if a complex core such as the ones shown in Figure 4.2 will be needed.

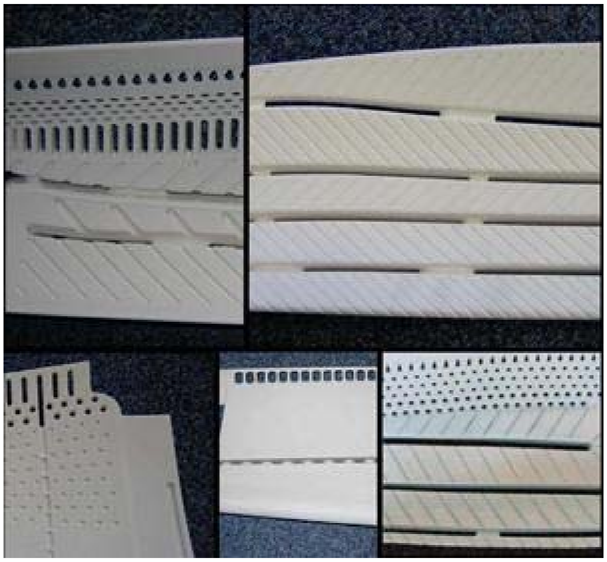


Figure 4.2. Examples of complex ceramic cores (obtained from CIC Limited (2009))

As of today, there is not yet an RP technology that can make cores directly and efficiently for IC (Mueller, 2009). However, the user can choose to use RT to create core tooling either directly or indirectly.

### 4.3.6 Tooling Options

There are two tooling options. The first option is indirect tooling and the second option is direct tooling.

#### 4.3.6.1 Solution: Indirect Tooling Step 1

There are two steps in indirect tooling. The first step is to create an RP-generated pattern and the user should be presented with a table that compares the lead time, build envelope size, and tolerances of each current and feasible process as exemplified in Table 4.1.

Table 4.1 Comparison of the most feasible RP options for creating a core pattern.

| **RP Process** | **Lead Time** | **Build Envelope Size*** | **Tolerances** |
|---|---|---|---|
| LENS® | Key process time: <1 day, Delivery time: 2-4 weeks | Max insert size: 920x460x600mm (36x18x24in) | ±0.125mm/ 25mm (0.005 in/in) |
| SL | 3-5 days | 660.4x762x558.8mm (26x30x22”) | ± 0.127mm (± .005”) |
| SLS | ~1 week | 381x330.2x457.2mm (15x13x18”) | ± 0.076mm (± .003”) |
| DMLS | Key process time: 1-2 days, Delivery time: < 1 week | Max insert size: 250x250x185mm (9.8x9.8x7.3in) | ±0.07% + 0.050 mm (0.07% + 0.002 in.) |

*Parts that are larger than the build envelope can be divided, created as separate pieces, and assembled.

#### 4.3.6.2 Solution: Indirect Tooling Step 2

Once an RP-generated pattern is created, a core tool can be created from an indirect RT process and the user should be presented with a table of options for comparison purposes.

#### 4.3.6.3 Solution: Direct Tooling

Figure 4.3 shows an example of a core tool created via direct RT. If direct tooling is desired, a comparison table of current and applicable processes should be presented to the user as shown in Table 4.2.

Figure 4.3. An example of a core tool.

Table 4.2. Comparison of the most feasible options for direct tooling.

| **RP Process** | **Lead Time** | **Build Envelope Size*** | **Tolerances** |
|---|---|---|---|
| LENS® | Key process time: < 1 day, Delivery time: 2-4 weeks | Max insert size: 920x460x600mm (36x18x24in) | ±0.125 mm/25mm (0.005 in/in) |
| DMLS | Key process time: 1-2 days, Delivery time: < 1 week | Max insert size: 250x250x185mm (9.8x9.8x7.3in) | ±0.07% + 0.050 mm (0.07% + 0.002 in.) |
| Mikro System's TOMO Lithographic Molding | Rapid Tooling: 4 weeks | Depending on part geometry. Max core experience = 46 inches, other structures = 3m | ± 50 microns |
| CNC | >14 weeks | n/a | ±0.051mm to ±0.013mm (±0.002" to ±0.0005") |

*Parts that are larger than the build envelope can be divided, created as separate pieces, and assembled.

At this point, the user has the option to create an insert for tooling, which is a removable section of a pattern or tooling that an engineer can easily remove and replace with an upgraded design iteration. The user should be notified of applicable options.

#### 4.3.6.4 Part Patterns

The user is now ready to consider RP for creating a pattern for the part. The biggest impact that RP has had on IC is the ability to make high-quality part patterns (Atwood et al., 1996) and investment castings can only be as accurate as the patterns from which they are produced (Dotchev and Soe, 2006). At this point, the user should be prompted to enter cost and lead time data and then presented with a comparison table of applicable RP options for part patterns, similar to the one presented in Table 4.3.

Table 4.3. Comparison of the most feasible RP options for creating a part pattern.

| **RP Process** | **Lead Time** | **Min. Wall Thickness** | **Build Envelope Size*** | **Tolerances** |
|---|---|---|---|---|
| FDM | 1-3 days | 0.508mm (.020”) | 254x254x304.8mm (10x10x12”) | ± 0.127mm (± .005”) |
| SLA-QuickCast | 3-5 days | 0.508mm (.020”) | 660.4x762x558.8mm (26x30x22”) | ± 0.127mm (± .005”) |
| SLS-CastForm | 3-5 days | 0.889mm (0.035”) | 381x330.2x457.2mm (15x13x18”) | ± 0.076mm (± .003”) |

*Parts that are larger than the build envelope can be divided, created as separate pieces, and assembled.

#### 4.3.6.5 Tooling for Part Patterns

The user will also be informed that once they have an RP-generated part pattern, they may want to consider using an indirect tooling process for creating tooling for short prototype or production runs or a direct tooling approach. The user should then be presented with an indirect tooling comparison table and a direct tooling comparison table as shown in Table 4.2. The user should also be presented with information on the option to create an insert for tooling.

## 4.4 Summary

Table 4.4 compares the attributes of the expert system presented in this thesis along with all of the expert systems reviewed in Chapter 3.

Table 4.4. Summary of features of existing expert system approaches for rapid technology selection.

| | **Direct RP for IC** | **Indirect RP&T for IC** | **IC** | **Sand Casting** | **Cores** | **RM** | **CNC** |
|---|---|---|---|---|---|---|---|
| Gallagher (2010) | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Palmer (2009) | ✓ | | | | | | |
| Pal and Ravi (2007) | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| Cheah et al. (2005) | ✓ | ✓ | ✓ | | | ✓ | |
| Rao and Padmanabhan (2007) | ✓ | | | | | | |
| Byun and Lee (2005) | ✓ | | | | | | |
| Campbell and Bernie (1996) | ✓ | | | | | | |
| Masood and Soo (2002) | ✓ | | | | | | |
| Lan, Ding, and Hong (2005) | ✓ | ✓ | | | | ✓ | |
| IVF Industrial Research & Development Corp. (no date) | ✓ | ✓ | ✓ | ✓ | | | |

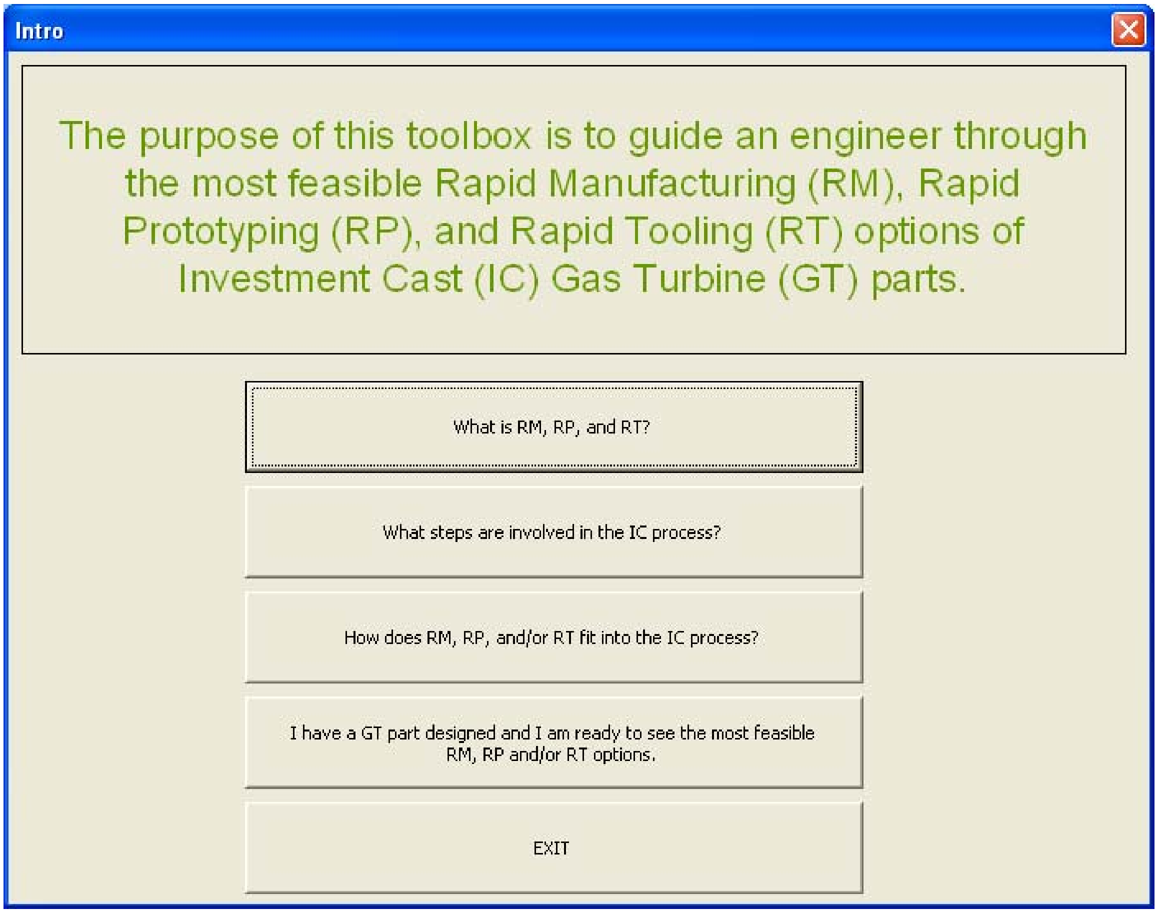
# CHAPTER 5
# AN IMPLEMENTATION OF THE PROPOSED RAPID PROTOTYPING EXPERT SYSTEM – AN INTERACTIVE PROGRAM

## 5.1 Introduction

Using the proposed methodology presented in Chapter 4, an interactive and user-friendly program has been created using Visual Basic (VB) programming within Excel. Even though this document summarizes the implementation of the proposed methodology in Visual Basic, the author does not proclaim that VB is the best implementation of the methodology. The purpose of this research investigation is to propose a methodology that achieves the GT design engineering goal.

The implemented interactive program, which is an instantiation of the proposed methodology, begins with the user (i.e., a gas turbine design engineer) being presented with the following choices (see Figure 5.1):

- What are RM, RP, and RT?
- What steps are involved in the IC process?
- How do RM, RP, and/or RT fit into the IC process?
- I have a GT part designed and I am ready to see the most feasible RM, RP and/or RT options.
- Exit.



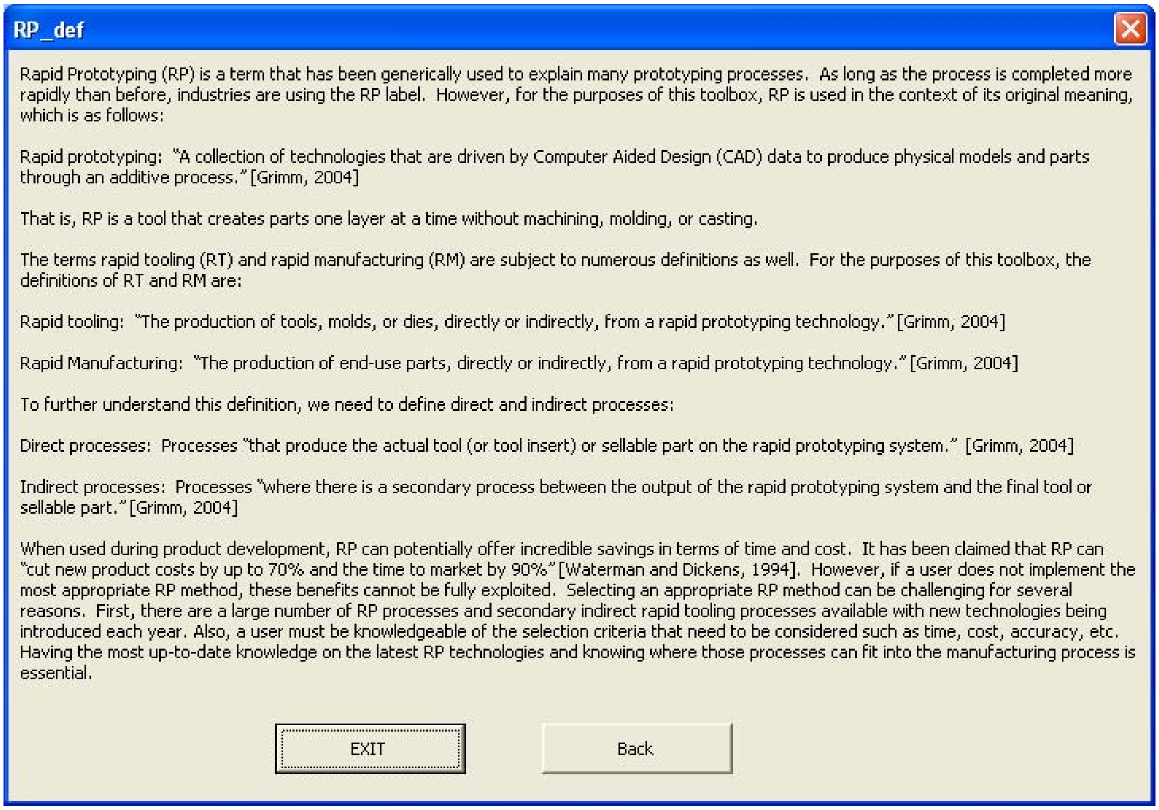
The purpose of this toolbox is to guide an engineer through the most feasible Rapid Manufacturing (RM), Rapid Prototyping (RP), and Rapid Tooling (RT) options of Investment Cast (IC) Gas Turbine (GT) parts.

Figure 5.1. The introductory selection options dialog user form for the interactive program.

This list of choices provides the user with the options to learn more about RP, RM, and/or RT as well as the IC process. Or, if the user prefers, he/she can bypass this information to be presented the best RP options for their part. Discussions of each section in the interactive program, which are based on the proposed methodology in Chapter 4, follow.

### 5.1.1 What is RM, RP, and RT?

If the user selects "What is RM, RP, and RT?", a user form is shown with the information discussed in Section 2.2 and as shown in Figure 5.2.



Rapid Prototyping (RP) is a term that has been generically used to explain many prototyping processes. As long as the process is completed more rapidly than before, industries are using the RP label. However, for the purposes of this toolbox, RP is used in the context of its original meaning, which is as follows:

Rapid prototyping: "A collection of technologies that are driven by Computer Aided Design (CAD) data to produce physical models and parts through an additive process." [Grimm, 2004]

That is, RP is a tool that creates parts one layer at a time without machining, molding, or casting.

The terms rapid tooling (RT) and rapid manufacturing (RM) are subject to numerous definitions as well. For the purposes of this toolbox, the definitions of RT and RM are:

Rapid tooling: "The production of tools, molds, or dies, directly or indirectly, from a rapid prototyping technology." [Grimm, 2004]

Rapid Manufacturing: "The production of end-use parts, directly or indirectly, from a rapid prototyping technology." [Grimm, 2004]

To further understand this definition, we need to define direct and indirect processes:

Direct processes: Processes "that produce the actual tool (or tool insert) or sellable part on the rapid prototyping system." [Grimm, 2004]

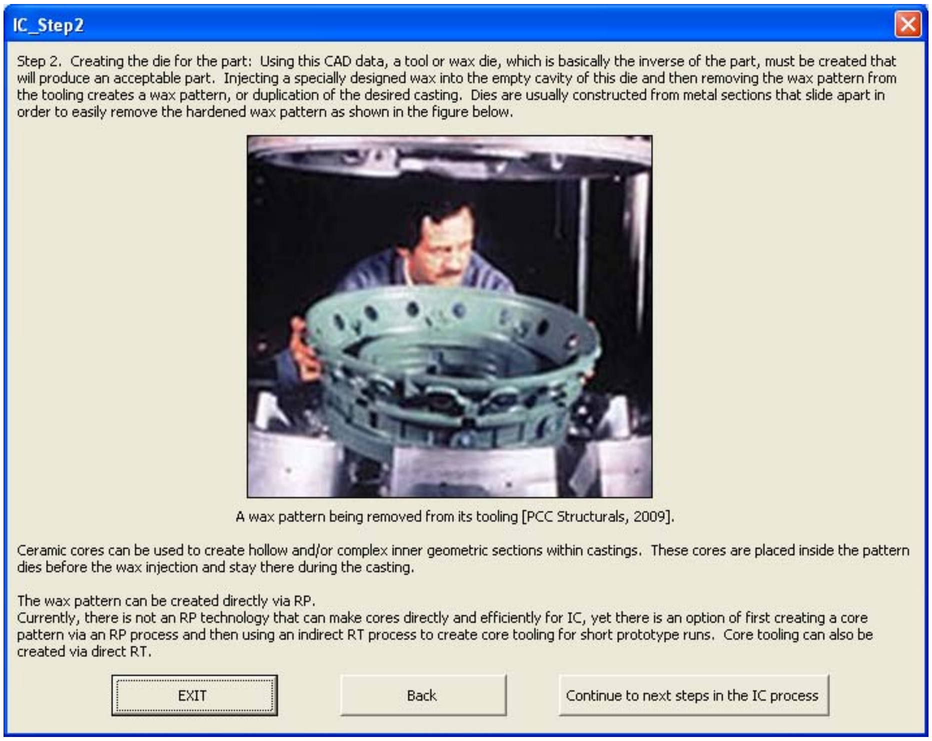
Indirect processes: Processes "where there is a secondary process between the output of the rapid prototyping system and the final tool or sellable part." [Grimm, 2004]

When used during product development, RP can potentially offer incredible savings in terms of time and cost. It has been claimed that RP can "cut new product costs by up to 70% and the time to market by 90%" [Waterman and Dickens, 1994]. However, if a user does not implement the most appropriate RP method, these benefits cannot be fully exploited. Selecting an appropriate RP method can be challenging for several reasons. First, there are a large number of RP processes and secondary indirect rapid tooling processes available with new technologies being introduced each year. Also, a user must be knowledgeable of the selection criteria that need to be considered such as time, cost, accuracy, etc. Having the most up-to-date knowledge on the latest RP technologies and knowing where those processes can fit into the manufacturing process is essential.

Figure 5.2. RP/RT/RM definition user form for the interactive program.

### 5.1.2 Steps of the Investment Casting process

If the user selects "What steps are involved in the IC process?", he/she is presented with an explanation of the steps involved in the IC process as described in Section 2.7. Refer to Figure 5.3 and Figure 5.4 for two of the user forms presented to the user.



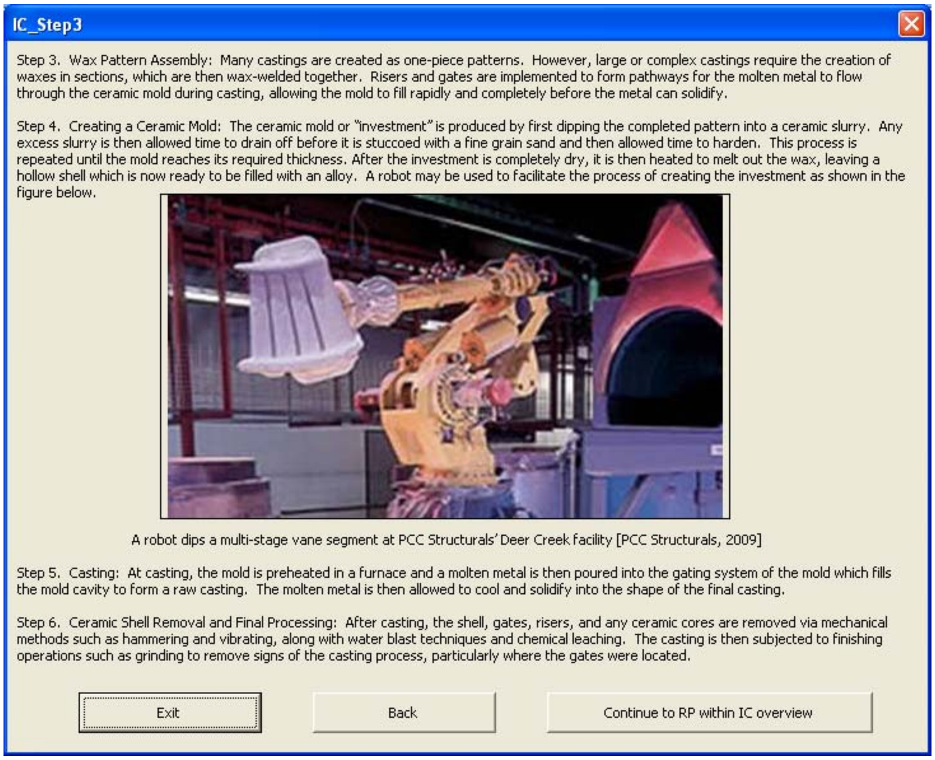
Step 2. Creating the die for the part: Using this CAD data, a tool or wax die, which is basically the inverse of the part, must be created that will produce an acceptable part. Injecting a specially designed wax into the empty cavity of this die and then removing the wax pattern from the tooling creates a wax pattern, or duplication of the desired casting. Dies are usually constructed from metal sections that slide apart in order to easily remove the hardened wax pattern as shown in the figure below.

A wax pattern being removed from its tooling [PCC Structurals, 2009].

Ceramic cores can be used to create hollow and/or complex inner geometric sections within castings. These cores are placed inside the pattern dies before the wax injection and stay there during the casting.

The wax pattern can be created directly via RP.
Currently, there is not an RP technology that can make cores directly and efficiently for IC, yet there is an option of first creating a core pattern via an RP process and then using an indirect RT process to create core tooling for short prototype runs. Core tooling can also be created via direct RT.

Figure 5.3. Interactive program user form describing Step 2 of the IC process.



Step 3. Wax Pattern Assembly: Many castings are created as one-piece patterns. However, large or complex castings require the creation of waxes in sections, which are then wax-welded together. Risers and gates are implemented to form pathways for the molten metal to flow through the ceramic mold during casting, allowing the mold to fill rapidly and completely before the metal can solidify.

Step 4. Creating a Ceramic Mold: The ceramic mold or "investment" is produced by first dipping the completed pattern into a ceramic slurry. Any excess slurry is then allowed time to drain off before it is stuccoed with a fine grain sand and then allowed time to harden. This process is repeated until the mold reaches its required thickness. After the investment is completely dry, it is then heated to melt out the wax, leaving a hollow shell which is now ready to be filled with an alloy. A robot may be used to facilitate the process of creating the investment as shown in the figure below.

A robot dips a multi-stage vane segment at PCC Structurals' Deer Creek facility [PCC Structurals, 2009]

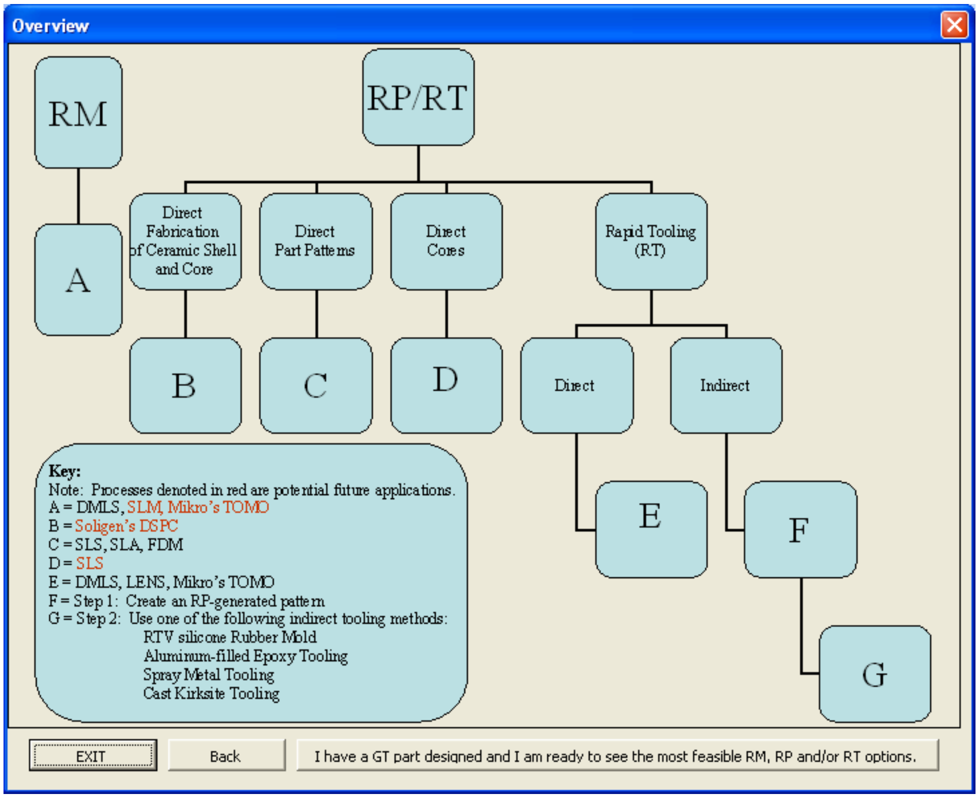
Step 5. Casting: At casting, the mold is preheated in a furnace and a molten metal is then poured into the gating system of the mold which fills the mold cavity to form a raw casting. The molten metal is then allowed to cool and solidify into the shape of the final casting.

Step 6. Ceramic Shell Removal and Final Processing: After casting, the shell, gates, risers, and any ceramic cores are removed via mechanical methods such as hammering and vibrating, along with water blast techniques and chemical leaching. The casting is then subjected to finishing operations such as grinding to remove signs of the casting process, particularly where the gates were located.

Figure 5.4. Interactive program user form describing Steps 3-6 of the IC process.

### 5.1.3 RM, RP and/or RT within the IC process

If the user selects “How does RM, RP, and/or RT fit into the IC process?”, the user is presented with the flow diagram presented in Section 2.8 and as shown in Figure 5.5.

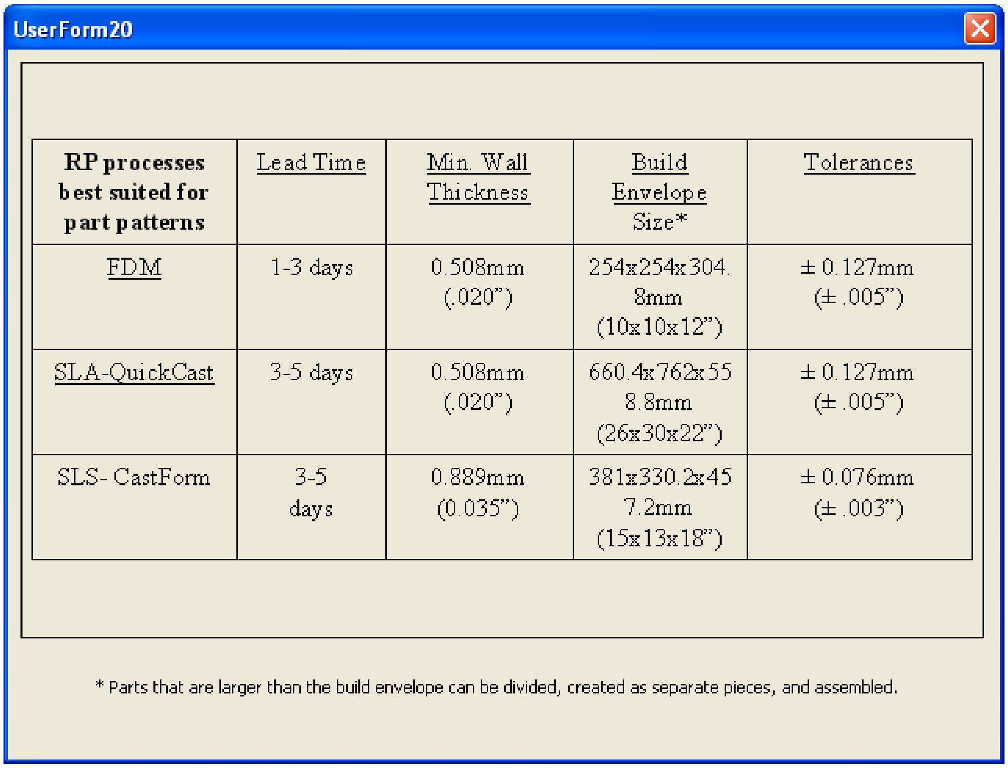


**Key:**
Note: Processes denoted in red are potential future applications.
A = DMLS, SLM, Mikro’s TOMO
B = Soligen’s DSPC
C = SLS, SLA, FDM
D = SLS
E = DMLS, LENS, Mikro’s TOMO
F = Step 1: Create an RP-generated pattern
G = Step 2: Use one of the following indirect tooling methods:
RTV silicone Rubber Mold
Aluminum-filled Epoxy Tooling
Spray Metal Tooling
Cast Kirksite Tooling

Figure 5.5. Overview of RM/RP/RT within IC of GT parts as shown in interactive program.

### 5.1.4 Most Feasible RP/RM/RT Options for a GT Part

If the user selects “I have a GT part designed and I am ready to see the most feasible RM, RP and/or RT options”, the user is ultimately provided with a comparison table of the most feasible RP/RM/RT options depending upon their provided input. An example is shown in Figure 5.6.



| **RP processes best suited for part patterns** | Lead Time | Min. Wall Thickness | Build Envelope Size* | Tolerances |
|---|---|---|---|---|
| FDM | 1-3 days | 0.508mm (.020") | 254x254x304.8mm (10x10x12") | ± 0.127mm (± .005") |
| SLA-QuickCast | 3-5 days | 0.508mm (.020") | 660.4x762x558.8mm (26x30x22") | ± 0.127mm (± .005") |
| SLS- CastForm | 3-5 days | 0.889mm (0.035") | 381x330.2x457.2mm (15x13x18") | ± 0.076mm (± .003") |

* Parts that are larger than the build envelope can be divided, created as separate pieces, and assembled.

Figure 5.6. Example of an output comparison table of the most feasible RP/RM/RT options of the interactive program.

More specifically, the user will first be asked the question: "Can the final part be made from any of the following alloys: 15-5, 17-4 PH Stainless, Cobalt Chrome, Inco 718, or Inco 625?" Note that this question covers the materials that are currently and specifically feasible for the rapid manufacturing of a GT part that are traditionally created via IC. It does not address materials and processes that could be utilized for localized areas, repairs, or inserts for tooling. If the answer to this question is "No", then the turbine or combustion GT part in question currently cannot be created via RM and must be created via IC. If the answer to this question is "Yes", then the part may be able to be created via RM depending upon the part size and accuracy desired.

If the final part can be made from one of the listed material choices, the next concern in selecting the most appropriate RP technology is the final part's size. The user is then asked: “Is the part size less than 254 x 254 x 190.5 mm (10 x 10 x 7.5”)? This is the current build size platform for DMLS. Although larger parts can be separately created and then welded together, this inevitably adds time and cost that should be taken into consideration. The user is informed of this inevitability via an information window within the tool.

The user is then prompted: “Is an accuracy of ±0.001”/in (0.0254 mm) acceptable?” This is the current accuracy that DMLS can provide. If the answer to this question is “Yes”, then the user is presented with the solution of RM and that using DMLS to directly create the final part and bypass the IC process is a possible option currently available.

If the final part cannot be made directly via RM, the next issue to consider is whether the part requires a complex intricate internal core. The first question asked to determine this is: “Does the design have any inaccessible passageways or hollow bodies or cavities of any kind?”. If the answer to this question is “No”, a complex core is not needed, and the user proceeds to determining an RP process for creating a part pattern. If the answer to this question is “Yes”, the user proceed to the question inquiring of the length to width ratio of the hollow cavity: “Is any hollow section length to width ratio > 3:1 and/or does the part have any intricate features with a width of < 6mm (1/4”)?”. If the answer to this question is “No”, the user can proceed to generating a part pattern. If the answer to this question is “Yes”, a complex internal core for the final part is needed.

Currently, there is not an RP technology that can make internal cores directly and efficiently for IC (Mueller, 2009). However, the user can choose to use RP to create core tooling either indirectly or directly. To create core tooling indirectly using RP, an RP-generated core pattern must first be created via SL, SLS, LENS, or DMLS and the user is presented with a summary table that compares the applicable processes. The user is then told that once an RP-generated pattern is created, a core tool can be created from one of the indirect RT options and the user is then shown a comparison table.

If direct tooling is desired, the most feasible options include DMLS, LENS®, or CNC machining and a comparison table of these processes is presented.

Now, at this point, the user is presented with information to create an insert for tooling, which is a removable section of a pattern or tooling that an engineer can remove and replace with an upgraded design iteration. In particular, the user is notified that LENS® and DMLS are ideal RT processes for fabricating inserts for tooling.

The user is now ready to consider RP for creating a part pattern. The user is also informed that, once they have an RP-generated part pattern, he/she may want to consider using an indirect tooling process for creating tooling for short prototype or production runs or a direct tooling approach. The user is then presented with both an indirect tooling comparison table and a direct tooling comparison table. The user is also presented with information to create an insert for tooling.

# CHAPTER 6:
# PERFORMANCE ASSESSMENT OF THE PROPOSED RAPID PROTOTYPING EXPERT SYSTEM – A CASE STUDY APPROACH

## 6.1 Introduction

The proposed expert system for rapid prototyping methodology selection for investment-cast gas turbine parts is assessed for performance efficacy. The interactive program that is based on the proposed expert system methodology described in Chapter 4 is used in two case study scenarios to evaluate the effectiveness of the proposed decision support system. The first case scenario is an air swirler study where the objective is to select the most appropriate RM process for a GT part that is traditionally created via IC. The objective of the second case study is to select the most appropriate RP process to facilitate design iterations for a newly-designed, unique GT part. Note that for both case study scenarios, all non-public, company-specific information has been modified due to proprietary reasons.

## 6.2 Case Study #1 – An Air Swirler Case Study

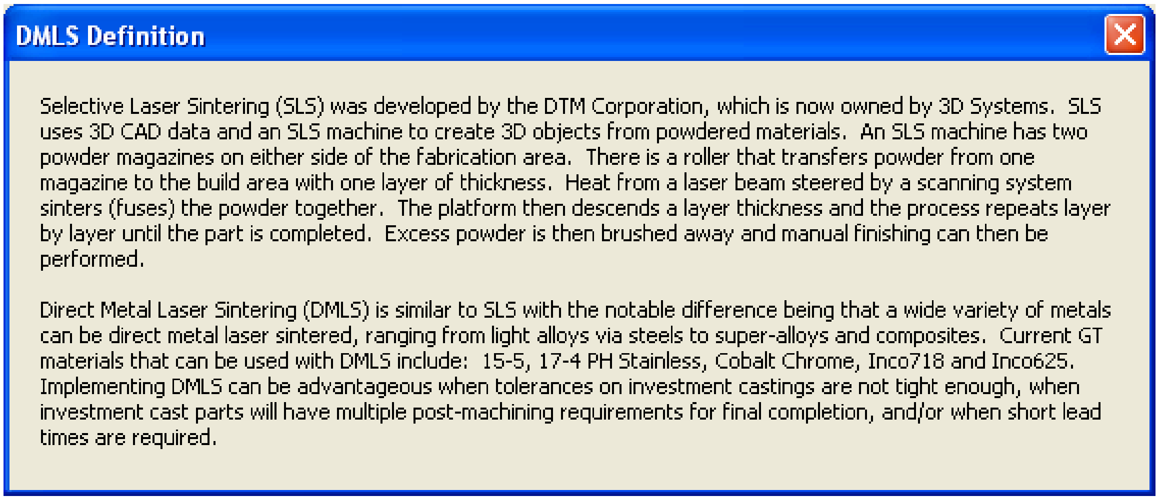
An air swirler, located in the head end of a gas turbine combustor, ensures proper mixing of the combustion air and fuel. Previously, IC methods have been implemented in producing some combustion swirlers and other swirlers have been machined from raw stock (McMasters et al., 2009). However, with advancements in RM, an air swirler can now be created directly via DMLS.

More specifically, the first question asked in the interactive program is: "Can the final part be made from any of the following alloys: Inco 718, Inco 625, Hast-X, Cobalt

Chrome, 17-4 PH Stainless, 15-5, or Ti64?”.The answer to this question is “Yes”, as the preferred metallic powder used to fabricate a swirler is Cobalt Chrome (McMasters et al., 2009). The next question from the interactive program is: “Is the part size less than 254.00 x 254.00 x 190.50mm (10x10x7.5”)? (Note that parts larger than the envelope size can be welded together, but this adds time and cost.)”. The answer to this question for this case scenario is “Yes”, which leads to the next question of “Is an accuracy of ± 0.001”/in (0.0254 mm) acceptable?”. The answer to this question is also “Yes”, which the interactive program informs the user that the final part can potentially be created directly via DMLS. More specifically, after the user uses the interactive program and answering the questions as described in this case study, the tool produces the output as shown in Figure 6.1, which directs the user towards DMLS for the air swirler part. If the user is unfamiliar with DMLS, the user has the option to learn about DMLS by pressing “What is DMLS?” and a definition DMLS is presented, as shown in Figure 6.2.

Final part can possibly be made directly from DMLS.

Figure 6.1. Final result generated by the interactive program for the air swirler case study.



Selective Laser Sintering (SLS) was developed by the DTM Corporation, which is now owned by 3D Systems. SLS uses 3D CAD data and an SLS machine to create 3D objects from powdered materials. An SLS machine has two powder magazines on either side of the fabrication area. There is a roller that transfers powder from one magazine to the build area with one layer of thickness. Heat from a laser beam steered by a scanning system sinters (fuses) the powder together. The platform then descends a layer thickness and the process repeats layer by layer until the part is completed. Excess powder is then brushed away and manual finishing can then be performed.

Direct Metal Laser Sintering (DMLS) is similar to SLS with the notable difference being that a wide variety of metals can be direct metal laser sintered, ranging from light alloys via steels to super-alloys and composites. Current GT materials that can be used with DMLS include: 15-5, 17-4 PH Stainless, Cobalt Chrome, Inco718 and Inco625. Implementing DMLS can be advantageous when tolerances on investment castings are not tight enough, when investment cast parts will have multiple post-machining requirements for final completion, and/or when short lead times are required.

Figure 6.2. User form with the definition of DMLS.

The result generated by the proposed expert system is evaluated using the US Patent database. According to US Patent Number US 2009/0255265 A1 dated October 15, 2009, “DMLS is a preferred method of manufacturing unitary swirlers” in which “unitary” denotes swirlers created “as a single piece during manufacturing”. Figure 6.3 shows an air swirler created via DMLS using a CoCr alloy.

Figure 6.3. Air swirler created via DMLS using CoCr alloy.

The benefits of using DMLS to create swirlers instead of IC can be substantial. In combustion, designs are often changed in order to effectively address emissions, dynamics, or other combustion performance issues. The most common change is the geometry of the air swirler. Table 6.1 is a comparison table in terms of estimated cost and lead time of various methods that could be used in fabricating an air swirler. It is important to note that this table is not generated by the proposed expert system.

Table 6.1. Comparison of process methods to create swirlers.

| **Process Method** | **Cost** | **Lead time** |
|---|---|---|
| Conventional (CNC) tooling used with IC | \$50K - \$60K (one-time tooling cost) + \$400/part | 1 year |
| SLA part pattern used with IC | \$1K/part | 12 weeks |
| DMLS | \$5K/part | 2-4 weeks |

Table 6.1 suggests that a DMLS-qualified material allows the production of critical parts in a much shorter lead time in order to meet customer contractual requirements. This case study shows how important it is for a design engineer to have a decision support system with up-to-date knowledge that is aligned with his/her specific industry when selecting an RP/RM/RT process.

### 6.3 Case Study #2 – “Part X” Case Study

Consider a newly-designed, unique GT part. This part is referred to as “Part X” in this case study due to proprietary information. Although transition pieces are not created via IC, a picture of a transition piece, shown in Figure 6.4, will be used in place of a picture of Part X for this case study as a transition piece has key physical parameters that are similar to the confidential GT part in question.

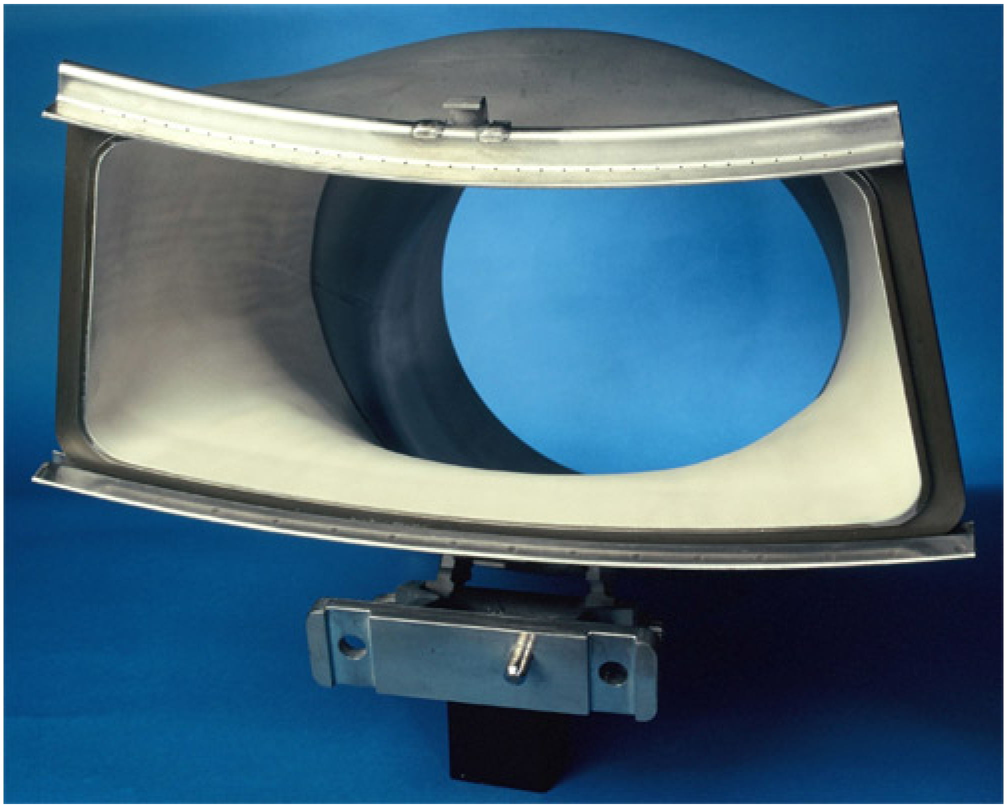
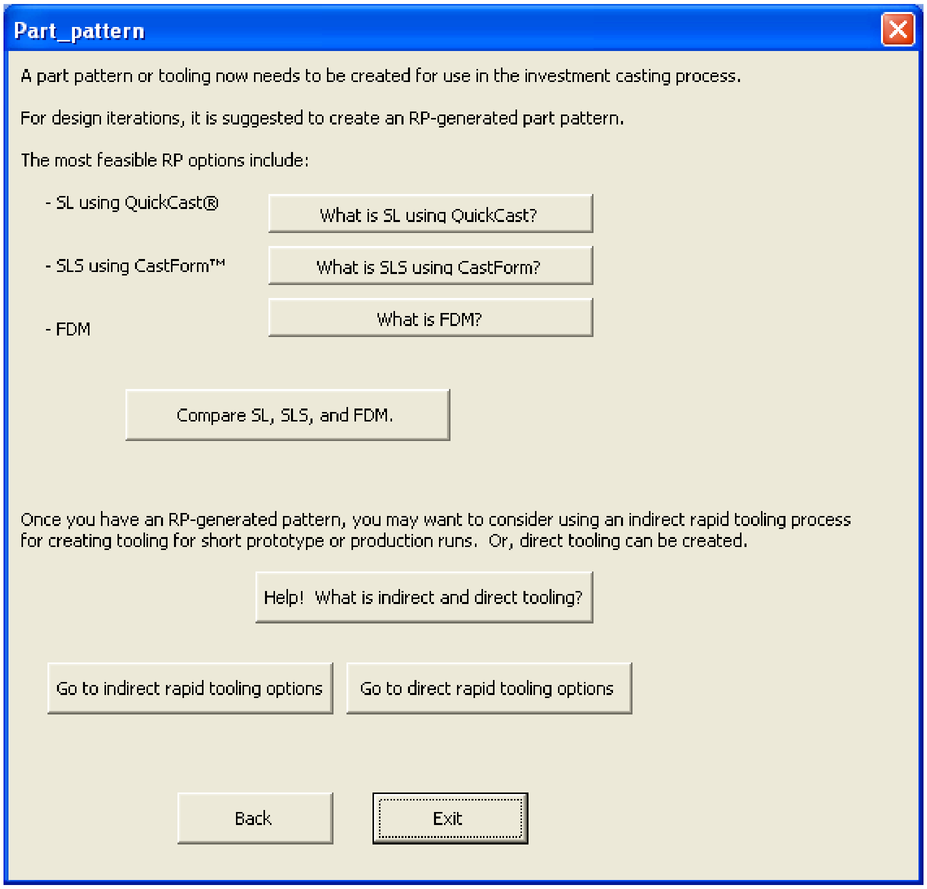


Figure 6.4. A gas turbine transition piece (Power-Technology.com (2010)).

There will be no information provided as to the function of Part X, but it is sufficient to note that Part X presents an opportunity in that it encompasses a brand new technology in which rapid design iterations are crucial.

Using the interactive program that is based on the proposed expert system methodology, the user begins with the first question, which is “Can the final part be made from any of the following alloys: Inco 718, Inco 625, Hast-X, Cobalt Chrome, 17-4 PH Stainless, 15-5, or Ti64?”. The answer to this question for Part X is “No”. The interactive program then decides if a core pattern is necessary. Part X has a hollow body, as shown in Figure 6.4, but the hollow section length to width ratio is < 3:1 and it does not have any intricate features with a width of < 6mm (1/4”). Therefore, a complex core pattern is not necessary, and the user can make a part pattern via RP. The output of the interactive program, as shown in Figure 6.5, informs the user that the most feasible RP options for creating a part pattern for this part include: SL using QuickCast, SLS using CastForm, or FDM.



A part pattern or tooling now needs to be created for use in the investment casting process.

For design iterations, it is suggested to create an RP-generated part pattern.

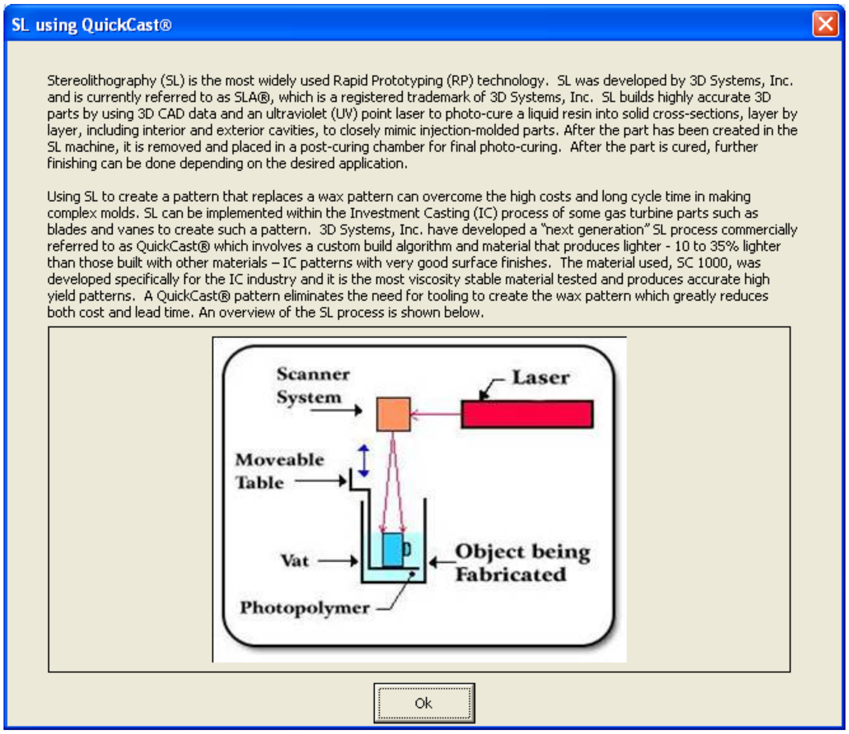
The most feasible RP options include:

- SL using QuickCast®
- SLS using CastForm™
- FDM

Once you have an RP-generated pattern, you may want to consider using an indirect rapid tooling process for creating tooling for short prototype or production runs. Or, direct tooling can be created.

Figure 6.5. Output for Case Study #2.

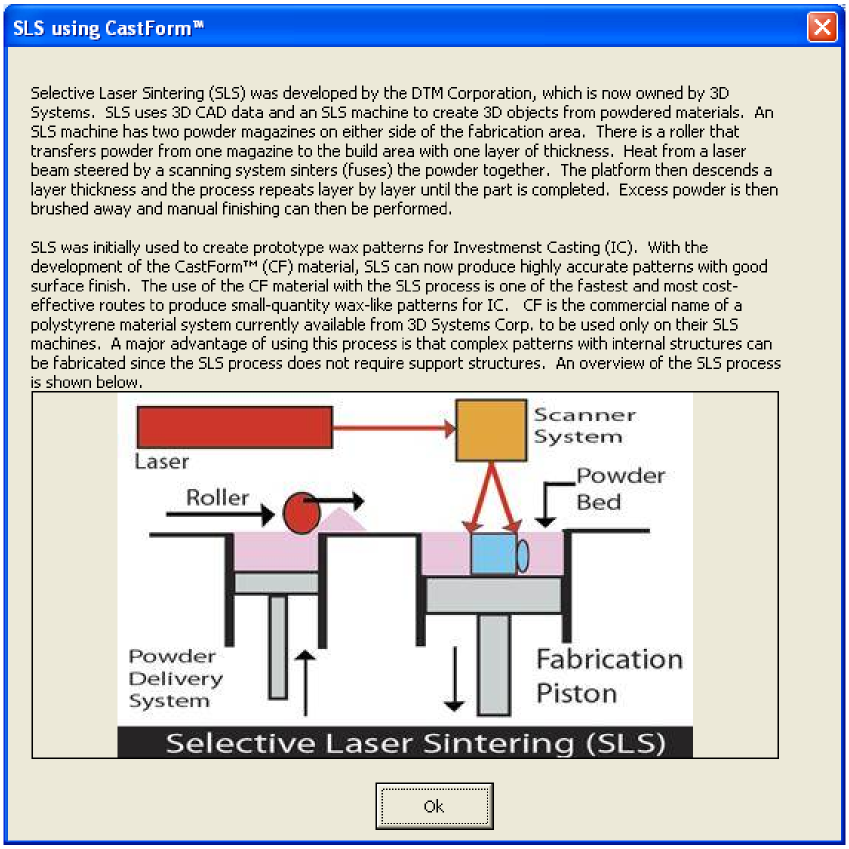
At this point, the user has the option of learning more about SL using QuickCast®, SLS using CastForm™, or FDM as shown in Figure 6.6, Figure 6.7and Figure 6.8.



Stereolithography (SL) is the most widely used Rapid Prototyping (RP) technology. SL was developed by 3D Systems, Inc. and is currently referred to as SLA®, which is a registered trademark of 3D Systems, Inc. SL builds highly accurate 3D parts by using 3D CAD data and an ultraviolet (UV) point laser to photo-cure a liquid resin into solid cross-sections, layer by layer, including interior and exterior cavities, to closely mimic injection-molded parts. After the part has been created in the SL machine, it is removed and placed in a post-curing chamber for final photo-curing. After the part is cured, further finishing can be done depending on the desired application.

Using SL to create a pattern that replaces a wax pattern can overcome the high costs and long cycle time in making complex molds. SL can be implemented within the Investment Casting (IC) process of some gas turbine parts such as blades and vanes to create such a pattern. 3D Systems, Inc. have developed a "next generation" SL process commercially referred to as QuickCast® which involves a custom build algorithm and material that produces lighter - 10 to 35% lighter than those built with other materials – IC patterns with very good surface finishes. The material used, SC 1000, was developed specifically for the IC industry and it is the most viscosity stable material tested and produces accurate high yield patterns. A QuickCast® pattern eliminates the need for tooling to create the wax pattern which greatly reduces both cost and lead time. An overview of the SL process is shown below.

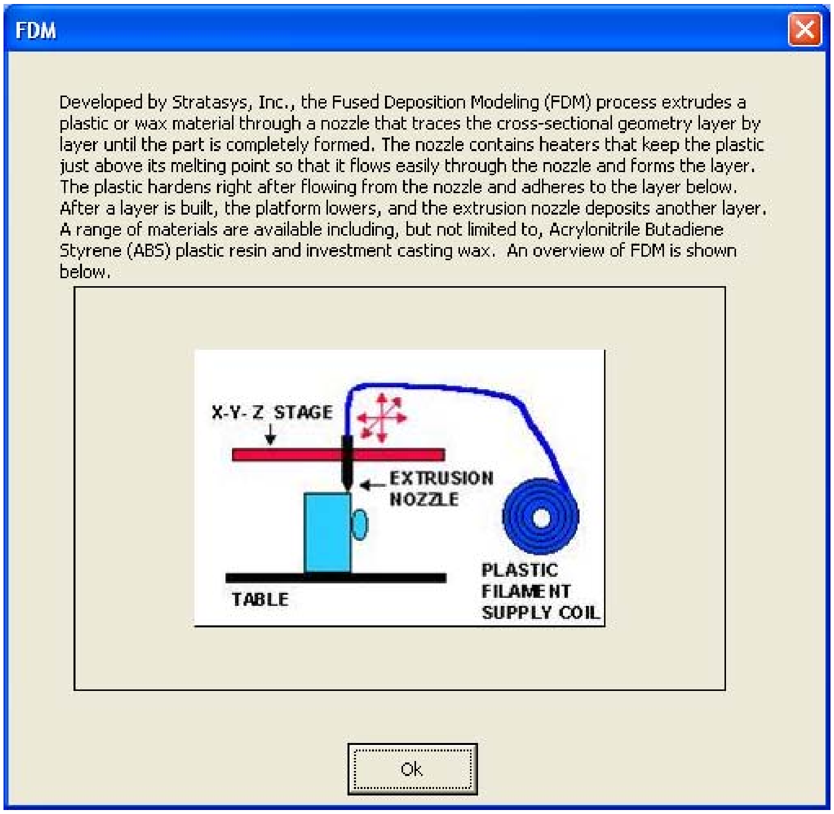
Figure 6.6. Interactive program output describing SL using QuickCast®.



Selective Laser Sintering (SLS) was developed by the DTM Corporation, which is now owned by 3D Systems. SLS uses 3D CAD data and an SLS machine to create 3D objects from powdered materials. An SLS machine has two powder magazines on either side of the fabrication area. There is a roller that transfers powder from one magazine to the build area with one layer of thickness. Heat from a laser beam steered by a scanning system sinters (fuses) the powder together. The platform then descends a layer thickness and the process repeats layer by layer until the part is completed. Excess powder is then brushed away and manual finishing can then be performed.

SLS was initially used to create prototype wax patterns for Investmenst Casting (IC). With the development of the CastForm™ (CF) material, SLS can now produce highly accurate patterns with good surface finish. The use of the CF material with the SLS process is one of the fastest and most cost-effective routes to produce small-quantity wax-like patterns for IC. CF is the commercial name of a polystyrene material system currently available from 3D Systems Corp. to be used only on their SLS machines. A major advantage of using this process is that complex patterns with internal structures can be fabricated since the SLS process does not require support structures. An overview of the SLS process is shown below.

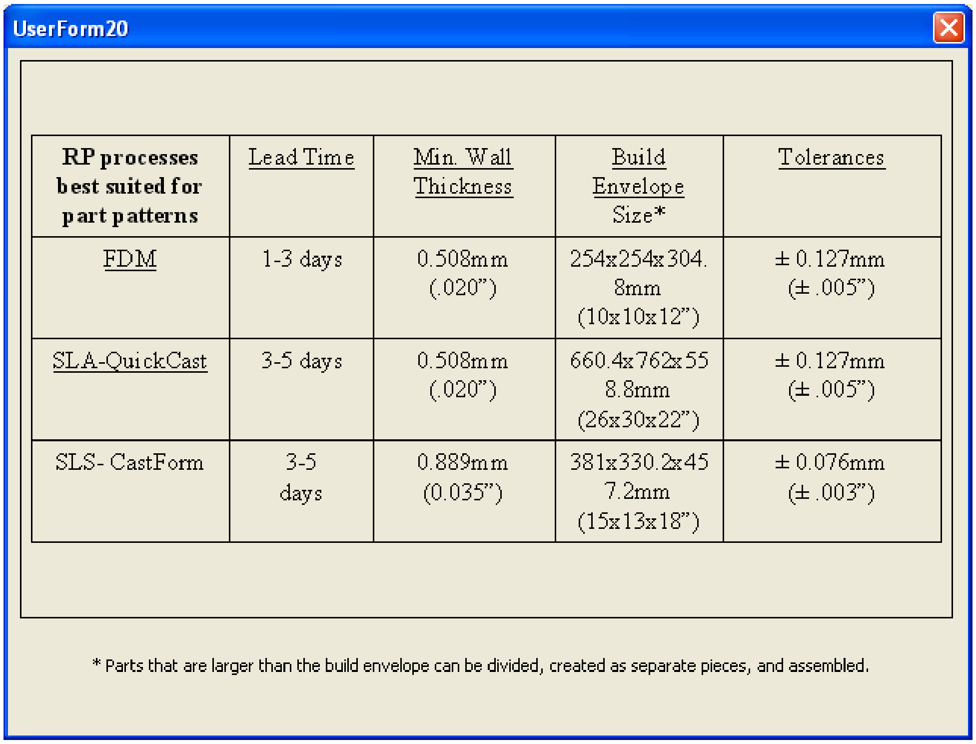
Figure 6.7. Interactive program output describing SLS using CastForm™.



Developed by Stratasys, Inc., the Fused Deposition Modeling (FDM) process extrudes a plastic or wax material through a nozzle that traces the cross-sectional geometry layer by layer until the part is completely formed. The nozzle contains heaters that keep the plastic just above its melting point so that it flows easily through the nozzle and forms the layer. The plastic hardens right after flowing from the nozzle and adheres to the layer below. After a layer is built, the platform lowers, and the extrusion nozzle deposits another layer. A range of materials are available including, but not limited to, Acrylonitrile Butadiene Styrene (ABS) plastic resin and investment casting wax. An overview of FDM is shown below.

Figure 6.8. Interactive program output describing FDM.

The user can also elect to compare these three processes and will be shown the comparison table (see Figure 6.9).



| **RP processes best suited for part patterns** | Lead Time | Min. Wall Thickness | Build Envelope Size* | Tolerances |
|---|---|---|---|---|
| FDM | 1-3 days | 0.508mm<br>(.020”) | 254x254x304.8mm<br>(10x10x12”) | ± 0.127mm<br>(± .005”) |
| SLA-QuickCast | 3-5 days | 0.508mm<br>(.020”) | 660.4x762x558.8mm<br>(26x30x22”) | ± 0.127mm<br>(± .005”) |
| SLS- CastForm | 3-5 days | 0.889mm<br>(0.035”) | 381x330.2x457.2mm<br>(15x13x18”) | ± 0.076mm<br>(± .003”) |

* Parts that are larger than the build envelope can be divided, created as separate pieces, and assembled.

Figure 6.9. Output Comparison Table of RP options for Case Study #2.

The part size of Part X is roughly 584x584x483mm (23x23x19”). Although parts that are larger than the build envelope stated for each process can be divided, created as separate pieces, and assembled, this adds time and money to the creation of the part. Using the tool output shown in Figure 6.9, the user can quickly compare the build envelope sizes of SL using QuickCast, SLS using CastForm, and FDM. From this comparison, it can be seen that the most feasible choice in this case is SL using QuickCast to directly create the part pattern. In validating the direction in which the tool guided the user, this decision aligns with the recommendation given by the actual foundry that will produce Part X.

The cost to create one Part X part pattern via SL with QuickCast is approximately $5,600, and there is a lead time of seven weeks, whereas CNC tooling for the pattern would have cost ~$200K with a lead time of 7-12 months. In addition to saving time and money on design iterations, RP allows for quick feedback issues from manufacturing to design for Part X including:

- Wall thickness taper,
- Flange locations/preferences,
- Panel thickness minimum,
- Rib size, spacing, taper, and
- Rib junction geometry.

# CHAPTER 7:
# SUMMARY OF RESEARCH AND DIRECTIONS FOR FUTURE WORK

## 7.1 Summary of Research

This thesis discusses the design and implementation of an RP technology selection expert system that can be used with investment-cast gas turbine engine parts.

Currently, the common practice in the gas turbine industry is to consult with subject matter experts within existing foundries to assist gas turbine design engineers in the selection of an RP process for a particular application. The proposed expert system is designed to provide expert knowledge-based assistance in the selection of an RP process and attempts to facilitate understanding by the gas turbine design engineer of how RP/RM/RT fits within the IC process of gas turbine parts.

The expert system serves to tailor many of the concepts covered in the existing literature to the GT industry as well as cover specific issues that a GT design engineer may encounter, such as the need for an intricate internal core or the need for specific superalloy materials. The expert system provides results without the need to enter large amounts of data, which is useful for the user with limited RP knowledge. The expert system does not rank the results but, rather, leaves the decision to the user as to the criteria that are most important for their particular application.

In particular, Chapter 1 of this thesis describes the motivation behind the research, the need for the expert system, as well as the expected contributions. Chapter 2 presents a brief overview of RP, RT, and RM and then further explains such processes that are pertinent to gas turbine parts that typically require investment casting. Chapter 2 also provides an overview of gas turbines, describes the IC process, and then presents an overview of how RP, RT, and RM fit within the investment casting process of gas turbine parts. Chapter 3 briefly summarizes the literature of existing RP/RT/RM decision support methodologies for RP technology selection, compares these methodologies, and explains why this research investigation is worthwhile. Based on the results drawn from the literature review, it is found that there are limitations with the existing decision support methodologies as these methodologies do not address intricate internal cores, GT exotic materials, and the possibility of replacing IC with RM for investment-cast GT parts. Chapter 4 introduces the proposed decision support methodology and explains the underlying logic of its expert system-based design. Chapter 5 describes a Visual Basic implementation of this proposed decision support system as an interactive program. To validate and assess the proposed methodology, the interactive program is applied to two case scenarios in Chapter 6. The results from the two case studies show that using the proposed decision support system potentially results in an 82% to 94% reduction in lead time and a 92% to 97% cost savings.

## 7.2 Directions for Future Work

This thesis lays the foundation for several extensions. For future work, instead of lead times being a fixed and known range, stochastic lead times could be implemented. Likewise, instead of costs being deterministic and known, costs that follow a known probability distribution could be implemented within the system.

Another recommendation is for GT companies to tailor this expert system for their specific needs, which would include updating the system to accommodate data on approved vendors or in-house capabilities and list past company projects associated with particular RP processes.

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