AUTOMATED COST ESTIMATION FOR 3-AXIS CNC MILLING AND STEREOLITHOGRAPHY RAPID PROTOTYPING

By

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Abstract

Rapid prototyping (RP) is a supplementary additive manufacturing method to the traditional Computer Numerical Controlled (CNC) machining. The selection of the manufacturing method between RP and CNC machining is currently based on qualitative analysis and engineers' experience. There are situations when parts can be produced using either of the methods. In such cases, cost will be the decisive factor. However, lack of a quantitative cost estimation method to guide the selection between RP and CNC machining makes the decision process difficult.

This thesis proposes an automated cost estimator for CNC machining and Rapid Prototyping. Vertical CNC milling and Stereolithography Apparatus (SLA) RP technology are selected in specific, for cost modeling and process comparison. A binary questionnaire is designed to help estimate the CNC setup cost. An SLA build time estimator is implemented based on 3D systems' SLA3500 machine. SLA post processing cost is also investigated. Based on the developed methods, a prototype software tool was created with an output to Excel chart to facilitate the selection. Five cases have been studied with the software and the predicted results are found reasonable and effective.

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1 Introduction

1.1 Background

In the past few decades, Computer Numerical Controlled (CNC) machining as a typical traditional subtractive manufacturing process, has been used extensively in the manufacturing industry. After years of development, Rapid prototyping (RP), as an additive manufacturing method, is emerging as a supplementary manufacturing method to the traditional subtractive manufacturing methods.

In general, RP targets mainly at prototyping and bears relatively high capital investment and material cost. It is suitable for quick, single part manufacturing and is not a cost effective way for mass production. RP is thus usually regarded as an alternative to the CNC machining for prototyping or single part production.

A designer has the choice of choosing an RP or CNC machining for single part production. The selection criteria are based on the part property, cost of production, and time taken to produce the part. Part property refers to the requirements such as dimensional accuracy, material property, surface quality, etc.

RP and CNC machining have their own individual strength. RP can build very complicated parts without the need for complex fixtures. CNC machining leads to high accuracy, more material choices, and need of fixtures which can be extensive in some cases. It is obvious that if a technology cannot yield the desired part properties, it will not be chosen to produce the part. For example, CNC can machine an aluminum part but current RP technologies can not use aluminum as the material. RP can build a part with internal features but CNC machining will have difficulty producing it. A classical example is a sail boat contained within a bottle (See Figure 1-1). On the other hand, CNC can machine easily and quickly, for example, a boss on a block (shown in Figure 1-2), but RP will take a longer time and a higher manufacturing cost.

Figure 1-1 Sailboat in a Bottle

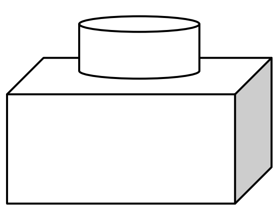


Figure 1-2 Boss on a Block

If both technologies satisfy the part property requirement, then the time to produce the part in conjunction with the cost must be considered when selecting a process. In general, CNC tool path generation for a complex part is a time consuming process because tool cutting points need to be interpolated in 3D space while RP manufactures a part in a layer by layer manner thus it simplifies a 3D manufacturing problem into a series of 2D problems. If CNC machining needs non-standard fixtures, extra time is needed to design and build the fixture. RP process is fixtureless and software setup is very quick. All these issues should be factored in when evolving a methodology for quantitative comparison between two processes.

This work was inspired from an industrial project, aiming at integrating RP into conventional sand casting pattern making process. Casting pattern making generally involves single part manufacturing processes and patterns are CNC machinable. In this study, the stereo-lithography apparatus, SLA 3500 RP system, from 3D Systems was chosen as the candidate RP process. Comparison was made between SLA, 3-axis CNC machining, and hand-carving. This study revealed that all these processes satisfy the sand casting pattern dimensional accuracy requirements and SLA was found to be cost effective for small, complex parts while CNC and hand-carving were found to be cost effective for simple parts with large volume. Such research results are subjective and lack quantitative details. To obtain detailed cost data, a quotation is often necessary. Depending on the schedule of contractors each quotation will usually take a few days. If designers want to do their own estimation, they can get the CNC machining time from Computer Aided Manufacturing (CAM) packages. Design and cost estimation of suitable fixtures, however, is not considered in most CAM packages. The setup and fixture cost in

CNC could play a significant role when compared with RP. On the other hand, Rapid Prototyping cost estimation is not included in commercial Computer Aided Design (CAD) packages, even though RP does not have the setup and fixture complexity. The cost estimation of RP remains an art and proprietary to RP service bureaus.

The result of literature review shows that most CNC machining cost estimators oversimplify setup cost estimation, either by using a fixed value for each setup or by using statistical formula based on part weight. The review also shows that most CNC machining and RP manufacturing process comparisons are based on part properties and not on cost and there lacks a dedicated cost estimation system for both CNC machining and RP.

Therefore, a cost estimator for both CNC machining and RP will be a valuable tool that gives a quick response in terms of manufacturing costs and provide valuable information to help designers select the cost effective manufacturing process. It's also helpful for CNC machining or RP service providers to know the cost of the alternative technology.

1.2 Objectives

The objective of the research is to develop a cost estimator that predicts CNC milling cost and stereo-lithography (SLA) cost for singe part production process selection. The first task is to develop a semi-automatic cost estimation method for CNC milling with a focus on the set-up cost estimation. The second stage is to develop a cost estimation method for

SLA RP process. The third step is to create a software prototype based on the developed cost estimation methods for CNC milling and SLA, which automatically or semi-automatically estimates the prototype cost of a given part and provides the users with valuable information on how to select the most cost effective process for the part under consideration.

This research focuses on the selection of the manufacturing process for situations where only single part is needed such as a master pattern, design concept model, custom made tool, and so on. This implies that the manufacturing process selection is for a single part manufacturing and not for mass production. The appearance, material properties, and dimensional accuracies of rapid prototyping technologies should satisfy the part's requirements. These two restrictions ensure the validity of the cost-based process selection method.

This research focuses on two popular techniques for selection, namely, the 3-axis CNC milling and the Stereo-lithography (SLA) rapid prototyping technology. The methods developed should provide guidance for selecting either CNC or RP techniques for producing a part.

1.3 Organization of the thesis

Following the introduction in Chapter 1, chapter 2 provides an overview of CNC cost estimation, Stereo-lithography cost estimation and existing comparison methods. Chapter

3 and 4 detail the proposed setup cost estimation method, CNC milling cost modeling, SLA3500 build time estimation method, and Stereo-lithography cost modeling. Chapter 5 is a brief introduction of the software prototype. Chapter 6 presents five case studies by using the developed methods and cost estimation software. Finally chapter 7 provides the conclusion arising from this study as well as some suggestions for future work.

2 Literature Review

This chapter presents a literature review on three topics related to the problem tackled in this thesis. The first section discusses the literature related to CNC machining cost estimation methods. This is followed by a survey of stereo-lithography cost estimation methods. The final section focuses on the review of comparison methods between CNC machining and stereo-lithography.

2.1 CNC cost estimation methods

Through years, many cost estimation methods have been developed. Roy (2003) classified cost estimation methods as traditional cost estimation ("first sight" and activity based costing), parametric estimating, feature based costing, neural network based cost estimation, and case based reasoning. They can also be classified as: qualitative approaches and quantitative approaches. Quantitative approaches are subdivided into statistical model, analogous model, and analytical model (Layer et al. 2002). When applied to CNC machining, cost estimation methods can be "first sight" costing, feature based costing, and analytical activity based costing.

2.1.1 First sight cost estimation

"First sight" or intuition cost estimation is a best educated guess based on estimator's previous experience of similar projects. It takes a long training time and the estimation of the new project is usually subjective and not justifiable (Roy 2003, Roztocki 2005).

2.1.2 Feature based cost estimation

"First sight" cost estimation was widely used before modern CAD/CAM software appeared. Using CAD/CAM software, users can generate NC tool path interactively and CAD/CAM software will precisely predict the machining time based on the generated tool path. The generated tool path should pass manufacturability or machinability check to ensure tool accessibility, avoid interference and part deformation (Gupta et al. 1997, Stage et al. 1997, Chen et al. 2002, Faraj 2003).

Feature based 3-D solid modeling improves the design and manufacturing automation. In feature-based modeling, a part is considered as a combination of positive volume features such as bosses and negative volume features such as holes, slots, pockets etc. Machining is a material removal process. In machining cost estimation all features are defined as negative volume features called machining features. Machining time estimation formulas are pre-set and assigned to the machining features and can be applied to the same features in different parts (Feng et al. 1996, Ou-Yang and Lin 1997, Roberts and Hermosillo 2000, Jung 2002).

With the advancements in feature recognition technologies (Han et al. 2000), machining features can be identified with minimal user interference. Based on the feature information, machining time and optimal setup plans can be automatically generated. A setup plan refers to a series of work-piece's orientations needed for the machining and it does not have fixture information. Das et al. (1995) and Han et al. (2001) used feature recognition technology to find an optimal setup plan with the minimum number of work piece setups, however details of fixture in each setup were not considered in their work.

Feature based modeling helps to estimate the machining time and generate the setup plan, but it does not cover the whole manufacturing process. Feature based costing is usually a subsystem of activity based cost estimation for the entire manufacturing process.

2.1.3 Activity based cost estimation

Manufacturing cost is conventionally considered as the sum of the direct cost such as labor, material and the indirect cost namely overhead cost. Large overhead cost reduces the precision of the estimation. In activity based costing, a manufacturing process is well defined and divided into activities like inspection, administration, and production processes (Roy 2003). By defining activities, most overhead cost can be classified as direct cost thereby increasing the estimation's precision. Average cost for each activity is assigned. A product's manufacturing cost is the summation of the cost of all its activities.

Each feature machining is an activity, and each setup is an activity. Therefore, feature based cost estimation is part of activity based cost estimation. Based on activities, CNC machining cost is the sum of machine operation, setup, tool, material, and overhead costs. Machine cost is the cost of operation when CNC machine is in production mode which equals the machining time multiplied by the operator's hourly salary rate. If the machining time includes the tool change and engagement time, then the tool change and engagement costs can be included in the machine operation cost. Alternatively, tool change and engagement costs can be obtained from a machine data table (Jung 2002). Tool cost is the tool replacement cost incurred due to regular wear. Another important cost element, setup cost, will be discussed in the next section.

2.1.4 Setup cost estimation

It is found that the most challenging task in CNC machining cost estimation is the setup cost estimation. Setup cost refers to the cost involved in work piece orientation, locating, and fastening. This review focuses on how to determine the setup cost. Setup plan generation (work piece orientation determination) is not considered in this research.

Generally, there are three ways to estimate the setup cost: weight based, fixed value based, and detailed plan based.

Weight based estimation

Jung (2002) used Boothroyd and Reynolds's (1988) approximation methods to calculate the total loading time (work piece setup time). Their approach considers factors such as number of loadings in a process, and the individual loading time for each setup. Loading time considers the weight of the work piece. Jung did not consider any particular type of holding devices. Boothroyd et al. (2002) defined a loading and unloading time lookup table based on work piece weight and statistical methods. This type of estimation can not reflect the specific requirements of individual part and has its limitations.

Fixed value based estimation

In this kind of method, a fixed cost is assigned for all setups and no detailed fixture plan is considered. For example, Diganta Das et al. (1995) assumed that parts were small in size which could be moved and reoriented manually by one person and a fixed value of two minutes was assigned for each setup that employs vise clamping only. This method can be regarded as a special case of weight based methods and has the same limitation as the weight based method. This method is fast and suitable for simple and small parts where each setup can be done quickly. However, it assumes no substantial difference between each setup, an assumption that is very questionable.

Detailed plan based estimation

These methods need detailed fixture plans. Setup cost is the sum of the cost of each setup operations. Wei and Egbelu (2000) used standard fixtures to decide the setup cost. The kind and number of clamping and supports are decided by the type of support at the seating surface, such as 3 point support, point and line support, and plane support. The cost of each element is computed by multiplying the number of items and their unit cost. The total setup cost is the sum of the cost of all elements. This method is intuitive but fixture plans are fixed and do not provide any flexibility for considering individual demands. Fixture principles such as 3-2-1 and 4-2-1 have also been discussed by (Young and Bell 1990, Trappey and Liu 1990, Hargrove and Kusiak 1993).

Fixture component selection can also be deduced from manufacturing features. Like other feature recognition based technologies, feature based fixture design is not mature and is still in its infancy.

To summarize, the CNC machining cost estimation is primarily activity based and setup cost estimation is not fully investigated. In this research, an activity based cost estimator with a focus on the setup cost estimation will be presented.

2.2 Stereolithography cost estimation Methods

Stereolithography Apparatus (SLA) may be the most widely used rapid prototyping technology. It utilizes laser to solidify liquid resin, layer by layer to build the part. Materials, build orientation, build styles and layer thickness are the most important SLA cost factors. Chapter 4 will describe SLA build process in detail.

Few papers have been published on stereolithography build cost estimation. Generally the stereo-lithography cost is the sum of material cost, build cost and post processing cost.

Material cost is obtained by the product's material volume and material unit cost. Build cost is the build time multiplied by machining cost per hour. Post processing cost will be discussed later on.

Some companies (Xpress3D 2005) provide online instant quote for SLA and other RP processes. Users provide STL files and select the material and finish level. For SLA, estimation without build orientation, build style, and layer thickness information are not reliable. Actual cost may be several times higher than estimated.

2.2.1 SLA build time estimation

The foundation of the Stereo-lithography build cost estimation is the build time estimation. The build time estimations for different kinds of Stereolithography (SLA) machines have been discussed (Chen and Sullivan 1996, McClurkin et al. 1996, Tata and Flynn 1996, J.Giannatsis et al. 2001, Huang et al. 2001). Though SLA machines share the same structure, implementations are different. Therefore, build time estimators are little different and not interchangeable.

Basically, there are two approaches: sliced geometry based and non-sliced Stereolithography Format (STL) file based methods. Both methods read geometry information from STL file. In CAD software, a solid can be represented by its surface and the STL file is the tessellated presentation of a solid's surface. According to the approximation accuracy specified by users, part surfaces are tessellated into connected triangles. Each triangle has three vertices and a surface normal indicating which side is the part material. Sliced geometry is an STL model sliced into layers of polygons. It is no longer a triangular tessellation. To generate a sliced geometry, an STL model is first oriented, support structure is then generated and the model is sliced into a series of parallel cross sections perpendicular to the build orientation (SLA machine's Z direction) in increments of the given layer thickness. Sliced geometry has more information such as build orientation and support structure than a STL file and hence its build time estimation is more precise than the latter. On the other hand, without the trouble to generate the support structure and slice the model, non-sliced estimation method is quicker and easier. It is very useful to find an optimal combination of build parameters, as well as to obtain quotes

In this research, non-sliced, original STL based estimation is applied to get a quick and reasonable estimation for SLA 3500 machine from 3D Systems, Inc.

2.2.2 Post Process cost estimation

Post processing refers to the cleaning, support structure removal, curing and sanding. Sanding is to reach a desired surface quality and is the major cost component in post processing. Cleaning, washing, support structure removal, and curing costs for SLA are assumed to be very small, usually omitted or included as overhead cost. The purpose of sanding is to sand off the stair stepping effects caused by the layer by layer manner of construction.

Some researches have employed CNC machining to machine off the stair stepping effects (Stucker and Qu 2003, Shi and Gibson 2000, Lai and Gibson. 2000). This requires a surface finishing CNC tool path generation and may also need fixture that neutralizes the benefit of RP technology as a featureless process and increases the cost.

Spencer (1993) found that automatic machine sanding either improved surface quality at the sacrifice of corners and edges or was unable to process the internal corners and restricted areas. It also may cause unaccepted damage to the part. Therefore, sanding is usually done manually. If a high surface quality is needed, it may take hours to finish.

Magics RP™ software (2004) estimates the sanding cost as the multiple of part surface area and labor rate per unit area. However, different surfaces have different accessibility and may need different finish levels. Hard to access areas usually take much more time than easily accessible areas. For parts with areas of different accessibility, this estimation method may not be suitable.

Many RP service providers use their experience to estimate the post processing cost based on the finish level needed. For example, Met-L-Flo (2005) defined four surface finish levels: Basic Finish, Mold Ready, Premium Finish and Photometric. A custom finish level is also supported. The higher the surface quality needed, the higher the cost will be. This approach is intuitive, practical and no complex calculation is involved. However the issue of different sanding cost owing to different area accessibility is not accounted for very well. In this research, exterior and interior surfaces are used to distinguish the surface accessibility.

2.3 Comparison methods for CNC machining and Stereolithography

Since SLA is competing with CNC machining for single part production, some researches have been done on when RP is a better choice than CNC machining.

Lennings (2000) listed the advantages and disadvantages of CNC machining and RP, and suggested that CNC machining should be selected for styling block models and concept models and RP for fully functional prototypes. Wohlers and Grimm (2003) compared the attributes of CNC machining and RP such as material choice, part complexity, dimensional accuracy etc., which gives guidelines to aid users to set their own criteria to select the proper manufacturing method. Schmidt (1997) also suggested that some basic criteria be established prior to the selection. These criteria include the purpose of the prototype, material preference, dimensional and finish requirements, time, budget etc. Kashka and Auerbach (2000) proposed a system to select the appropriate manufacturing process from CNC machining and many rapid prototyping technologies. It is primarily a part property based selection. Cost estimation is not detailed and CNC machining setup cost is not mentioned. All of the above comparisons are part property based. For those cases where CNC machining and RP are both a choice, cost may be the determining factor. Marinov (1995) gave an intuitive rule that stereo-lithography is cost effective for complicated shapes and CNC machining is cost effective for simple shapes. It is subjective to decide whether a part is complex or simple, and the result is not reliable.

It is found that there is no quantitative comparison method to guide the selection of CNC or stereolithography. This research aims at developing such a method and associated software.

2.4 Summary

Existing CNC cost estimation methods utilize machining time as a primary factor and setup cost is not well addressed. Rapid Prototyping is a fixtureless process and hence setup cost is not a significant factor. For stereolithography, there is sliced geometry and non-sliced STL based build time estimation methods. The latter is quicker but less precise than the former. The SLA build time estimation should be specific to certain machine, material, and build style. Post processing cost estimation is a focus of many researches. Current comparison methods for CNC machining and Stereo-lithography only give qualitative guidelines on the selection between CNC machining and RP. There is a definite need for a system that is based on quantitative manufacturing cost estimation for both processes for any given part.

In this research, a dedicated cost estimator for CNC machining and Stereo-lithography is developed to help users select one of the two processes based on quantitative cost estimation.

3 Proposed CNC milling cost estimation method

In this research, a semi-automated activity based CNC cost estimator with a focus on setup cost estimation will be proposed. The proposed CNC milling cost modeling is introduced first, followed by the setup cost estimation method.

3.1 CNC milling cost modeling

A CNC machining job is subdivided into tool path generation, machining, tool replacement, and setup activities. Tool change and engagement activities are included in the machining activity. Correspondingly, the total CNC machining cost is the sum of tool path generation cost, machining cost, tool cost, material cost, setup cost, and overhead. The total cost of a CNC machining job will be

$$\begin{aligned} CNCCost = {} & CToolPathGeneration + CMachining + CTool + CSetup + \\ & CMaterial + COverhead \end{aligned}$$

3-1

$CToolPathGeneration$ is the cost of tool path generation. It can be calculated by the time used to design and generate the tool path multiplied by the programmer's salary rate.

$$CMachining = MachiningTime \times (MachineCostPerHour + LaborCostPerHour)$$

3-2

To simplify the process and use existing CAD/CAM software, the machining time is directly read from CAM software after the user generates CNC tool path. Most CAM software can output all the operations in plain text format. This output includes tool cutting time, total machine time, and cutting operation parameters. The difference between the tool cutting time and total machine time is the tool change and engagement time. In this work the tool change and engagement cost is included in the total machining cost.

Machine investment is converted to the machine cost per hour and is included in the cost to reflect the capital investment on the CNC machine.

$$\text{MachineCostPerHour} = \frac{\text{MachinePurchaseCost}}{\text{YearsOfReturn} \times \text{AverageWorkHoursPerYear}}$$

3-3

$\text{MachinePurchaseCost}$ is the total investment of the CNC milling machine.

YearsOfReturn is the years the investment will pay off.

$\text{AverageWorkHoursPerYear}$ is the average annual machine work hours.

LabourCostPerHour is specified by the user.

CTool is the sum of the cutting tool costs for the machining job. Cutting tools need to be replaced when they are worn out.

$$\text{CTool} = \sum_{i=1}^{n} (\text{ToolLifeUsed}_i \times \text{ToolPurchaseCost}_i)$$

3-4

where

$i = 1, 2...n$ i is the number of cutting tools used.

ToolLifeUsed_i is the used tool life for tool i.

$\text{ToolPurchaseCost}_i$ is the tool purchase cost for tool i.

Tool life can be calculated by Taylor's formula with operation parameters read from CAM software's output. Taylor's formula is $V \times T^n = C$

where

V is the cutting speed in ft. /min.

T is the tool life in minutes.

n is a constant based on the tool material.

C is a constant based on the tool material, work piece material and the cutting condition.

n, C can be obtained from manufacturer's manual or determined experimentally. With this information, tool life can be calculated for any given cutting speed.

A tool may be used several times in the machining. The used tool life for a tool can be calculated as following

$$\text{ToolLifeUsed}_i = \sum_{j=1}^{n} \frac{\text{ToolUsageTime}_j}{\text{ToolLife}_j}$$

3-5

where

ToolLifeUsed_i is the used tool life for tool i, expressed as a decimal fraction. If it equals to or is larger than 1, it means the tool is worn out and needs to be replaced.

$j = 1, 2 \ldots n$ A tool may be used in many operations during the whole machining process. n is the number of operations of tool i ; j is the index of operations of tool i.

ToolUsageTime_j is the tool usage time of operation j for tool i.

ToolLife_j is the tool life at the cutting speed of operation j for tool i.

C_{Setup} is the total cost related to work piece location and clamping and will be discussed in detail in the next section.

$C_{MaterialCost}$ is the product of work piece volume and the material cost per unit volume.

$C_{Overhead}$ is for all other costs that machining involves but not listed above such as management, rent, electricity, etc. In this work, the fixture component inventory is included in the overhead; the setup operation cost and custom-made fixture cost are included in the setup cost.

3.2 Setup cost estimation

A binary questionnaire based fixture plan selection process is proposed. Interactively it can quickly find the feasible fixture plans and it is flexible to adapt to special fixture condition.

3.2.1 Setup definition

Without a setup plan that determines work piece orientation, the users cannot generate a valid and complete CNC tool path for the model. Hence it is assumed that the setup plan is available, but the fixture plan (how to locate and fasten) needs to be defined.

For the purpose of estimation of costs, exact locating points and clamping forces are not considered in this research. Clamping methods and fixture components will be investigated. Clamping methods are limited to side clamping and top clamping. Fixture components include standard clamps, standard locators and standard auxiliary supports, pin fixtures, and custom made fixtures.

A setup activity or operation is defined as a process that involves sub operations such as measuring, alignment, clamping, and placing locators, auxiliary supports, pin fixtures, and custom made fixtures. Each operation has its related cost. A setup operation cost is the sum of all the sub operation costs.

Measuring and alignment of a work piece constitute an alignment operation. A setup operation has only one alignment operation. An alignment operation can be long or short in time. Therefore, the alignment cost is measured by its time multiplied by the labour rate rather than a fixed cost.

Setting up auxiliary supports is regarded as a supportive operation to a clamping operation. To distinguish the level of difficulty of different clamping conditions, supportive operations are subdivided into three levels: simple, medium and complex. A difficult clamping operation will be a clamping with one or more complex supportive operations.

Pin fixture is widely used to keep alignment between setups. There are three cost items related to pin fixture: pin fixture manufacturing cost, pin fixture setup cost, and pin hole drilling cost. Pin hole drilling is a machining operation and its cost is included in machining cost and not in setup cost. Pin fixture manufacturing and setup costs are directly decided by the user.

Under some situations, a custom made or special fixture is needed. Its cost includes manufacturing cost and setup cost and is directly decided by the user.

Therefore, a setup operation cost will be

$$CSetup = \sum \begin{array}{l} (NumberOfSideClampingOperations \times CostPerSideClampingOperation + \\ NumberOfTopClampingOperations \times CostPerTopClampingOperation + \\ NumberOfComplexSupportiveOperations \times CostPerComplexSupportAddOperation + \\ NumberOfMediumSupportiveOperations \times CostPerMediumSupportAddOperation + \\ NumberOfSimpleSupportiveOperations \times CostPerSimpleSupportAddOperation + \\ AlignmentTime \times UnitLabourCost + \\ CostOfPinFixtureSetupOperation + PinFixtureManufacturingCost + \\ CostOfSpecialFixtureSetupOperation + SpecialFixtureManufacturingCost) \end{array} \quad \textbf{3-6}$$

The total setup cost of a machining task is the sum of the cost of each setup.

3.2.2 Questionnaire

A binary questionnaire is proposed in order to find a suitable fixture plan about the number, the type of clamping and supportive operations needed.

This questionnaire is a binary tree and each node presents a question. The questionnaire begins from the root question. If the users answer “Yes” to this question, the left sub node question is selected as the next question. If users answer “No” to this question, the right sub node question is selected as the next question. When a leaf is reached, all necessary information is collected and pre-set feasible fixture plans are prompted for users to select.

Currently the questionnaire is based on six questions and can be further expanded as knowledge grows.

The six questions are listed below:

(1) Does this setup need contour machining to separate it from the work piece?

(2) Is a pin fixture applied in this setup?

(3) Can this setup use top clamping?

(4) Can this setup use side clamping?

(5) Does top clamping need supportive operations?

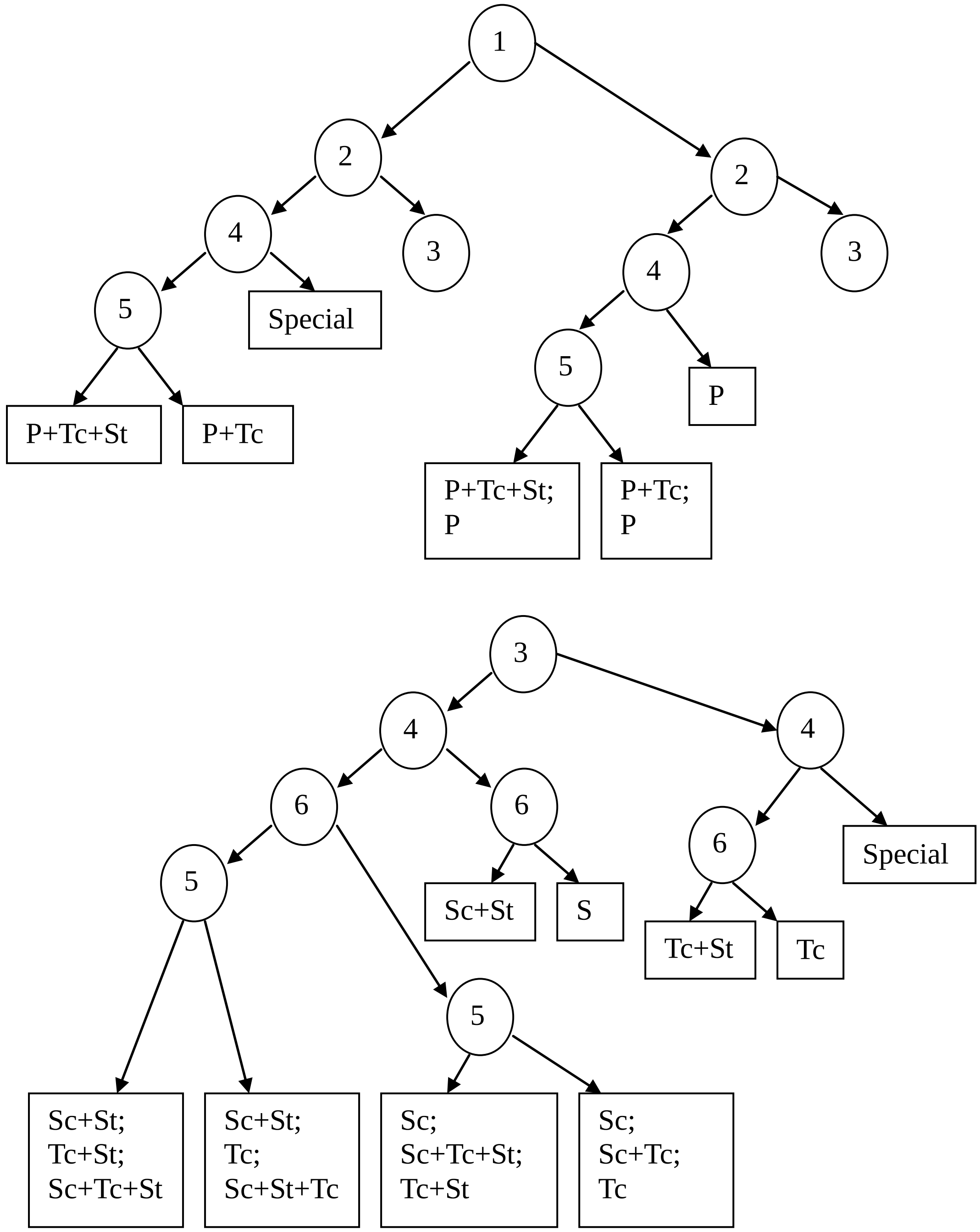
(6) Does side clamping need supportive operations?

Figure 3-1 is the questionnaire tree. The sequence for the questions is designed in such a way that it first finds out what kind of clamping should be used and then determines whether supportive operations need to be used. If both top and side clamping are not adequate then custom made fixture should be used.

In Figure 3-1, feasible fixture plans are represented in a rectangle. A fixture plan indicates what kind of clamping is used, whether supportive operations, pin fixtures or custom made fixtures are needed. In order to be flexible to meet the different requirements for different parts, the number of each kind of selected fixture components and the level of difficulty associated with the supportive operation are left for users to specify.

If more than one fixture plan is available, each feasible fixture plan is separated by “;”. Users can select one of them. For example, P+Tc+St means this fixture plan includes pin fixtures, top clamping, and supportive operations.

After the user specifies the amount of fixture components and the difficulty level of supportive operations, the setup cost can be calculated by Equation 3.6.



P means Pin Fixture.
Tc means Top clamping.
Sc means Side Clamping.
St means Supportive Operations.
Special means custom made fixtures

Figure 3-1 Binary Questionnaire

For example, to decide the fixture plan for drilling a hole, the following questions will be asked.

Question 1 is “Does this setup have a contour machining to separate the part from the work piece?”

For this example, the setup is for drilling a hole, and the answer is “No” to this question.

Question 2 is “Is a pin fixture applied in this setup?”

Pin fixture is not needed for pin hole drilling; and hence the answer is “No” to this question.

Question 3 is “Can this setup use side clamping?”

For pin hole drilling, both top clamping and side clamping are applicable and sufficient and no supportive operations are needed. The answer is “Yes”.

Question 4 is “Can this setup use top clamping?”

The answer is “Yes”.

Question 5 is “Does side clamping need supportive operations?”

The answer is “No”.

Question 6 is “Does top clamping need supportive operations?”

The answer is “No”.

This leads to three feasible fixture plans: side clamping only, top clamping only, combined top and side clamping. The user can select one of them. Two top clamps will be adequate for this setup.

Figure 3-2 is an example in which pin fixture and support are needed. The following questions are asked.

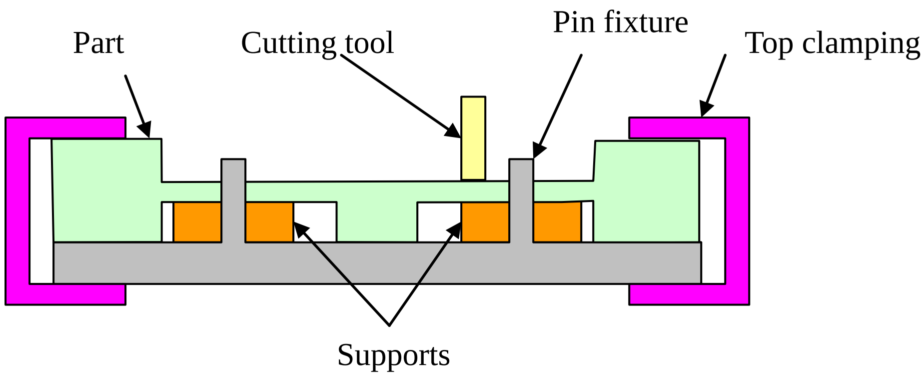


Figure 3-2 Pin Fixture and Supports

Question 1 is “Does this setup have a contour machining to separate the part from the work piece?”

For this example, the answer is “Yes”.

Question 2 is “Is a pin fixture applied in this setup?”

Pin fixture is applied and the answer is “Yes”.

Question 3 is “Can this setup use top clamping?”

The answer is “Yes”.

Question 4 is “Does top clamping need supportive operations?”

The answer is “Yes”.

This leads to one feasible fixture plan: Top clamping, pin fixture and supportive operations. Two top clamps and a simple or medium complex supportive operation are needed.

3.3 Summary

An activity based CNC machining cost estimation method is proposed in this chapter. The CNC setup operation is analyzed with the assistance of a specially designed binary questionnaire. The selection of associate cost will be described in a subsequent chapter.

4 Proposed Stereolithography cost estimation

This chapter proposes a cost estimation method for 3D Systems SLA3500 machine. The first section provides a brief introduction of SLA machine, SLA build parameters, and SLA build time estimation methods. This is followed by the SLA 3500 laser scanning speed calculation and the proposed STL based cost estimation method.

4.1 An introduction of SLA machine

Stereo-lithography (SL) or Stereo-lithography Apparatus (SLA) is probably the most popular rapid prototyping technology. An SLA machine has a cabinet that contains a vat filled with liquid resin (polymer) and a horizontal platform that moves vertically and the part is built on the platform (see Figure 4-1). The laser beam projected from a generator is reflected by a high speed rotating mirror to control its path. When a laser beam is projected into the resin vat, resin at that spot absorbs the laser energy and solidifies. The solidified resin is in a bullet shape and the attenuated laser beam has no effect on the resin outside the 'bullet'. The laser's energy affects the height of the 'bullet' which determines the layer thickness. SLA machine builds a part layer by layer by adding a layer to the previous built layer. The initial position of the platform is coincident with the resin surface. The first step to build a layer is to dip the platform by a layer thickness below its last position. The last built layer is now one layer thickness below the resin surface. The system waits a few seconds for the viscid liquid resin surface to settle down because resin is viscid. Then a wiper (sweeper) sweeps over the resin surface to ensure that exactly one layer thickness height of resin is evenly distributed on top of the last built layer. Then the laser scans the boundary (called contouring) and the inside of the slice (called hatching) on the resin surface (see Figure 4-3). The laser energy is controlled to solidify only one layer thickness in depth. After the laser finishes scanning, the system waits a few seconds for the slice to solidify and the resin surface to settle down. Thus the new built layer stacks over the last layer and is coincident with the resin surface. Then the platform drops by one layer thickness again to build the next layer iteratively until all layers are done which signals the finish of the build phrase. Besides the part body, SLA machine also builds some extra frames to locate and support the part. These frames are called supports (see Figure 4-1). Supports are built similarly to the way the parts are built, layer by layer. Some supports created on the bottom of the part allow the separation of the part from the platform so that the part can be taken off from the platform without damage. These supports are called the base supports.

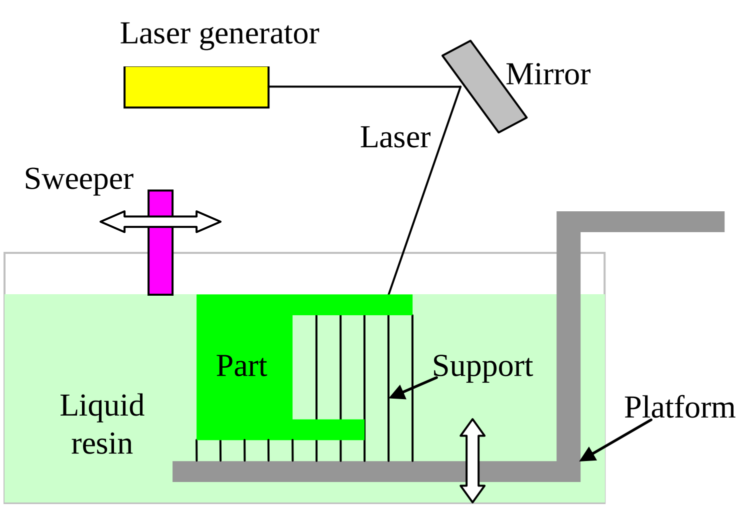


Figure 4-1 Stereolithography Machine Structure

A 3D systems SLA build task involves three steps:

1) Software preparation.

2) Construction, or build process.

3) Post Processing.

Software preparation involves:

a. Setting build environment that includes selecting machine, layer thickness, material, and build style that will satisfy the quality requirements.

b. Verification and removal of errors in STL files.

c. Placement of the part in build platform and setting an orientation that will reach a desirable trade-off between build time and surface quality.

d. Generation and modification of support structure.

e. Slicing the geometry and evaluation of the build time.

The build process follows the process introduced earlier in a layer by layer manner, from the bottom to the top of the part.

Post processing involves:

a. Cleaning off the liquid resin attached on the part surface.

b. Support structure removal.

c. Curing uncured or not fully cured resin in Post Curing Apparatus (PCA).

d. Sanding off stair-stepping effects and sand blasting to get a good surface finish and other special treatments.

4.2 Build parameters in SLA

A major and most flexible cost item of a SLA build task is the build time. Layer thickness, part orientation, and build style are the three major factors that affect the build time.

Layer thickness

Layer thickness determines how thick each layer is and how many layers are needed to be built. A thinner layer leads to better surface quality but longer build time.

Part orientation

Part orientation determines the height in the build direction which is the Z direction of the SLA machine cabinet. There are infinite orientations to locate a part in the machine cabinet. Different orientations will have different extensions in X, Y and Z directions. If the layer thickness value is fixed, the higher the part is in the Z direction, the more layers the machine needs to build the part. Owing to RP's typical stair stepping effect, the build orientation affects the surface quality (see Figure 4-2). How to find an orientation to get an optimal balance point between the surface quality and build time is a major research topic in RP (Lan et al. 1997, Pham et al. 1999, Xu et al. 1999).

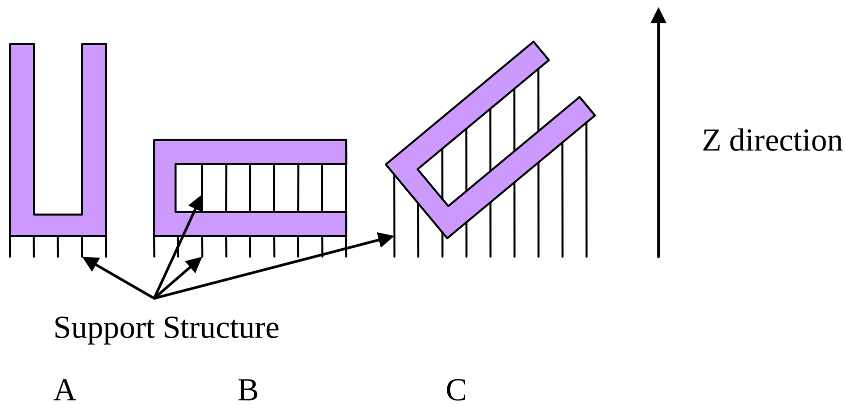


Figure 4-2 Part Orientation

With reference to Figure 4-2, orientation A will have the best surface quality, but the longest build time. Orientation B will have the least build time and a good surface quality. Orientation C will have the worst surface quality and a long build time.

Build style

Build style defines the laser scanning path (see Figure 4-3) and the waiting period for each layer. Therefore, build style determines the build time each layer will probably take and affects the part dimensional accuracy (Jacob 1992, Williams et al. 1996, McClurkin 1998, Joneja et al. 1998, Onuh and Hon 2001, Rajan et al. 2001). Hatching path 1 will have a uniform quality and a good dimensional accuracy in both x and y directions, but it takes more scanning time. Hatching path 2 will have good dimensional accuracy in x direction, but worse in y direction. Hatching path 3 will have fair dimensional accuracy in both x and y directions and less scanning time. Build style is related to layer thickness. The thinner the layer thickness, the longer will be the waiting period.

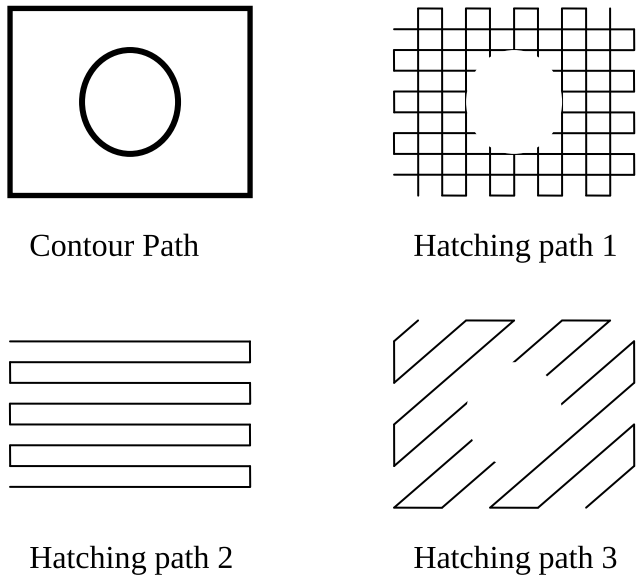


Figure 4-3 Build Style and Laser Scanning Path

Equation 4-1 is an illustration of how these three factors affect the build time.

$$\text{BuildTime} \approx \frac{\text{PartHeightInBuildDirection}}{\text{LayerThickness}} \times \text{AverageLayerBuildTime} \tag{4-1}$$

4.3 An introduction of SLA build time estimation methods

As given in the literature review, there are two kinds of SLA build time estimation methods. One is based on sliced information and the other is non-sliced.

4.3.1 Sliced geometry based build time estimation

The sliced geometry-based build time estimation method is based on the idea that the total build time is the sum of each layer's build time.

$$TPart = \sum_{i=1}^{m} TLayer_i$$

4-2

where

$TPart$ is the total build time of a part.

$TLayer_i$ is the build time of the i^{th} layer.

m is the total number of layers.

Each layer build process is composed of a preparation phase and a laser scanning phase.

$$TLayer_i = TPreparation_i + TLaserscanning_i$$

4-3

where

$TPreparation_i$ is the sum of the time for the platform to dip down, the resin surface to settle down before recoating (called Pre Dip), the wiper to recoat (called Recoating), and the resin surface to settle down after scanning (called Z Wait).

$TLaserscaming_i$ is the laser scanning time of the i^{th} layer.

Preparation Time

$$TPreparation_i = TPlatformDipping_i + TRecoating_i + TPreDip_i + TZWait_i$$

4-4

where

$TPlatformDipping_i$ is the platform dip time for the i^{th} layer.

$TPreDip_i$, is the Pre Dip time for the i^{th} layer.

$TZWait_i$ is the Z Wait time for the i^{th} layer.

$TRecoating_i$ is the recoating time for the i^{th} layer.

$TPlatformDipping_i$, $TPreDip_i$ and $TZWait_i$ are specified in build style as constant values and can be measured.

$$RecoatingTime = RecoatingTimes \times \frac{RecoatingDistance}{RecoatingSpeed}$$

4-5

Recoating speed is specified in build style, and recoating times is specified by the user for each layer. Recoating distance is based on the part's extension in SLA machine cabinet's y direction.

Laser scanning time

$$TLaserscaming_i = TContouring_i + THatching_i + TFilling_i + TJump_i$$

4-6

The laser scanning time is composed of the contouring (contour scanning) time, hatching time, filling time, and laser jump time. Laser jumps between hatching vectors, from the end of one vector to the beginning of the next vector.

$$TContouring_i = \frac{ContourLength_i}{CoutourScanningSpeed}$$

4-7

is the contouring length of the i^{th} layer.

$$THatching_i = \frac{HatchingLength_i}{HatchScanningSpeed}$$

4-8

is the hatching length of the i^{th} layer.

$$TFilling_i = \frac{FillingLength_i}{FillScanningSpeed}$$

4-9

is the hatching length of the i^{th} layer.

$TJump_i$ usually is small and negligible.

The contouring, hatching, and filling paths are generated on each layer and the scanning lengths can be precisely calculated for each. The laser scanning speed will be discussed later on.

4.3.2 Non-Sliced STL based build time estimation

Independent from the part geometry, each layer's preparation time and laser scanning speed are determined by the build style. Therefore the difference between sliced geometry based estimation and non sliced based estimation lies in the different ways to calculate the laser scanning length.

In sliced geometry based estimation, an STL file is sliced and each layer is a cross section of the model. Given the shape information of the cross section, each layer's contouring, hatching, and filling paths are generated and their lengths can be calculated precisely. In contrast, the non-sliced STL based estimation approximates the total contouring, hatching and filling lengths of the model.

Slicing, as well as the generation of laser path and support structure, is a time consuming process. The non-sliced STL based estimation produces a quick and reasonable result which is very desirable for quotation purpose where many orientations may be tried. Therefore, in this research a SLA cost estimator based on the none-sliced STL based build time estimation method has been chosen.

The total area of sliced layers can be approximated by

$$\text{Total Area Of Layers} \cong \frac{\text{Part Volume}}{\text{Layer Thickness}}$$

4-10

Contouring follows the boundary of a layer. The total contouring length of a part can be approximated by using the following method. For any STL triangle, project it to a vertical plane (parallel to Z axis of the triangle) whose normal vector has the same X, Y components as the triangle. Project all triangles of the STL part and sum up the projected area and then divide it by the layer thickness. This provides the approximated total contouring length.

$$\text{ContourLength} \cong \frac{\text{TotalProjectedArea}}{\text{LayerThickness}}$$

4-11

Given the laser hatching space between two adjacent parallel laser vectors, the total hatching length can be approximated by:

$$\text{HatchingLength} \cong \frac{\text{TotalAreaOfLayers}}{\text{HatchingSpaceIn X Direction}} + \frac{\text{TotalAreaOfLayers}}{\text{HatchingSpaceIn Y Direction}}$$

4-12

Total filling length can be calculated by the same method.

$$\text{FillingLength} \cong \frac{\text{TotalAreaOfLayers}}{\text{FillingSpaceIn X Direction}} + \frac{\text{TotalAreaOfLayers}}{\text{FillingSpaceIn Y Direction}}$$

4-13

Then the total build time will be

$$Tstl = \frac{ContourLength}{ContouringSpeed} + \frac{HatchingLength}{HatchingSpeed} + \frac{FillingLength}{FillingSpeed} + n \times (TPtDip + TPreDip + TZWait + m \times TRecoating) \quad \textbf{4-14}$$

n is the total amount of layers, m is the sweep times for each layer.

$Tstl$ is the total build time.

$TPtDip$ is the platform dip time for each layer.

$TPreDip$ is the Pre Dip time for each layer.

$TZWait$ is the Z Wait time for each layer.

$TRecoating$ is the recoating time for each layer.

$TPtDip, TPreDip$ and $TZWait$ are determined by the build style selected. In most cases, only one build style is used during the part build process. Thus platform dip, Pre Dip, and Z Wait time are constant values for all layers. Recoating time is proportional to the part extension in the y direction. Since it is not sliced, the y direction extension of each layer is not available, and the maximum y direction extension of the part plus an additional two inches is used as the recoating length for all layers.

4.4 SLA3500 laser scanning speed calculation

Laser speed is an important factor that affects the build time. It is decided by the material type, machine type, and build style.

4.4.1 Theoretical laser scanning speed calculation

Laser scanning speed of SLA machine is determined by the following formula (Jacobs 1992).

$$C_d = D_p \ln(\frac{E_{max}}{E_c}), E_{max} = \sqrt{(\frac{2}{\pi})} \frac{P_L}{W_O V_S},$$

Or in another form

$$V = \sqrt{\frac{2}{\pi}} \left[\frac{P_L}{W_0 E_c} \right] \exp\left(\frac{C_d}{D_p} \right)$$

4-15

where

C_d is the curing depth.

D_p is the depth of penetration.

E_c is the critical energy.

E_{max} is the maximum energy exposure per unit area.

P_L is the laser power.

W_0 is the half width of the laser beam.

V_s is the scanning velocity.

E_c, D_p are the resin properties. C_d is decided by build styles. P_L and W_0 are determined by the SLA machine. Therefore the laser scanning speed is determined by the laser power, laser diameter, curing depth, and resin property.

Contouring speed is different from hatching speed and filling speed because of different curing depths. Experiments show that there is a deviation between the theoretical and actual laser speed, and hence some adjustments are needed to compensate the deviation. Chen and Sullivan's (1996) study shows that the actual speed may be about 70% of the theoretical value.

4.4.2 SLA 3500 laser scanning speed estimation

Through curing depth, layer thickness, laser scanning speed, and build style are linked together. In this research two choices of 0.004 inch and 0.005 inch for layer thickness are used since these two are the most widely used values. For the SLA 3500 machine, EXACT represents the build style for 0.004 inch and FAST represents the build style for 0.005 inch layer thickness.

Scanning speed and build time data were generated for twelve parts chosen from local industries. The recorded laser scanning speeds are different from the theoretical values calculated by Jacobs' formula. Appendix A shows the ratio of the actual speed to the theoretical speed for these samples.

For the EXACT build style (0.004 inch layer thickness):

the mean value of actual contouring speed over theoretic contouring speed is 0.51;

the mean value of actual hatching speed over theoretic hatching speed is 0.99; and

the mean value of actual filling speed over theoretic filling speed is 0.89.

For the FAST build style (0.005 inch layer thickness):

the mean value of actual contouring speed over theoretic contouring speed is 0. 49;

the mean value of actual hatching speed over theoretic hatching speed is 0. 56; and

the mean value of actual filling speed over theoretic filling speed is 0. 92.

The approximation methods shown below were used in this study.

For the EXACT build style (0.004 inch layer thickness):
Estimated contouring speed = theoretical contouring speed × 0.51;
Estimated hatching speed = theoretical hatching speed × 0.99; and
Estimated filling speed = theoretical filling speed × 0.89.

4-16

For the FAST build style (0.005 inch layer thickness):
Estimated contouring speed = theoretical contouring speed × 0. 49;
Estimated hatching speed = theoretical hatching speed × 0. 56; and
Estimated filling speed = theoretical filling speed × 0. 92.

4-17

4.4.3 STL based SLA 3500 build time estimation and optimization

Based on the previous discussion in Section 2.2, the SLA3500 build time estimation formula is

$$\begin{aligned} TEstimated = {} & TContouring + THatching + TFilling + \\ & TWaiting + TSweeping + TDipping \end{aligned}$$

4-18

where

$$TContouring = \frac{TotalContourLength}{LaserContouringSpeed}$$

$$THatching = \frac{TotalHatchingLength}{LaserHatchingSpeed}$$

$$TFilling = \frac{TotalFillingLength}{LaserFillingSpeed}$$

Contouring, hatching and filling length can be approximated by using Equations 4-11, 4-12, and 4-13.

Contouring, hatching, and filling speed can be calculated using Equation 4-16 and 4-17.

$TEstimated$ is the estimated total build time.

$TContouring$ is the estimated total contouring time.

$THatching$ is the estimated total hatching time.

$TFilling$ is the estimated total filling time.

$TSweeping$ is the estimated total sweeping time and equals to each layer's sweep time times the number of layers; each layer's sweep time = (part extension in y direction + 2 inches) / wiper velocity (1 inch/second) * sweep times per layer. Each layer is assumed to have the same sweep times.

$TDipping$ is the estimated total platform dipping time, observed as 1 second for each layer.

$TWaiting$ is the estimated total Z wait and Pre Dip time. This includes the Z waiting and Pre Dip time in both part layers and base support layers.

$$TWaiting = BaseSupportLayerWaitingTime * NumberOfBaseSupportLayers + PartLayerWaitingTime * NumberOfPartLayers \quad \textbf{4-19}$$

$BaseSupportLayerWaitingTime$ is the Z wait time for each base support layer, There is no pre dip time in base support building process.

$NumberOfBaseSupportLayers$ is the number of layers for base support structure. In the proposed formulation, the widely chosen value of 100 layers with a layer thickness of 0.004 inch has been chosen.

$PartLayerWaitingTime$ is the Z wait and Pre Dip time for each part layer.

The Z wait and Pre Dip time is specified by build style. For the EAXCT build style, Z Wait time is 15 seconds and Pre Dip time is 45 seconds. For the FAST build style, Z Wait time is 15 seconds and Pre Dip time is 15 seconds.

$NumberOfPartLayers$ is the number of the build layers for part volume.

Comparing the estimated build time to the recorded actual build time, for six samples of 0.004 inch layer thickness, the minimum prediction error is 0.6% and maximum prediction error is 19.5% (see Table 4-1).

Sample Index	1	2	3	4	5	6
Errors: $\frac{\|\| T_{Estimated} - T_{Actual} \|\|}{T_{Actual}}$	0.088	0.008	0.073	0.179	0.195	0.006

Table 4-1 Prediction Errors for 0.004 Inch Layer Thickness Samples

For six samples of 0.005 inch layer thickness, the minimum prediction error is 5.5% and the maximum prediction error is 19.0% (see Table 4-2).

Sample Index	1	2	3	4	5	6
Errors: $\frac{\lVert T_{Estimated} - T_{Actual} \rVert}{T_{Actual}}$	0.067	0.055	0.174	0.185	0.165	0.190

Table 4-2 Prediction Errors for 0.005 Inch Layer Thickness Samples

A number of factors can attribute to the maximum prediction errors of 19.5% and 19.0%. First, STL based approximation has been reported to produce an average error of 5% (J.Giannatsis et al. 2001). Second, only laser scanning for the part volume is considered and the scanning time of support is omitted. Support structure is needed to separate the part from the platform and support any hanging features of the part. Scanning support usually takes a few percentage of the total build time. Third, SLA3500 machine and its software are proprietary. For the users, it's a black box. It has many settings that are not transparent to the users. With the above discussion in mind, optimization is applied to improve the prediction accuracy.

Let

$$\begin{aligned} TActual = {} & TSupportStructure + A_1 \times TContouring + A_2 \times THatching + A_3 \times TFilling + \\ & TWaiting + TSweeping + TDipping \end{aligned}$$

where

$TActual$ is the actual total build time.

$TSupportStructure$ is the actual total Laser scanning time for support structure.

$TContouring$ is the estimated total contouring time.

$THatching$ is the estimated total hatching time.

$TFilling$ is the estimated total filling time.

A_1 is the compensation coefficient for contouring.

A_2 is the compensation coefficient for hatching.

A_3 is the compensation coefficient for filling.

$TWaiting$ is the actual total Z waiting and Pre Dip time.

$TSweeping$ is the actual total sweeping Time.

$TDipping$ is the actual total platform dipping Time.

Three coefficients are assigned to compensate the STL approximation errors and laser speed difference. $TWaiting$, $TSweeping$, and $TDipping$ are fixed values specified by the build style.

To normalize it, divide both sides of the equation by $TActual$. We get

$$Y_o = A_o + A_1X_1 + A_2X_2 + A_3X_3$$

$$Y_o = 1 - \frac{TWaiting}{TActual} - \frac{TSweeping}{TActual} - \frac{TDipping}{TActual},$$

$$A_o = \frac{TSupportStructure}{TActual}, X_1 = \frac{TContouring}{TActual}, X_2 = \frac{THatching}{TActual}, X_3 = \frac{TFilling}{TActual}$$

4-20

The build time predication of 3D Systems' SLA software is based on sliced geometry information and accurate machine status. These results are very accurate predictions. Owing to the laser power fluctuation, the actual SLA machine time is slightly different from the software's prediction. In most cases, the difference falls within 1%. In this work, 3D Systems' SLA software's prediction has been used as the actual build time.

Support structure is determined by the part's geometry and the build orientation. STL file does not include support structure information. To simplify the estimation process, the support structure scanning time has been estimated by using statistical methods. $A_0 = \frac{TSupportStructure}{TActual}$ represents the percentage of support structure scanning time over the total build time. This ratio has been set as the fourth coefficient. Therefore we have four coefficients to find a prediction to fit our samples with the least error.

Objective function: $Min(Max(Y - Y_i)), i = 0,1,2,..n$

$$Y = A_0 + A_1 X_{1\_i} + A_2 X_{2\_i} + A_3 X_{3\_i}$$

$$Y_i = 1 - \frac{TWaiting_i}{TActual_i} - \frac{TSweeping_i}{TActual_i} - \frac{TDipping_i}{TActual_i}$$

$$X_{1\_i} = \frac{TContouring_i}{TActual_i}, X_{2\_i} = \frac{THatching_i}{TActual_i}, X_{3\_i} = \frac{TFilling_i}{TActual_i} \qquad \textbf{4-21}$$

i is the sample part number.

n is thetotal amount of sample parts.

Design variables:

A_0 is the support structure laser scanning time as a percentage of the total build time;

A_1 is the coefficient for contouring;

A_2 is the coefficient for hatching; and

A_3 is the coefficient for filling;

The constraints are:

0< A_0 < 1;

0< A_1 < 2;

0< A_2 < 2; and

0< A_3 < 2.

Using Matlab's Optimization Tool Box, the optimal solution is A_0 = 0.044, A_1 = 0, A_2 = 1.402, A_3 =0.233 with minimized maximum prediction error of 0.03 for layer thickness of 0.004inch. Laser scanning time for support structure takes about 4.38% of the total build time. Contouring time is very small and can be omitted. The maximum prediction error for all six samples is within 3% if the above coefficient values are applied.

Therefore for layer thickness of 0.004 inch

$$\begin{aligned} TEstimated = (&TWaiting + TSweeping + TDipping + 0 \times TContouring \\ &+ 1.402 \times THatching + 0.233 \times TFilling) / (1 - 0.044) \end{aligned}$$

4-22

with maximum error of 0.03 and an average error of 0.026 (see Table 4-3).

For layer thickness of 0.005 inch, we get

$$TEstimated = (TWaiting + TSweeping + TDipping + 0 \times TContouring + 1.089 \times THatching + 1.014 \times TFilling)(1 - 0.072)$$

4-23

with maximum error of 0.118 and average error of 0.095 (see Table 4-4).

Average error is within 10% and it's an acceptable result.

Sample Index	1	2	3	4	5	6
Errors(before)	0.088	0.008	0.073	0.179	0.195	0.006
Errors(after)	0.012	0.030	0.030	0.030	0.026	0.028

Table 4-3 Prediction Errors before & after Optimization (0.004")

Sample Index	1	2	3	4	5	6
Errors(before)	0.067	0.055	0.174	0.185	0.165	0.190
Errors(after)	0.118	0.0002	0.117	0.117	0.098	0.117

Table 4-4 Prediction Errors Before & After Optimization (0.005")

4.5 SLA cost modeling

The cost of a SLA process is the sum of the costs of all its operations.

$$CSLA = CPreparation + CBuilding + CMaterial + CPostprocessing + COverhead$$

4-24

where

C_{SLA} is the total cost for a Stereo-lithography process.

$C_{Preparation}$ is the cost for software preparation.

$C_{Building}$ is the cost for SLA building process.

$C_{Material}$ is the cost for material.

$C_{PostProcessing}$ is the cost for post processing.

$C_{Overhead}$ is the overhead cost.

Preparation Cost

$C_{Preparation}$ is the labor cost to set up the build job including selecting the proper build style, layer thickness, build orientation, and other parameters. This is usually done with the SLA preparation software. The preparation process can usually be done quickly, and takes about ten to thirty minutes. Depending on the prior experience in setting up SLA build jobs, users can specify the preparation cost.

Building Cost

Similar to CNC machining cost, SLA machine purchase cost is reflected in machine cost per hour. Like cutting tools, the laser generator will wear out after a certain hours of service and need to be replaced. For simplicity, the laser replacement cost is included in the building cost as the laser cost per hour.

$$CBuilding = (MachineCostPerHour + LaserCostPerHour) \times BuildTime$$

4-25

$$MachineCostPerHour = \frac{MachinePurchaseCost}{YesrsOfReturn \times AverageWorkHoursPerYear}$$

4-26

$MachinePurchaseCost$ is the initial investment of the Stereo-lithography machine.

$YearsOfReturn$ is the years the investment will pay off.

$AverageWorkHoursPerYear$ is the average annual machine work hours.

$BuildTime$ is the machine operation time. It is calculated by Equations 4-22 or 4-23.

$$LaserCostPerHour = \frac{LaserReplacementCost}{LaserLifeInHours}$$

4-27

Material Cost

$$CMaterial = MaterialCostPerLitre \times MaterialVolumeUsed$$

$MaterialVolumeUsed$ is the volume of resin used for this build. It is the sum of part volume, support structure volume, and the resin discarded during the cleaning process. Part volume can be calculated from a STL file. STL file based cost estimation does not have the support structure information; the support structure volume and the resin discarded cannot be calculated. Based on the observation of the volume of the resin filled into the SLA machine over many build jobs, the part volume is found to be about 70% of the resin volume used. Resin volume change caused by solidification can be omitted. That means 30% of the resin is transferred to support structure and wasted during cleaning.

Based on this observation,

$$MaterialVolumeUsed = PartVolume/0.7$$.

$MaterialCostPerLitre$ is specified by user.

Part volume calculation

To calculate the part volume, we first move the STL part above the z=0 plane. This ensures that all Z coordinates are positive. Then project every triangle into the z = 0 plane and calculate the volume of the projection prism. If a triangle faces upwards (z component of the triangle normal > 0) its volume is positive, otherwise it is negative. The summation of the volume of all projection prisms is the volume of the part.

Post Processing Cost

$$CPostProcessing = LabourCostPerHour \times SandingHours$$

For SLA35000 system, post processing includes cleaning, support structural removal, post curing, and sanding. Post curing uses Post Curing Apparatus (PCA) to fully cure uncured liquid resin inside the part. The costs of sanding facility, ventilation system, washing cabinet, and PCA are hard to calculate precisely for a single job. It is more reasonable to regard these facilities as part of the SLA machine and assign the costs to machine purchase cost. Therefore post processing cost is primarily a sanding cost. The finish level value is used to estimate the sanding time. To reflect different surface accessibility, part surfaces are naturally subdivided into interior surfaces and exterior surfaces. Exterior surfaces face outside and interior surfaces face inside (see Figure 4-4). Interior surfaces are usually harder to reach than exterior surfaces and cost more time to sand.

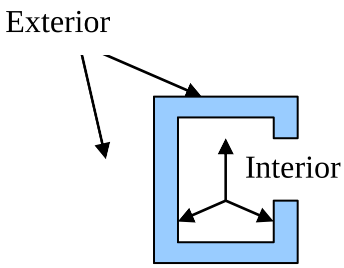


Figure 4-4 Exterior and Interior Surfaces

Sanding time for exterior and interior surfaces is estimated based on surface finishing experience. Table 4-5 lists a reasonable guess of sanding time needed for resin SL5510. This table can be updated as more data is made available. Time is in minutes.

Surface Quality	BASIC	COARSE	MEDIUM	SMOOTH
Interior	10	20	60	120
Exterior	2	10	30	60

Table 4-5 Surface Finishing Time

Four surface levels are defined: BASIC, COARSE, MEDIUM, and SMOOTH.

BASIC stands for the removal of support structure only.

COARSE represents that support structure is removed and supported area is sanded. This is designed for cases where appearance is not important.

MEDIUM is based on COARSE and all stair-stepping effects removed, usually for pattern making.

SMOOTH is based on MEDIUM with smoother surface and any imperfection removed. This is suitable for cases where surface finish is very important such as models for trade show.

Users select one finish level for exterior surfaces and one for interior surfaces.

For example, if user needs a COARSE interior surface quality and a MEDIUM exterior surface quality, the total sanding time will be 50 (20 + 30) minutes.

$LabourCostPerHour$ is the sanding labor cost per hour, specified by the user.

$COverhead$ is the overhead cost. It includes rent, electricity, cleaning material costs, etc.

Small parts have less surface area than large parts, but it does not necessarily reduce the surface finishing time because small surfaces and limited spaces significantly restrict the efficiency of the surface finishing tools. Hence the influence of the part size is omitted in this research. Users can adjust the sanding time according to the part geometry and part size.

4.6 Summary

This chapter proposes a non-sliced STL based stereolithography cost estimation method for 3D system’s 3500 machine. Two build styles, EXACT for 0.004 inch layer thickness and FAST for 0.005 inch layer thickness are analyzed. The material is SL5510. Post processing cost estimation is also included. Laser scanning speed is theoretically calculated and statistically adjusted. The SLA build time estimation is also optimized to reduce the prediction error. The average estimated build time error is within 10%.

5 Introduction of the software prototype

This program has four major modules: STL viewer, SLA cost estimation, CNC machining cost estimation, and Comparison. STL viewer is a 3D viewer for STL files and it also serves as a SLA build orientation setup interface. SLA cost estimation is a cost estimation process for SLA3500 machine. CNC machining cost estimation is a cost estimation process catered for CNC milling machines. Comparison module shows the cost items and exports the result into the Excel chart for a visual comparison.

This program is developed by Microsoft Visual C++ and Microsoft Foundation Class (MFC) on the Windows XP operation system.

This program is MFC dialog based. Each dialog has some pre-designed questions. This program collects necessary information from the user’s answers and guides the user through the estimation process.

The dialog flow chart of program is shown in the following.

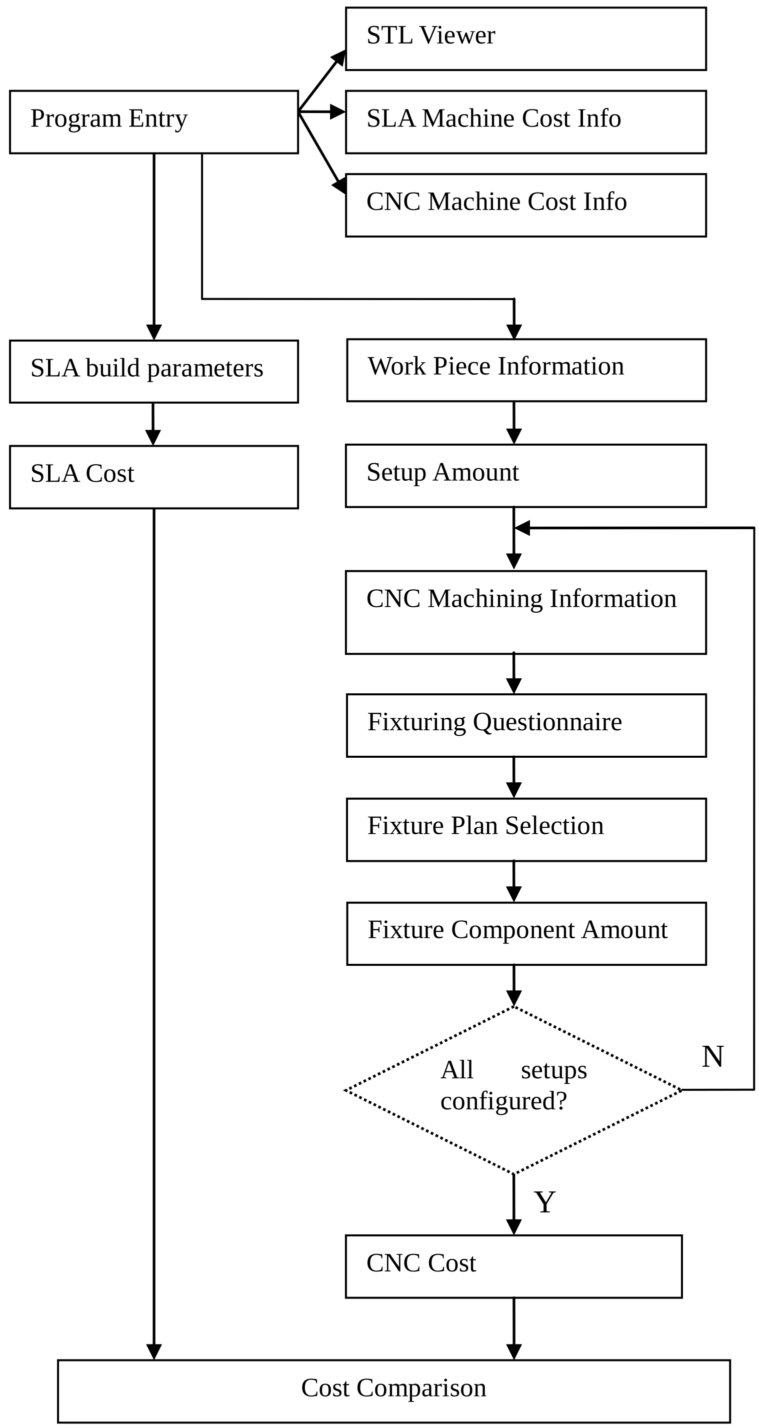


Figure 5-1 Program Flow Chart

This section gives a brief introduction to the dialogs and how they are connected.

“Program Entry” dialog (see Figure 5-2) is the entry point for the program.

“STL Viewer” button opens a STL viewer.

“CNC Env Info” button starts the CNC machine cost information configuration.

“CNC Estimation” button starts the CNC machining cost estimation process.

“SLA Env Info” button starts the SLA machine cost information configuration.

“SLA Estimation” button starts the SLA cost estimation process.

“Result Comparison” button compares the cost results.

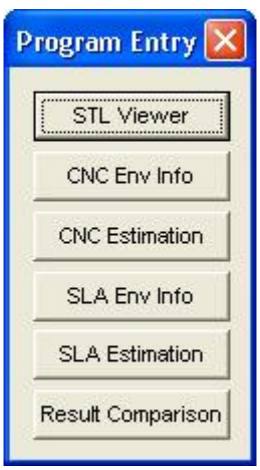


Figure 5-2 Program Entry

Selecting “STL Viewer” in “Program Entry” dialog launches the STL Viewer (see Figure 5-3). A new cost estimation process starts by loading a STL file into the STL viewer. The user can zoom or rotate the model around the reference coordinate system to select an appropriate build orientation for the SLA build job. This system also provides an orientation with the least height in the z direction.

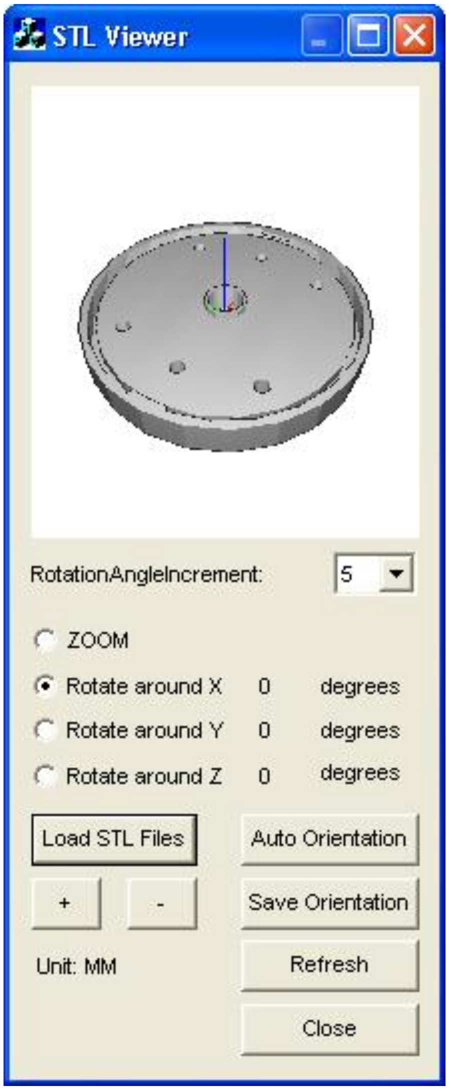


Figure 5-3 STL Viewer

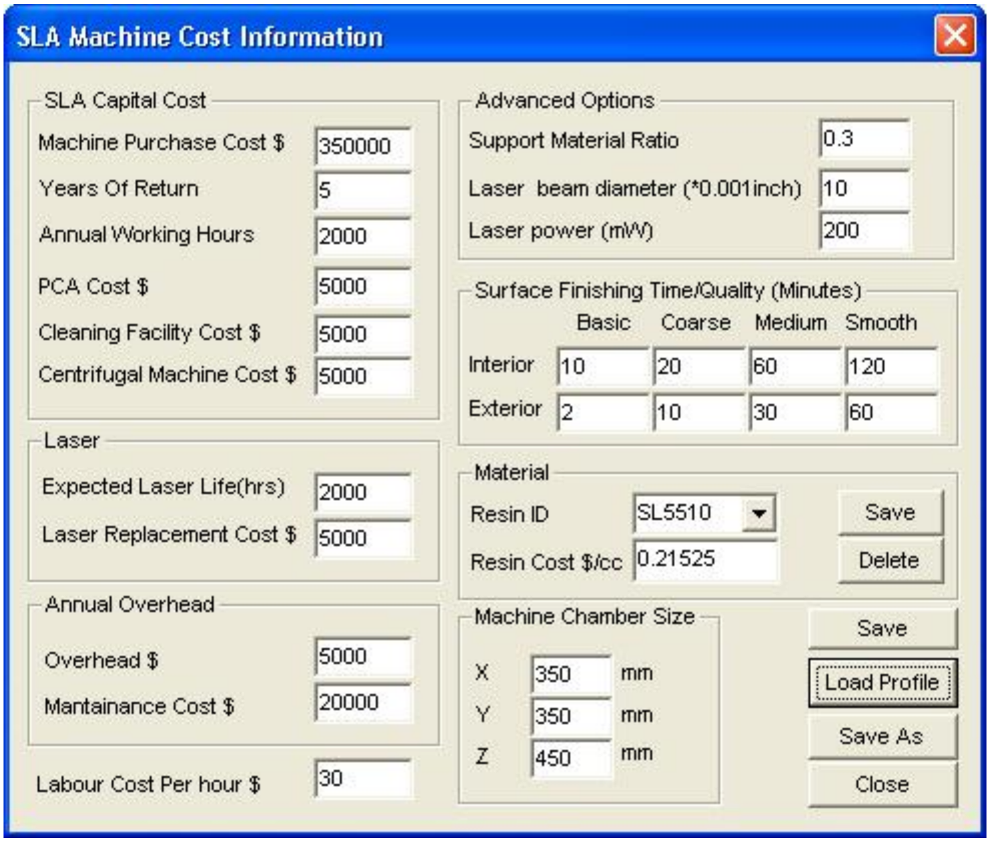


Figure 5-4 SLA Machine Cost Information Dialog

By selecting “SLA Env Info” button in the “Program Entry” dialog, the user enters “SLA Machine Cost Information” dialog as shown in Figure 5-4 to specify all the necessary cost related information for the SLA machine. The meanings of most of the boxes are straightforward and some needs to be explained. Support material ratio is the ratio of the resin wasted and used for support structure versus the total resin consumed for this job. The Laser beam diameter is a pre-set value for the SLA machine. The laser power may be different from job to job and it affects the build time. In this case, it is set at its average value, 200mW. The surface finishing time stands for the post processing time. These values are pre-set and can be modified by users to cater for the individual requirements. The SLA machine has a limited space and therefore a large part must be divided into small components, built separately and glued together. The machine chamber size is to verify whether the work area of the SLA machine is adequate for the desired model. All these information can be saved for reuse.

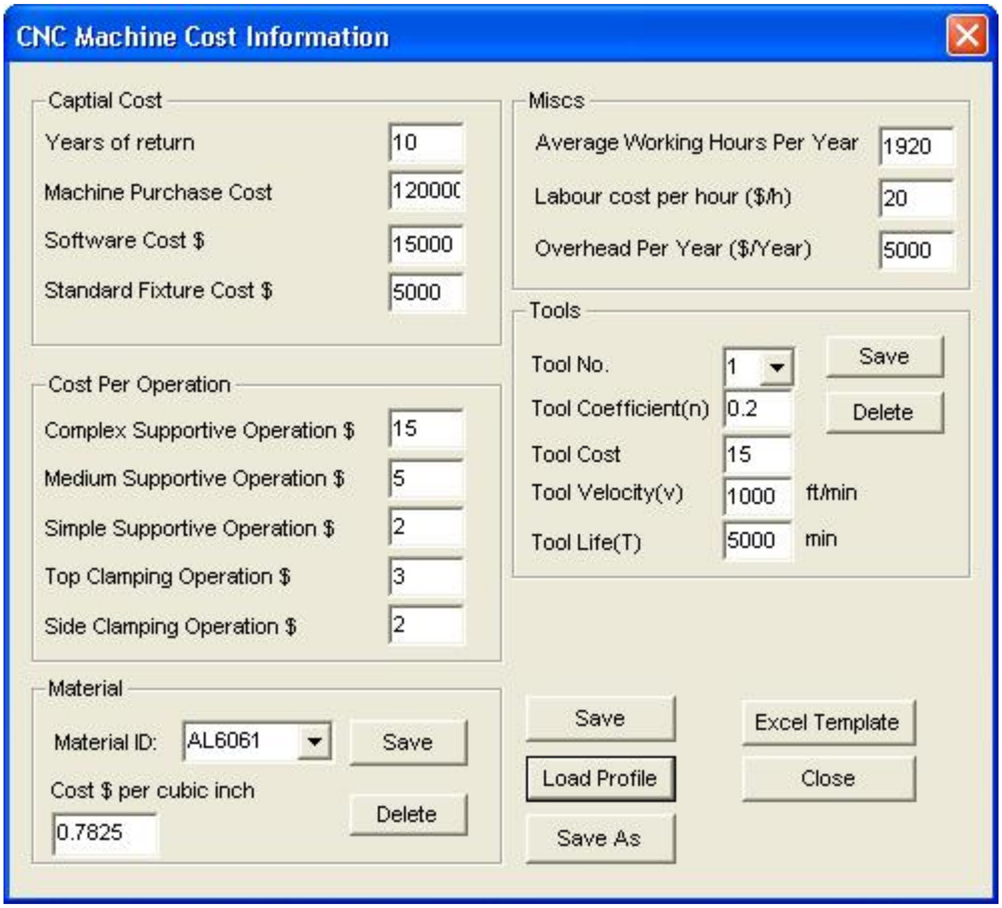


Figure 5-5 CNC Milling Machine Information Dialog

By selecting "CNC Env Info" button in the "Program Entry" dialog, the user enters the "CNC Machine Cost Information" dialog as shown in Figure 5-5 to specify all the necessary cost information for the CNC milling machine. The meanings of most of the boxes are straightforward and some needs to be explained. "Tool No." is the tool index used in the machining job. "Tool coefficient", "Tool velocity" and "Tool life" are parameters in Taylor's formula $C = VT^n$ for tool life estimation. "Excel Template" button sets the path of the Excel chart template for the cost comparison. All these information can be saved for reuse.

After SLA and CNC machine cost information are set, cost estimation process can begin. The SLA cost estimation process is introduced below:

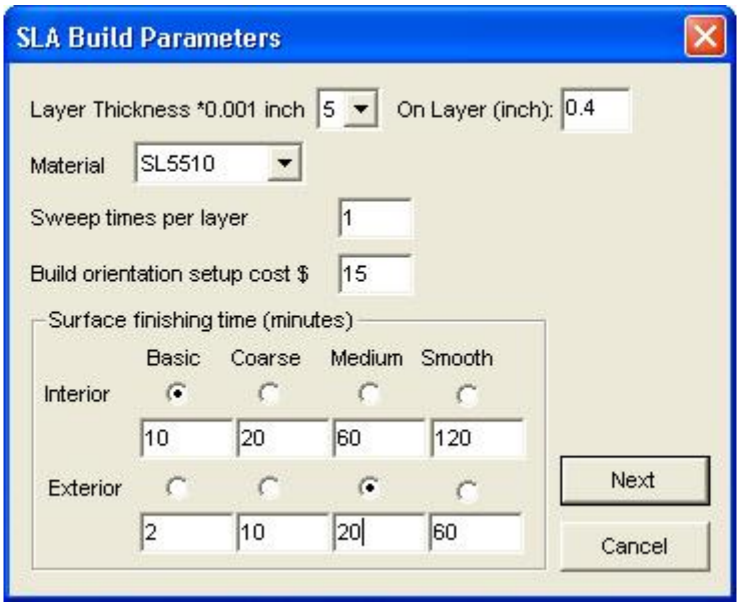


Figure 5-6 SLA Build Parameter Dialog

By selecting "SLA Estimation" button in "Program Entry" dialog, the user enters "SLA Build Parameters" dialog as shown in Figure 5-6 to specify the major SLA build parameters. "On Layer" refers to the height of the base support. For example, 0.4 inch means the bottom layer of the part will be located at 0.4 inch above the platform. In this work, on layer is fixed to 0.4 inch. The user specifies the build orientation setup cost based on the build orientation selection determined in the STL Viewer. The user also can modify the suggested sanding time to fit the individual requirement of the part. After specifying the SLA build parameters, the user selects "Next" button. The "SLA Estimation Result" dialog is prompted as shown in Figure 5-6.

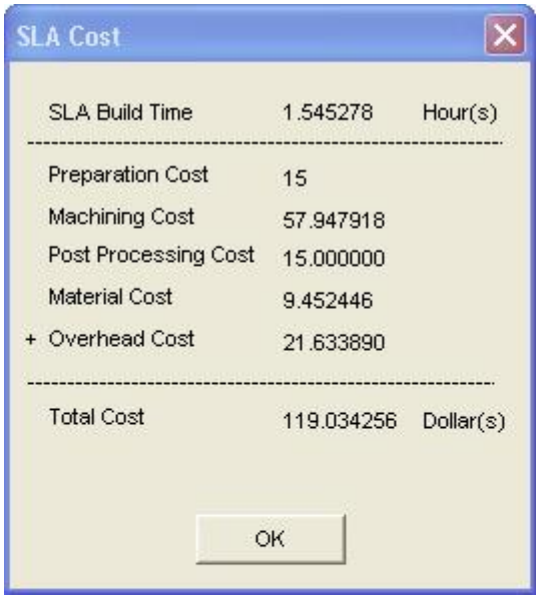


Figure 5-7 SLA Cost Dialog

CNC machining cost estimation process is introduced below:

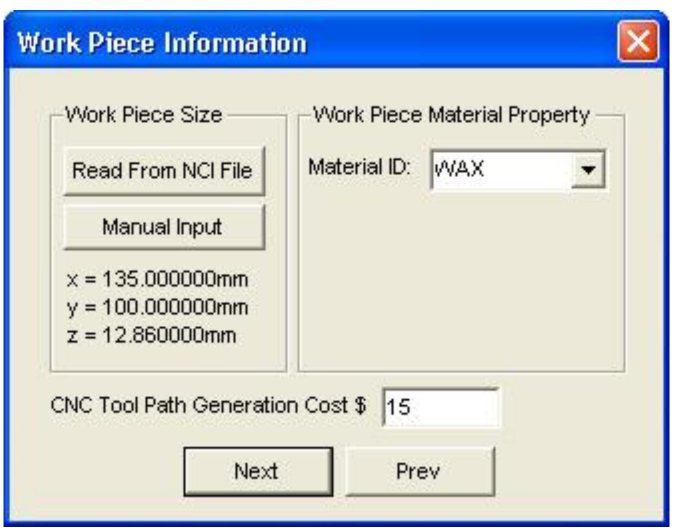


Figure 5-8 Work Piece Information Dialog

By selecting the "CNC Estimation" button in the "Program Entry" dialog, the user enters

“Work Piece Information” dialog as shown in Figure 5-8. The work piece size can be read from the same CAM package, with which the CNC machining tool path is developed. Or users can manually set the work piece size. Work pieces are assumed to be cubic blocks. The user also specifies the work piece material. Similar to the build orientation setup cost in SLA, CNC tool path generation cost is specified through the prior experience in creating the CNC tool path of this or similar parts. In this work, the work piece size is read from a MasterCAM software output file. MasterCAM is a popular CAM software from CNC Software Inc. The material chosen is machinable wax as shown in Figure 5-8. Click the “Next” button; and the estimation process enters the “Setup Amount” dialog shown in Figure 5-9.

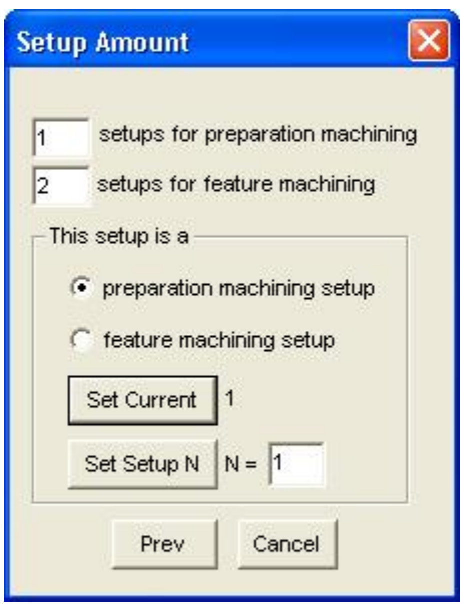


Figure 5-9 Setup Amount Dialog

In the “Setup Amount” dialog, the user specifies how many setups are needed for this job. Setups are subdivided into preparation machining setups and feature manufacturing setups. A preparation machining setup is a setup to remove the coarse work piece surfaces and/or drill pin holes. A feature machining setup is a setup for machining manufacturing features. The "Set Current" button goes to the configuration of the first un-configured setup. The index of the first un-configured setup is shown besides the button. "Set Setup N" button goes to the configuration of the n-th setup. Clicking the "Set Current" button begins the configuration of the first un-configured setup and the "CNC Machining Information" dialog shown in Figure 5-10 will be prompted.

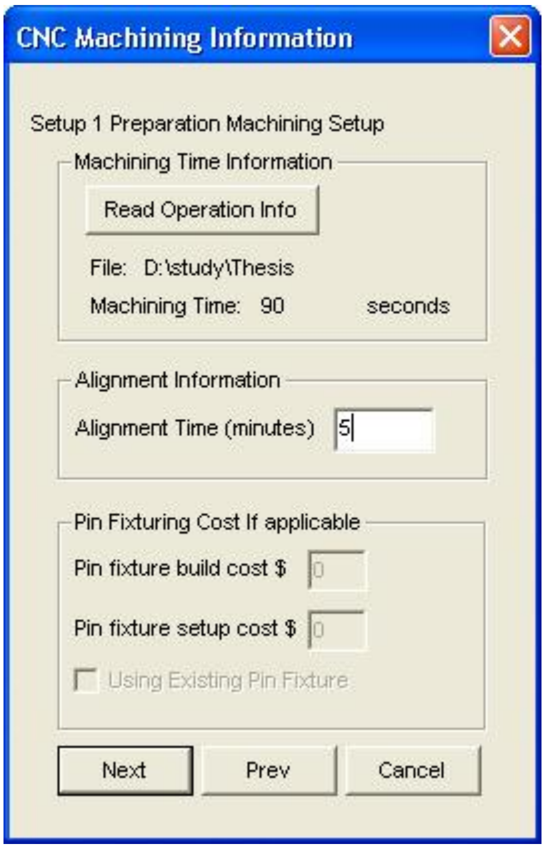


Figure 5-10 CNC Machining Information Dialog

The user specifies the machining time, alignment time, and pin fixture cost as needed in this dialog. The machining time is read from the MasterCAM software output file. The alignment time is the time used to align the work piece with the cutting tool. Clicking the "Next" button enters the "Fixturing Questionnaire" dialog shown in Figure 5-11.

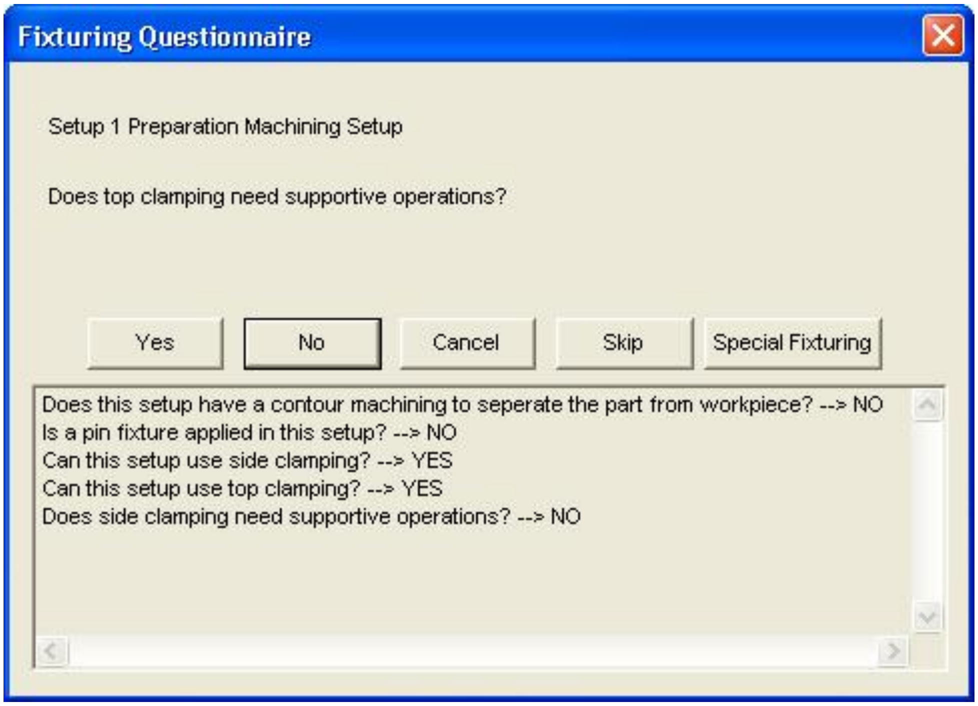


Figure 5-11 Fixturing Questionnaire Dialog

This dialog is a binary questionnaire which asks questions sequentially and adaptively depending on the user's answers. After the program has gathered enough information, feasible fixture plans are prompted for selection as shown in Figure 5-12.

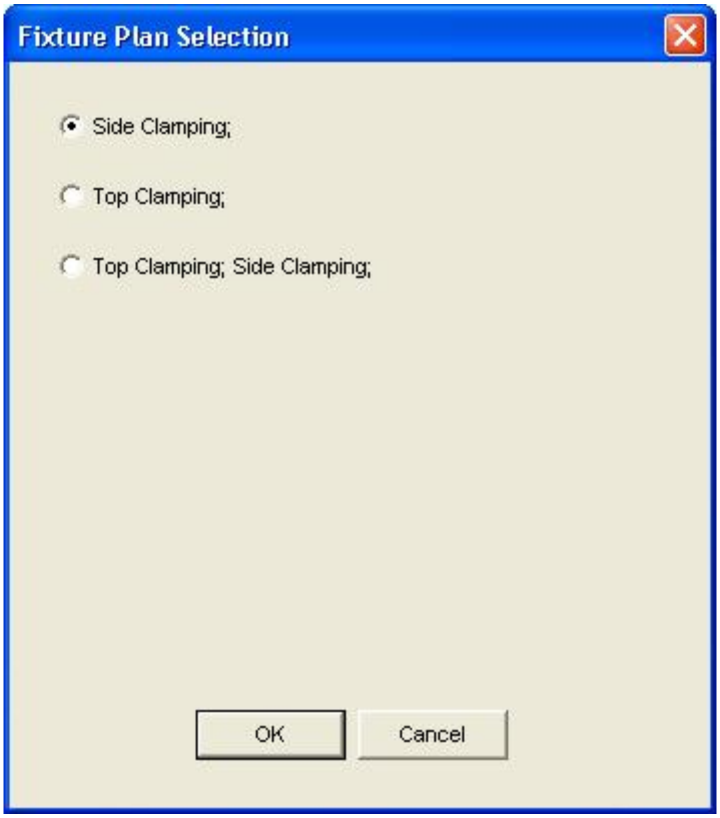


Figure 5-12 Fixture Plan Selection dialog

All feasible fixture plans are listed for users to select. The default selection is the first one which usually has the least effort and thus the least cost. The user may accept the default selection and click the “OK” button to enter the “Fixture Component Amount” dialog as shown in Figure 5-13.

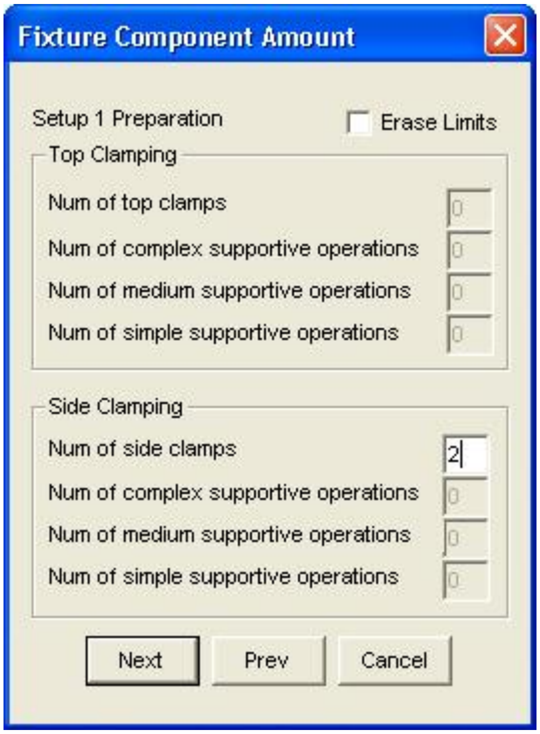


Figure 5-13 Fixture Component Amount dialog

In the "Fixture Component Amount" dialog, the user specifies the number of clamps and supportive operations needed for this setup. Only the components that the selected fixture plan includes are enabled for the user to specify the amount. If the user wants to change the plan, it can be done by clicking the "Erase Limits" button and all options are enabled for modification. This is the final step of a setup configuration. Clicking the "NEXT" button continues to the next un-configured setup configuration following the same steps from Figure 5-8 to Figure 5-13. When all the setups are configured, the estimated cost is prompted as shown in Figure 5-14.

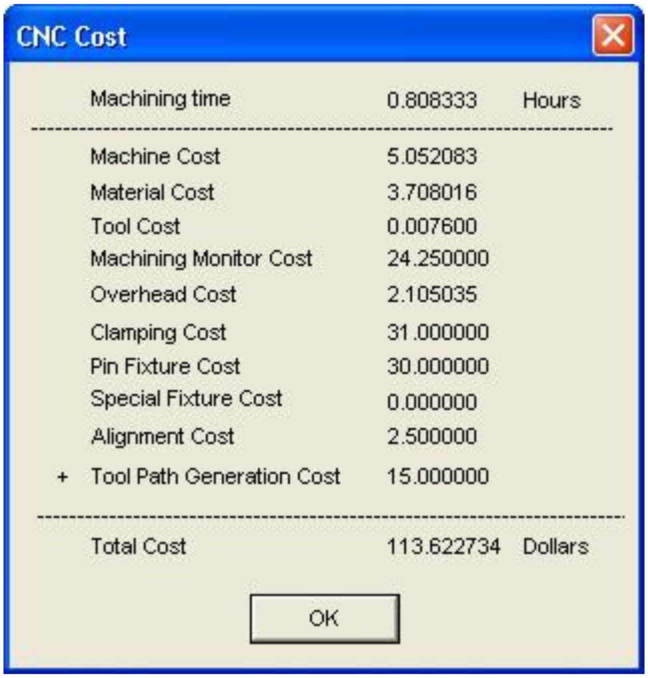


Figure 5-14 CNC Cost Dialog

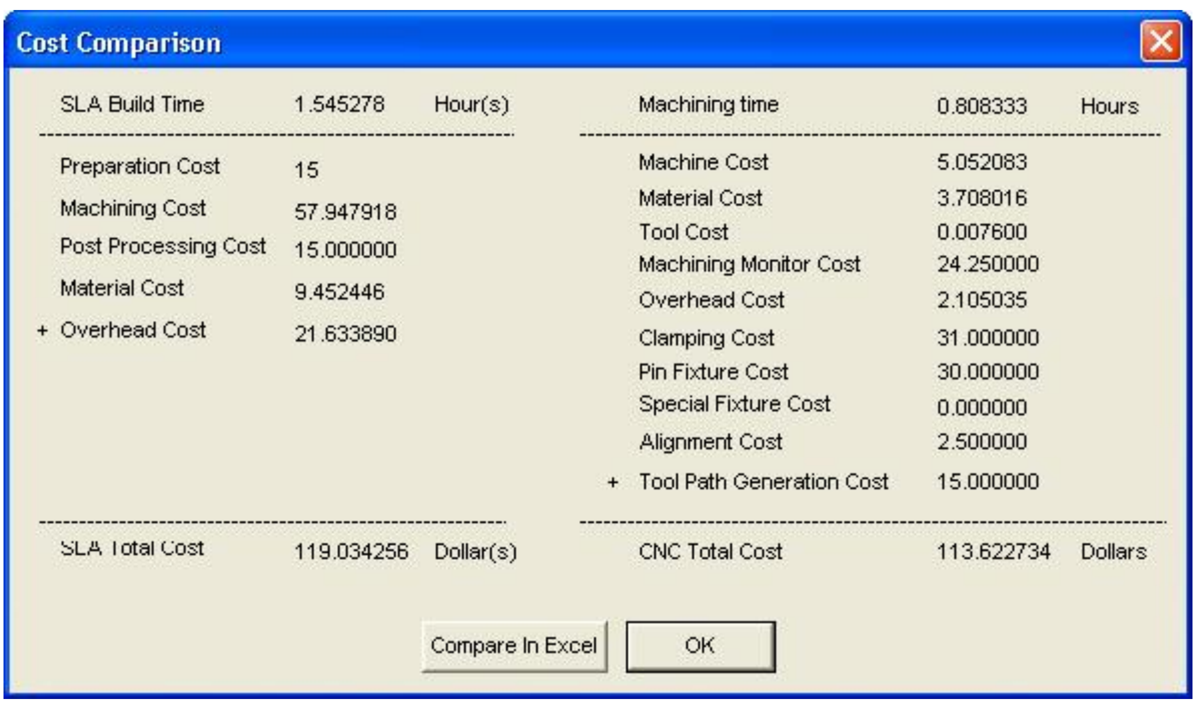


Figure 5-15 Cost Comparison Dialog

Selecting the "Result Comparison" button in the "Program Entry" dialog displays the comparison result as shown in Figure 5-15. Selecting the "Compare in Excel" button, the results will be output to the Excel chart as shown in Figure 5-16.

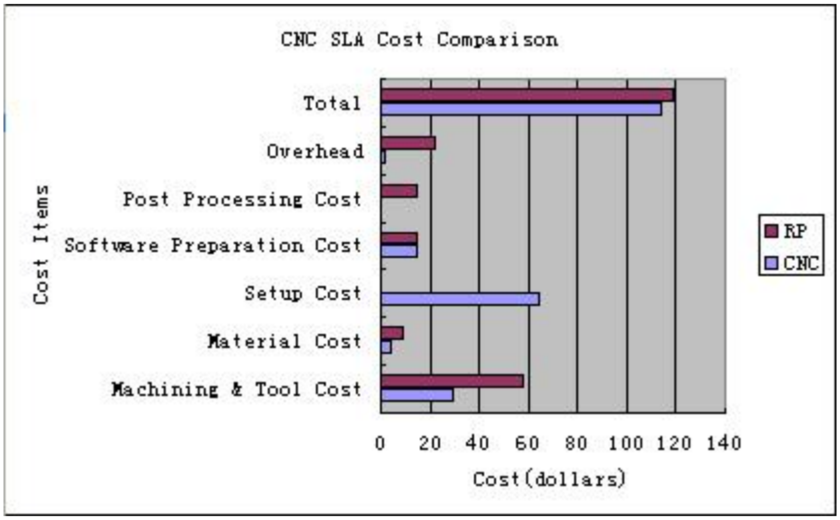


Figure 5-16 Cost Comparison in Excel Chart

Figure 5-15 and Figure 5-16 provide valuable cost information for the user to make the selection between CNC and SLA.

This chapter has briefly introduced the software prototype. In the next chapter, five cases will be investigated to verify the system.

6 Case studies

In this chapter, results from five case studies will be presented. The five parts analyzed are a lamp base, a component of a robot gripper, a rotary engine rotor, a blood pump rotor, and a blood pump cavity. In all cases, the work piece material is machinable wax for CNC machining and SL5510 resin for Stereolithography manufacturing. The units in the drawings are millimeter.

6.1 Lamp base

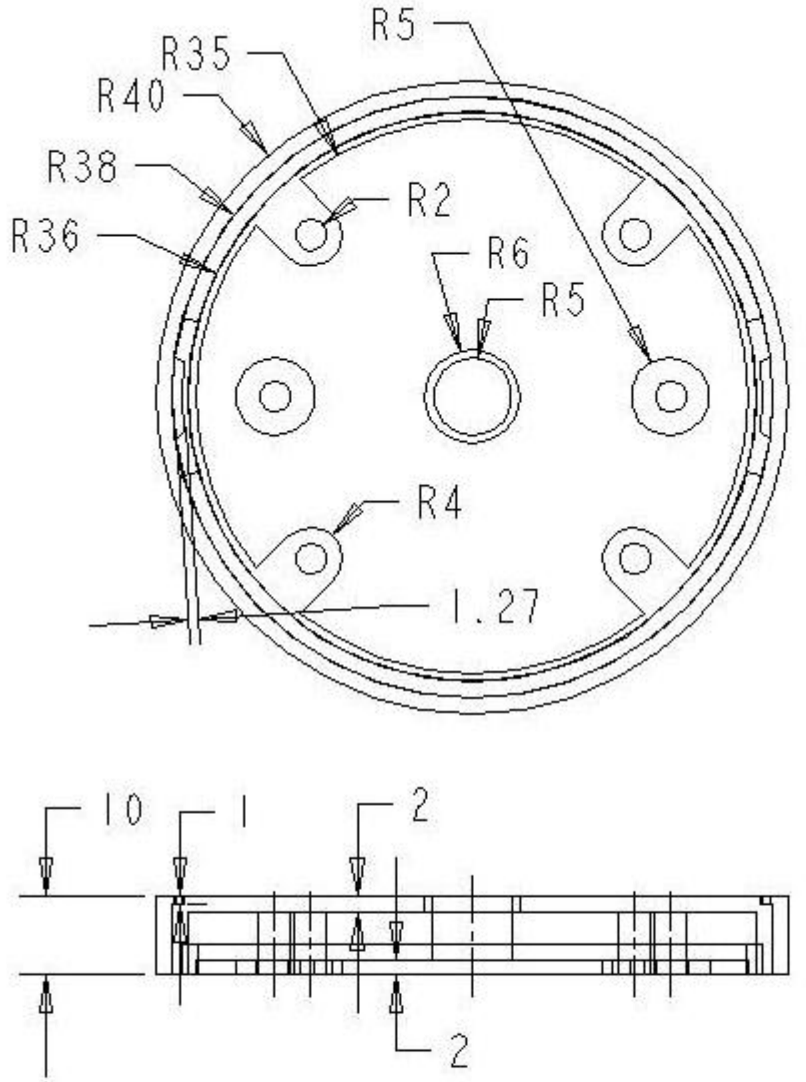


Figure 6-1 Dimension of Lamp Base

The lamp base (shown in Figure 5-3 and Figure 6-1) is a flat round part, and has two sides (top and bottom). Both sides have features that need to be machined. In Figure 5-3, the lamp base is in an orientation with the least z height and this will be the SLA build orientation for this case.

SLA and CNC machine cost information are set as in Figure 5-4 and 5-5. For SLA build parameters, 0.005 inch of layer thickness, SL5510 resin and one sweep times per layer will satisfy the requirements. The lamp base is a flat piece and the bottom surfaces provide good accessibility for the cleaning tools. A MEDIUM surface finish level is required for the exterior surfaces. The default value is thirty minutes. The lamp base is small and a surface finishing time of 20 minutes is appropriate. Interior surfaces such as the vertical surfaces of the holes have a good surface quality and do not need sanding. The only interior surfaces that need sanding are the little hard to access locking surfaces. Interior surfaces surface finish level is set to be BASIC and the default value of ten minutes is reasonable for the lamp base. The total SLA cost is about one hundred and nine dollars, and the SLA build time is about 1.55 hours. The post processing time is not included.

The CNC tool path of the lamp base is generated by MasterCAM software. The work piece size for the lamp base is read from the NCI file, output from MasterCAM. The material is machinable WAX. The CNC tool path generation cost is set to be 15 dollars. The lamp base needs three setups: (i) one preparation setup for the pin-hole drilling assuming the work piece is of the right size and surface is smooth; (ii) one setup for feature machining on the top side; (iii) one setup for feature machining on the bottom side. Pin fixture is applied to secure the alignment of the two sides. Pin hole drilling time and two sides' feature machining time are read from MasterCAM's output files. Pin fixture is not needed for the preparation setup; it is used for the top machining and bottom machining.

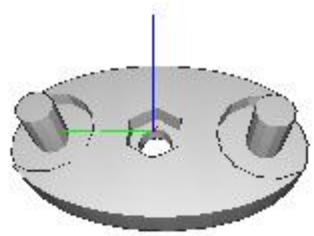
The derived fixture plan for the pill hole drilling setup is side clamping with two clamps.

The derived fixture plan for the top machining is pin fixture and side clamping with two clamps.

The derived fixture plan for the bottom machining is pin fixture, top clamping with two clamps and two medium complex supportive operations.

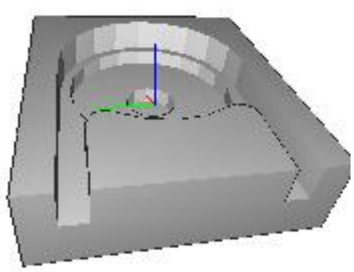
For the lamp base, the estimated CNC machining cost on machinable wax is about 114 dollars and the estimated SLA cost is about 119 dollars as shown in Figure 5-14 and 5-15. The costs of CNC machining and SLA are close, either way is acceptable.

6.2 Blood pump cavity and rotor



Work piece Size: $50\times70\times20mm^3$

Figure 6-2 Blood Pump Rotor



Work piece size: $100\times110\times35mm^3$

Figure 6-3 Blood Pump Cavity

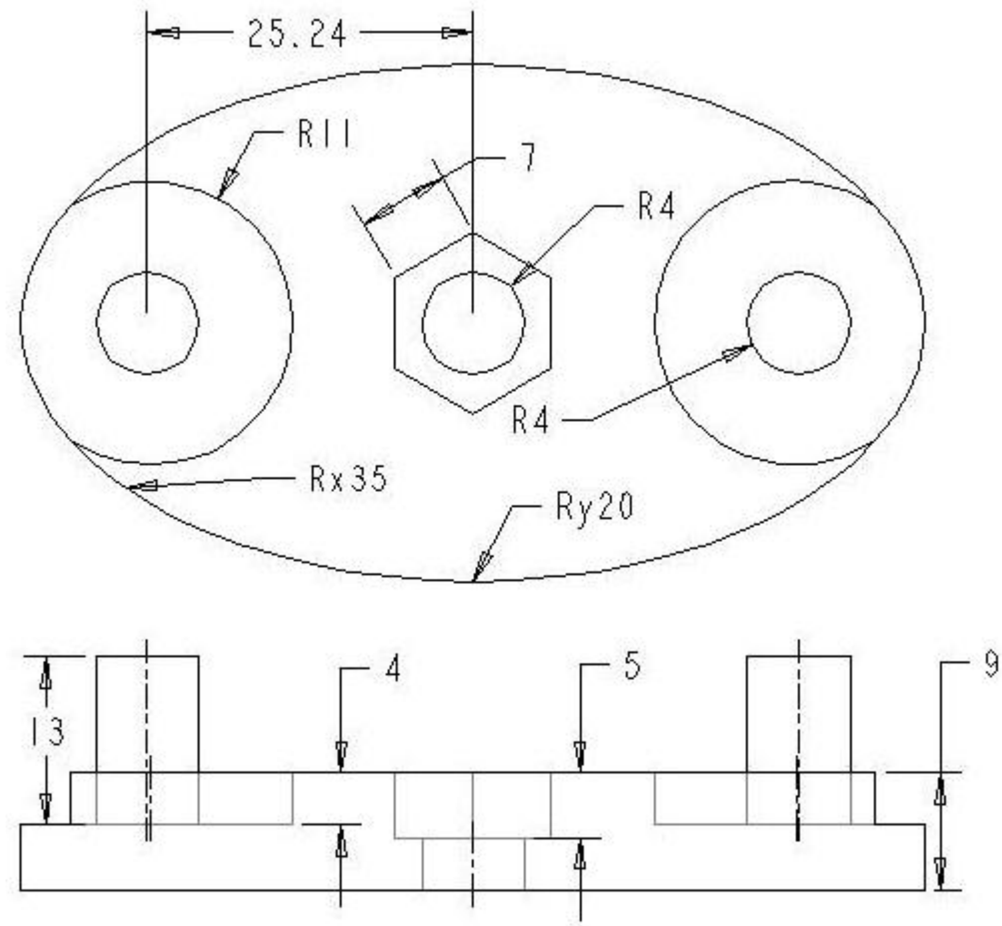


Figure 6-4 Dimension of Rotor

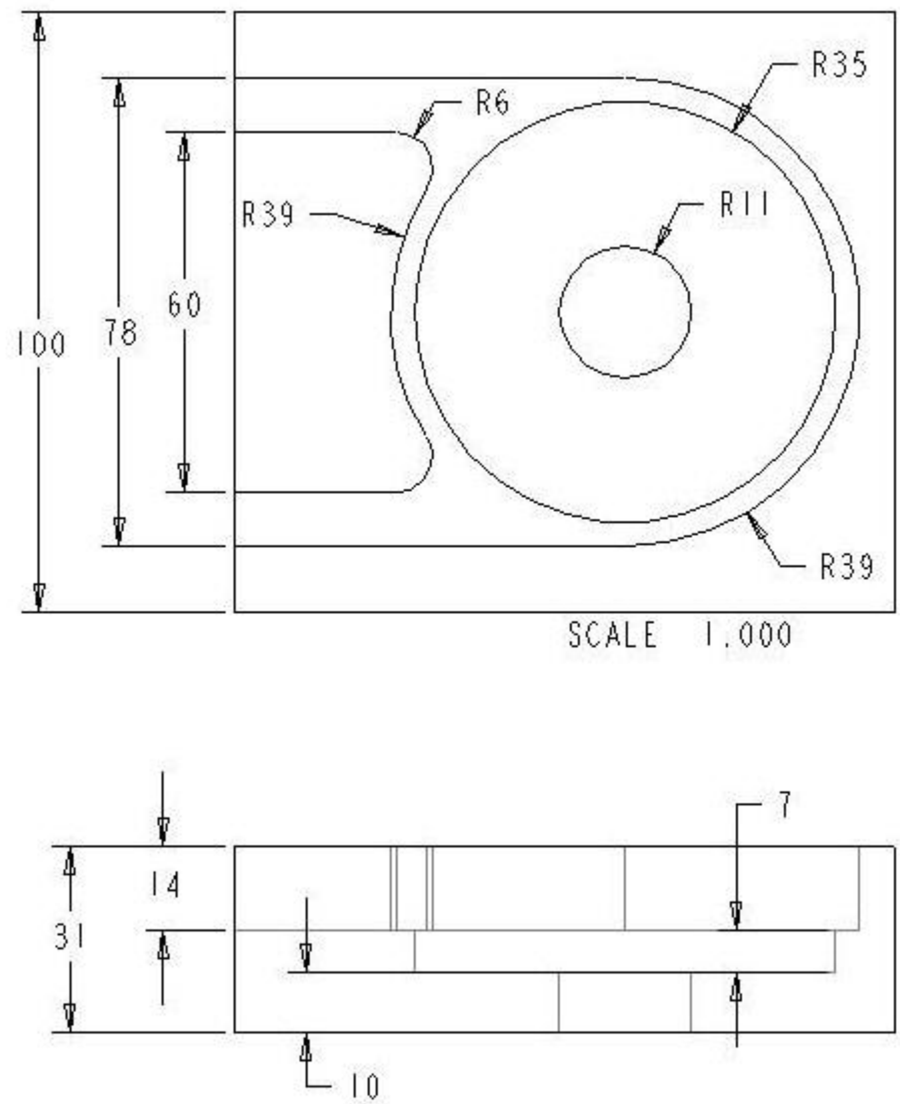


Figure 6-5 Dimension of Cavity

The cavity and the rotor are two components of a blood pump as shown in Figures 6-2, 6-3, 6-4, and 6-5.

The heart pump has three basic components: a rotor, a cavity and a plastic tube. The rotor rotates at the center of the cavity. A tube is clamped by the rotor's two cylinder arms against the cavity wall. When the rotor rotates, the arms squeeze along the tube thus pushing the fluid inside the tube. The rotor has a hexagon nut hole and a through hole in the center, as well as two cylinder arms at both ends. The rotor is a small piece and all the features are on one side. The CNC machining is done in one setup with two top clamps and no supportive operations.

The estimated CNC machining cost for the rotor on machinable wax is 75 dollars and the estimated SLA cost is 121 dollars (see Figure 6-6). CNC machining should be selected over SLA for the rotor.

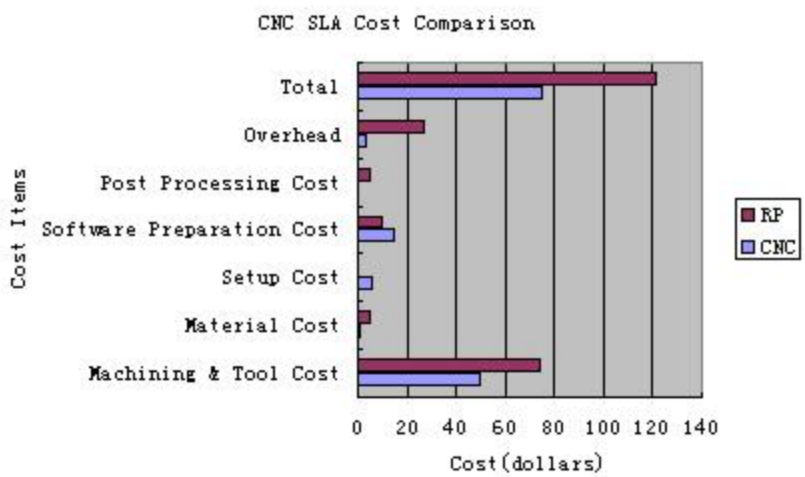


Figure 6-6 Excel Chart for the Rotor

The cavity is a cubic block with an arch shaped cavity. In the middle of the cavity is a through hole (see Figure 6-2). All these features are on one side. The cavity machining is done with one setup and two side clamps without any supports.

The CNC machining cost for the cavity on machinable wax is 122 dollars and SLA cost is 371 dollars (see Figure 6-7). CNC machining will be selected over SLA for the cavity.

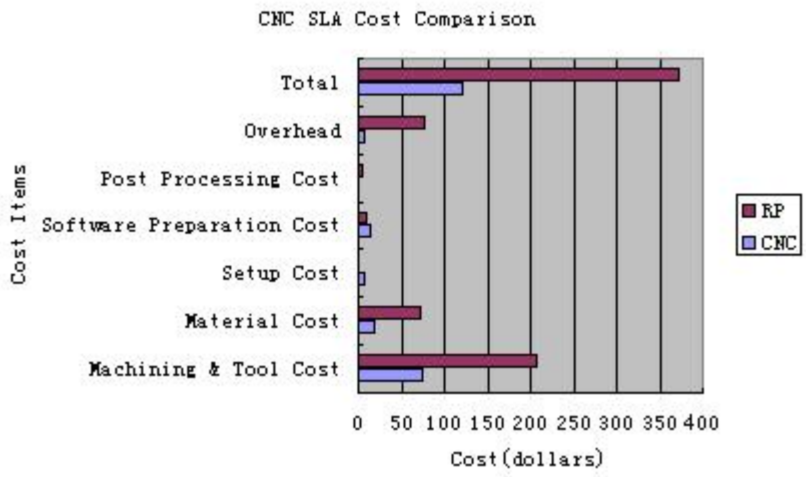
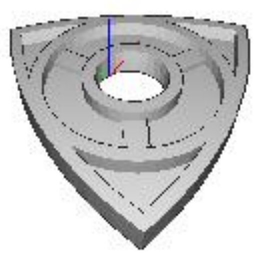


Figure 6-7 Excel Chart for the Cavity

6.3 Rotary engine rotor



Work piece size: $150\times115\times10mm^3$

Figure 6-8 Rotary Engine Rotor

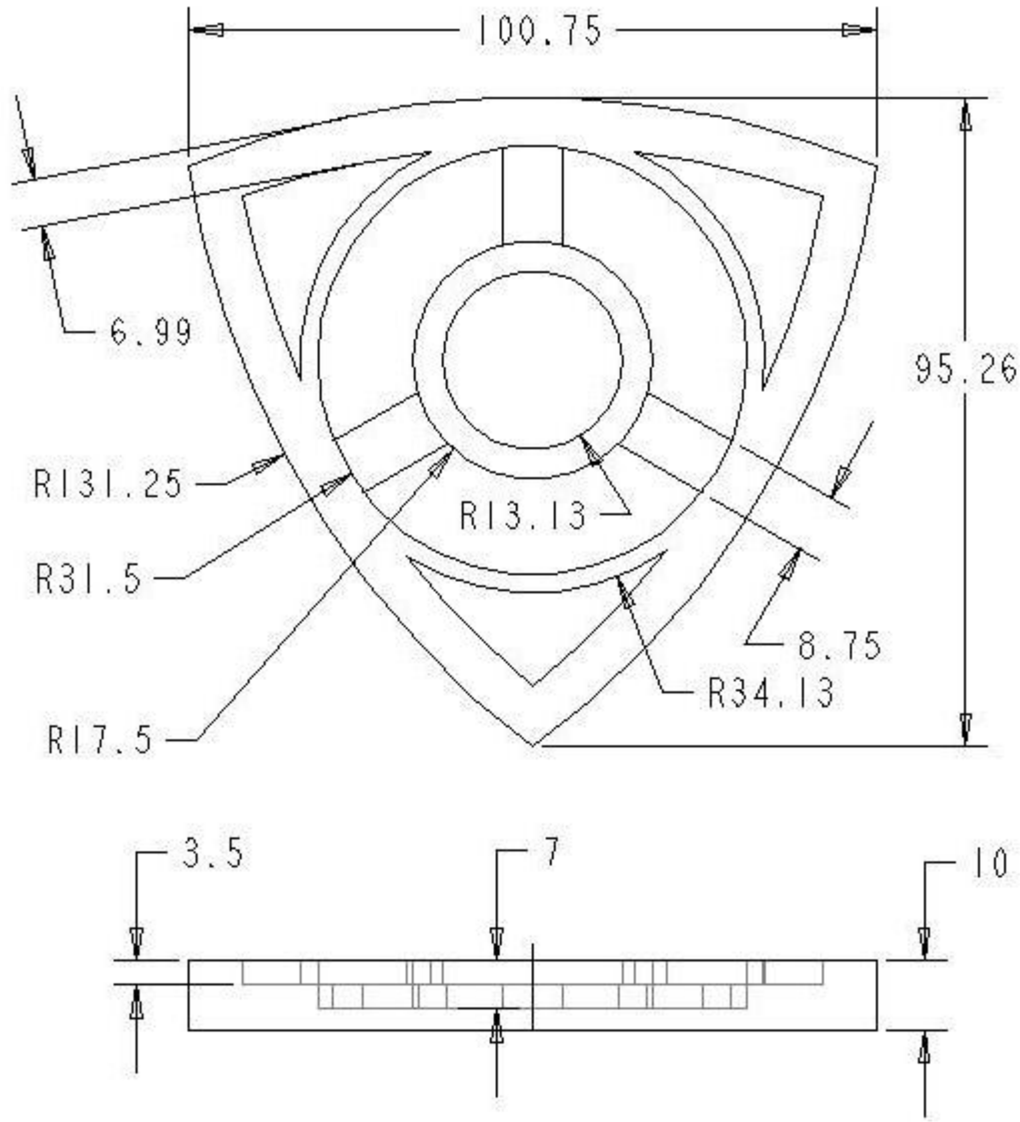


Figure 6-9 Dimension of the Rotary Engine

This is a rotary engine rotor. It has many pockets and a through hole in the middle (see Figures 6-8 and 6-9). All the machining features are on one side and machining is done with one setup and two top clamps without supports. The estimated CNC machining cost on the machinable wax for this rotor is 41 dollars and SLA cost is 108 dollars (see Figure 6-10). CNC machining will be selected over SLA.

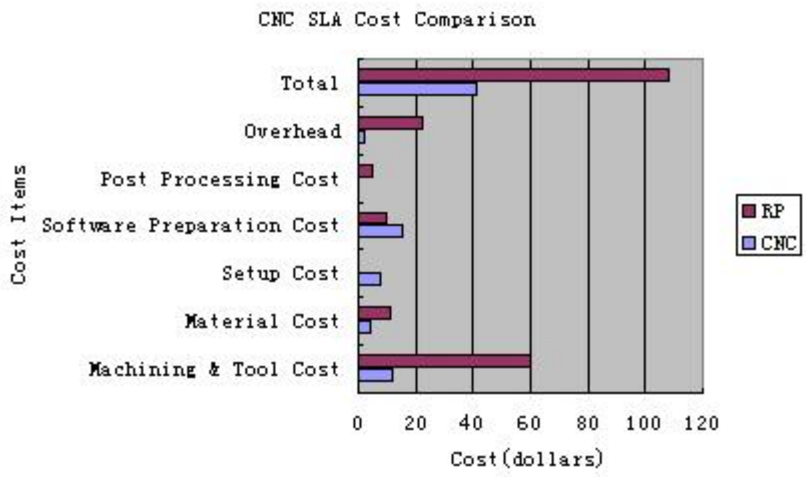
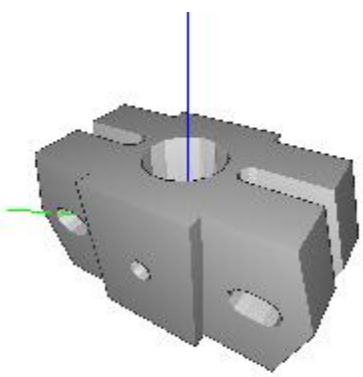


Figure 6-10 Excel Chart for the Rotary Engine Rotor

6.4 Robot gripper core



Work piece size: $40\times20\times21mm^3$

Figure 6-11 Robot Gripper Core

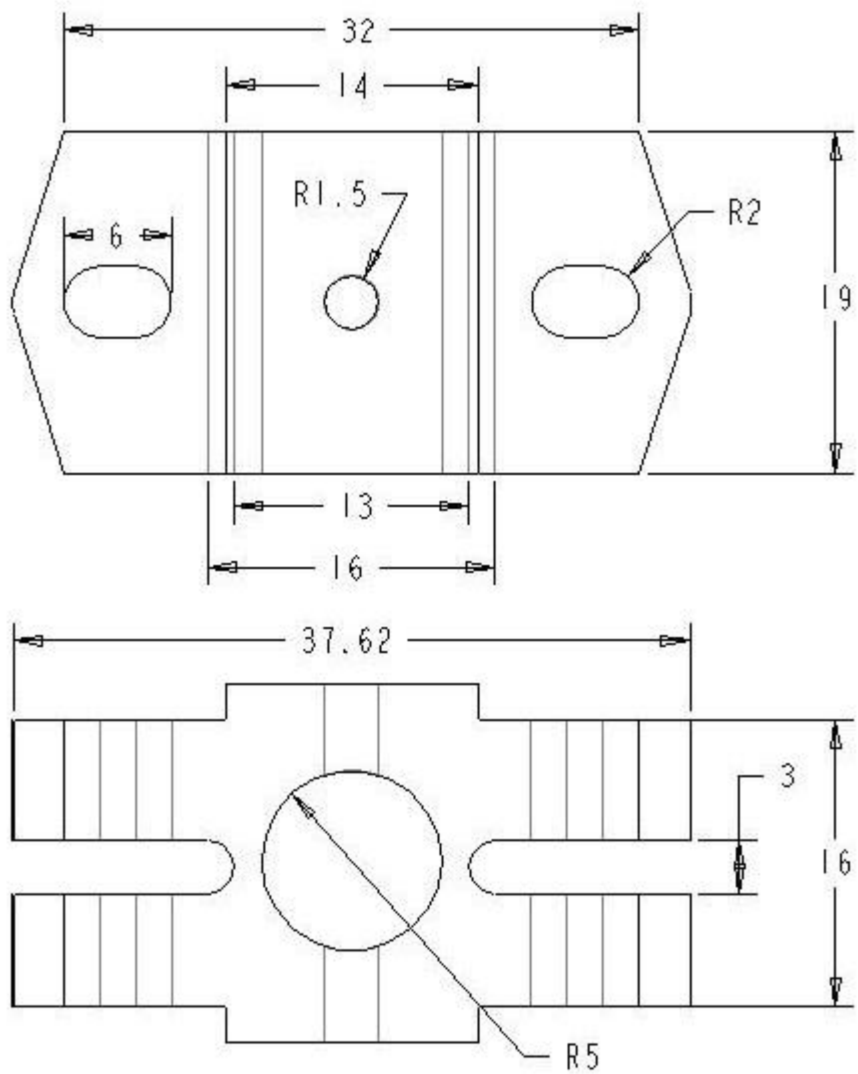


Figure 6-12 Dimension of the Gripper Core

The part shown in Figure 6-11 and 6-12 connects robot gripper fingers. It is a small part but needs 4 setups and a pin fixture. The first setup is to drill the small pin hole on the front surface (see Figures 6-11). The next setup is to machine the two slots and the large hole on the top surface. Pin fixture is applied in the third setup and the fourth to machine the front and back steps, holes and the V shape. The estimated cost for CNC machining is 142 dollars, for SLA is 118 dollars (see Figure 6-13). The estimated CNC machining cost is higher than the SLA cost. The design of the machining process, CNC tool path generation, and multiple setups are the major cost items in the machining. For the gripper core, SLA should be chosen over the CNC machining.

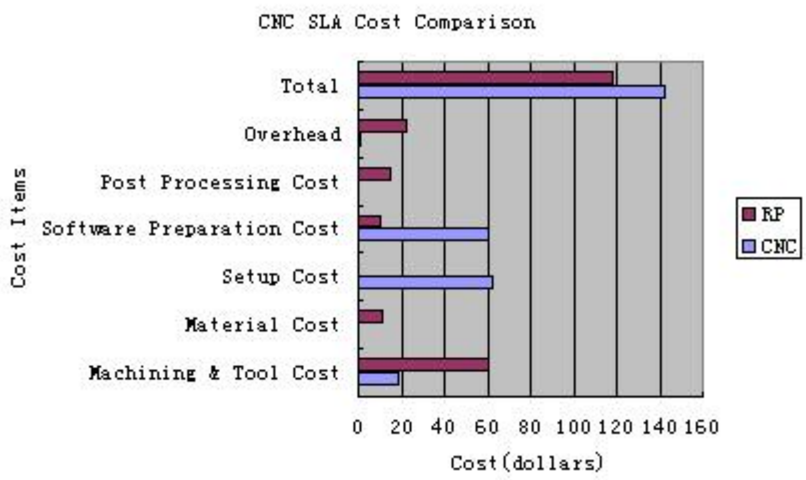


Figure 6-13 Excel Chart for the Gripper Core

6.5 Summary

In terms of cost, SLA is generally higher in material cost and overhead cost. This is due to the high SLA machine purchase cost, maintenance cost, and resin cost. If CNC machining uses machinable wax as the material, SLA is also higher in Machining and Tool cost. If the material is metal, CNC machining time and tool cost will increase dramatically. CNC tool path generation usually costs more than SLA software preparation. Fixture setup only applies to CNC machining and post processing only applies to SLA. For parts with multiple setups and/or pin fixtures, it's more likely the CNC machining cost will be higher than the SLA cost. The estimated cost is not an exact cost; it only indicates the range of the cost. Users should investigate the cost items to understand the pros and cons of these two methods. This information is helpful to improve the design and process selection.

7 Conclusions

This thesis proposed a number of new cost estimation methods as well as a dedicated cost estimator for both Stereolithography rapid prototyping and CNC machining. It provides valuable cost information of the Stereolithography process and the CNC machining process.

A non-sliced, original STL file based Stereolithography cost estimator catered for 3D systems' SLA 3500 machine is implemented. By specifying just a few fundamental build parameters such as build orientation, layer thickness and surface finishing level, without the time consuming support structure generation, layer slicing, and parameter tuning, users get quick and reliable cost estimation results. As the base for Stereolithography cost estimation, the predicted laser scanning speed is statistically adjusted to fit the experimental data and the predicted total build time is optimized to minimize the average prediction error. The post processing cost is also included by the classification of surface finish level for external and internal surfaces, which is a practical way to accommodate the part geometry difference.

Based on the assumption that users have CAM packages to generate the CNC tool paths, an activity based CNC milling machining cost estimator is implemented. A questionnaire based setup cost estimation is also included in the CNC machining cost. The adaptive questionnaire based on the combination of predefined questions quickly leads to feasible fixture plans. With the option for the users to specify the fixture components and their amount, this setup cost estimation can count for most 3D milling machining.

A clustered bar chart is presented in MS Excel file to visualize the total costs and sub item costs of Stereolithography and CNC machining, which is a valuable visual indicator for the users to understand the strength and weakness of the two technologies.

Five cases have been studied to test the system. The test results are reasonable and reliable. The developed methods and the software tool can benefit the manufacturing industry in selecting a suitable process for their single part or low-volume production needs.

This software can be further improved in the following areas. Additional SLA material and build styles can be added into the program. Group technology concepts can be incorporated to quickly and precisely predict fixture plans. The group technology will also help better predict the SLA post processing cost. The SLA cost estimator can be expanded to estimate the cost of multiple items in one SLA build which is a common way to reduce the SLA cost.

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Appendix A: SLA Speed Ratio

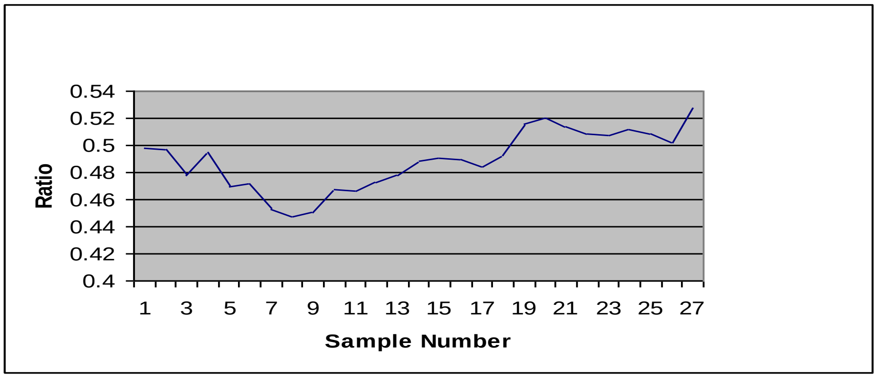

Figure A-1 Border Scanning Speed Ratio for 0.005 Inch Layer Thickness

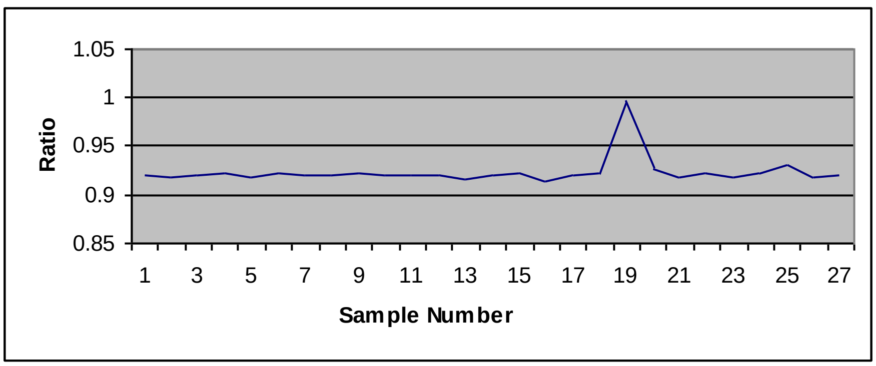

Figure A-2 Filling Speed Ratio for 0.005 Inch Layer Thickness

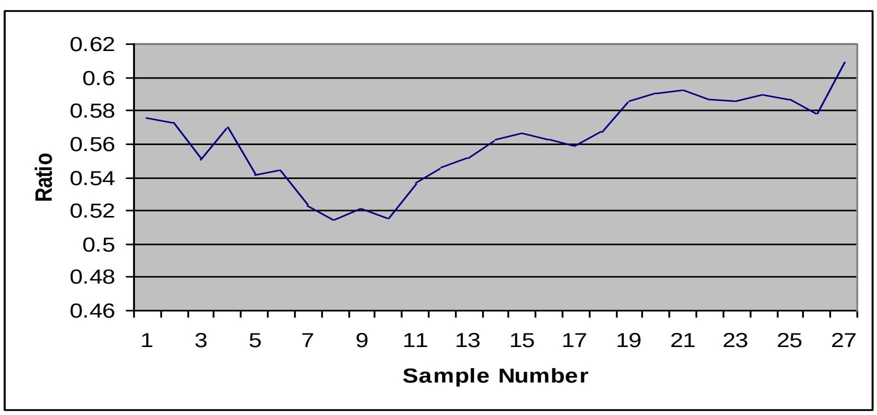

Figure A-3 Hatching Speed Ratio for 0.005 Inch Layer Thickness

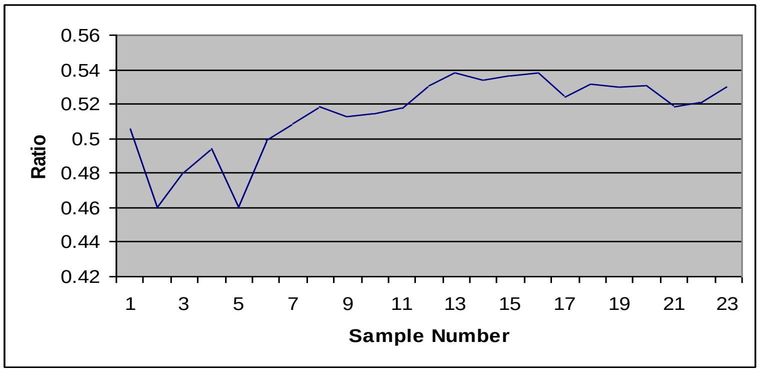

Figure A-4 Border Scanning Speed Ratio for 0.004 Inch Layer Thickness

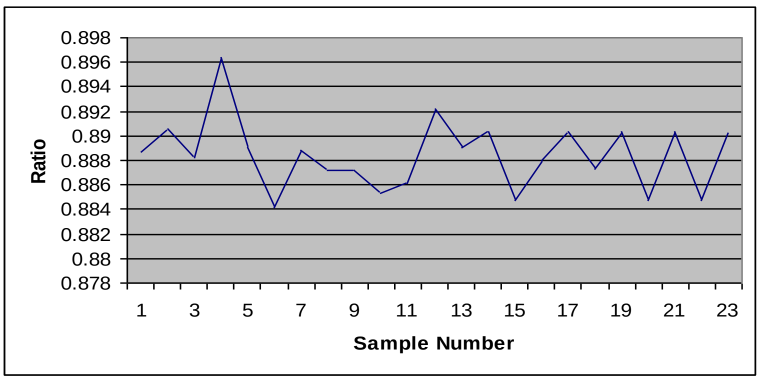

Figure A-5 Filling Speed Ratio for 0.004 Inch Layer Thickness

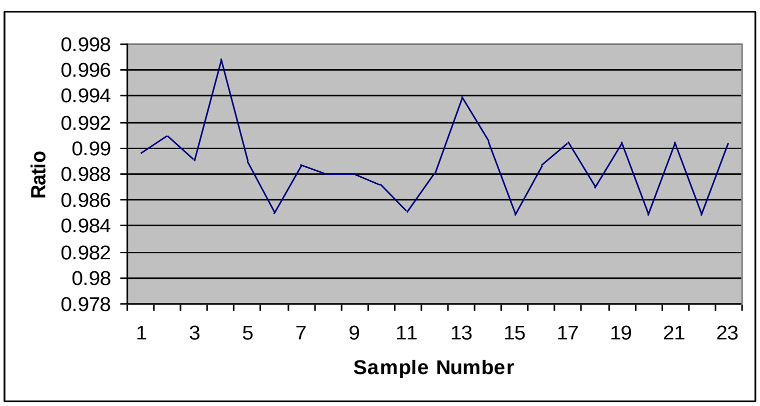

Figure A-6 Hatching Speed Ratio for 0.004 Inch Layer Thickness

Appendix B: CD Contents

Directory Name	Description
Code/CNCSLACostEstimator	VC++ Cost Comparison Program
Code/ExcelWriterCom	Visual Basic COM Program Called by CNCSLACostEstimator to convert cost information to Excel charts
Machine Cost Information Files	Machine cost information files for CNC milling machines and SLA machines.
MasterCAM Files	MasterCAM software output files for the case study samples
Matlab Optimization Files	Matlab optimization code for SLA build time estimation optimization
Case Study ProE Models	ProE models for the case study samples
Case Study STL Files	STL models for the case study samples
STL Sample Files	STL samples for SLA laser scanning speed estimation
CostComparisonChartTemplate.xls	Cost comparison Excel chart template
SLASpeedApproximationCharts.xls	SLA Speed Ratio calculation