Achieving Optimal Product Design by Integrating Design For Production Methodology and Design Automation

by

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Abstract

The goal of optimal product design is to minimize the production cost while satisfying the product functional requirements. In order to quantitatively compare different product designs in search of the optimum, detailed information on all the related engineering activities needs to be gathered and analyzed. However, it is a very challenging task to address all the related issues from the supply chain, throughout the manufacturing processes, until the final product sale. The presence of unlimited possible product design solutions, the complexity of manufacturing process planning, and production scheduling can further increase the difficulties of optimal product development. In addition, product development is often constrained by deadlines, which demands a rapid optimal design process.

A promising approach is to achieve the optimal product design by integrating Design for Production (DFP) methodology and design automation. The proposed DFP methodology refers to methods that lead to the product design with minimum production costs while satisfying all the functional requirements. This approach qualitatively captures the relationships between product design and production and provides general guidelines on quantification of such relationships. In this work, design related production issues are identified and quantified using a systematic cost analysis method, the Operation-based Method. The Operation-based costing method categorizes eight cost elements for each operation of a manufacturing process. By establishing relationships between design variables and cost elements, one can then apply an appropriate optimization algorithm to drive the design change and obtain the optimal design with minimum production costs. Pro/Engineer was used as the parametric product design tool.

An optimization algorithm, called the Adaptive Response Surface Method (ARSM), is then integrated to drive the design change and search for the optimal product design. The Pro/Engineer customization tool, Pro/Toolkit, is used to integrate the cost analysis model with the CAD model and to automate the whole product design process, greatly shortening the product development time.

The proposed DFP methodology is illustrated with the design of two industry products, an industrial silencer and a linear air diffuser. The results from the two product designs have shown a significant reduction in production cost. The proposed method can be potentially applied to other product designs.

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Chapter 1 Introduction

1.1 General Background

Since the industrial revolution century in the 1750-1850, manufacturing processes and industrial management have increasingly become more sophisticated and complex. Product design has also become a real challenge to many product designers. Every product design has to be specifically analyzed for the best manufacturing process option. Through process planning, there are many interdependent production issues and often tradeoffs have to be made. The development of concurrent engineering further enhances integration of teamwork management and computer technologies to increase productivity. This is due to the fast-paced global market that drives faster production and better quality product. Since the product design phase influences the total production cost, intensive research is involved nowadays in improving product design. This is because during product design, it is difficult for engineers to identify the relationship between design parameters and manufacturing processes. These problems can be widely seen in traditional manufacturing systems. The traditional approach is unaware of the influences of product design and thus causes lots of money and time investment in the redesign and testing stages. Since for every manufacturing organization, the goal is to obtain the highest possible profit, the time-to-market and production cost are critical. During the product design stage, the considerations of production aspects such as design specification, manufacturing process selection and synchronization with supplier and customer, are all important as well as many factors have indirect effects and are difficult to predict. Many in-depth manufacturing activities have to be considered simultaneously and most activities are interdependent, so the tradeoff is often difficult for decision

makers. Indeed, altering product design might change the manufacturing process and supplier, so that risk has to be taken in determining an optimal product. Other product design problems can be affected by production constraints such as environmental impact, political influences, and product safety issues. A large quantity of cost analysis approaches and design methods that are discussed in Chapter 2 have been developed to accommodate the complexity of manufacturing activities in product design. However, most are limited in applications while some are considered better than others.

1.2 Research Objectives

This research aims at developing a practical Design For Production (DFP) methodology and its software tool to help design engineers examine all the related production issues and constraints to achieve a minimum-cost product and production strategy design. Specifically, the proposed methodology includes four elements:

1. The use of the operation-based costing method as the ultimate measure of productivity and quantification of production cost.

2. The relationship and boundaries between product design and production are defined.

3. A systematic approach to establish relations between product design variables or parameters and cost elements of production.

4. The use of meta-modeling based design optimization algorithm as an integral ingredient of DFP.

The approach is expected to be generally applicable to various product designs that minimize production costs. A careful identification of design considerations, constraints and relationship between design variables and production costs are required to serve as the design guidelines. The overall methodology is to be tested on several industrial design problems and be implemented into a preliminary software tool. The integration of operation-based costing, design automation and optimization algorithm into the software prototype should give the optimum product design with minimum production costs.

1.3 Research Scope

The focus of this research is to develop the DFP methodology and its applications. The scope of Chapter 2 is a brief literature review on related studies that include *design for excellence, design for assembly, design for manufacture,* and *design for production.* In addition, a review of different cost analysis approaches that serve as a quantification tool for DFP is also given. In Chapter 3, the four elements of the DFP methodology will be introduced and discussed in detail. A detailed elaboration of the relationship between product design and production activities will be given. The relationships between design parameters and various cost elements are also quantified. An example of a simple round table will be given to illustrate the procedure and strategy of the Operation-based Costing (OBC) method, based on which the proposed DFP methodology is developed. A brief discussion of the meta-modeling based optimization algorithm called Adaptive Response Surface Method (ARSM) is also presented. Chapter 4 will discuss case studies on the design of industrial silencer and Chapter 5 is about linear air diffuser for two companies, Philips & Temro Ltd. and E.H. Price Ltd. respectively, by applying the proposed

methodology. Chapter 6 presents the design automation strategy and its implementation based on the design of the industrial silencer. The implemented automatic design tool is developed on the CAD modeling software (Pro/Engineer 2000i) using its programmatic toolkit called Pro/Toolkit. Finally, Chapter 7 will conclude the overall research for the DFP methodology.

Chapter 2 Literature Review

2.1 Concurrent Engineering and DFX Background

Today's manufacturers are striving to develop cheaper, quicker, and better products in a globally competitive market. The collaboration of these three product's attributes determines its success and therefore increases profits of enterprises. However, the approaches and steps required to achieve this goal are rather difficult. Product design plays an important role in this matter. It is widely recognized that the product design stage influences nearly 80% of final product costs even though only a small amount of expenditure incurs at this very preliminary stage (Booth 1994, Boothroyd 2002).

Under the umbrella of Concurrent Engineering (CE) philosophy, which proposes the simultaneous consideration of product life-cycle issues at the early design stage, Design for Excellence (DFX) has achieved great success over the past two decades. The DFX philosophy mainly consists of categories of design methodologies such as *design for manufacturability/assembly* (DFMA), *design for quality, design for serviceability/ reliability*, and so on, with 'X' stands for any legitimate product life-cycle consideration (Remich 1998). The evolvement of DFX philosophy in 70's has helped engineers with useful cost analysis guidelines for product design. It can be defined as a knowledge-based approach that attempts to maximize all product design characteristics (Bralla, 1999). A recent work done by Kalyan-Seshu (1998) documented the integration of various DFX tools with commercial CAD systems. A few main attributes of product design such as cost, performance, quality, safety, and manufacturability are considered in these tools.

Among the various DFX methodologies, the widely used DFMA developed by Boothroyd and Dewhurst is the most successful and has been commercialized to software tools (Boothroyd 2002). They considered the issues of manufacturability and assemblability. The term DFMA is defined as the combination of *design for assembly* (DFA) and *design for manufacturability* (DFM). The DFM means the design for the ease of manufacturing and DFA means the design for the ease of assembly. Boothroyd and his colleagues have studied how the product design decisions influence each manufacturing operation, such as casting, injection molding, and CNC milling. To quantify such an influence, cost estimation is used. They provide a general guideline for design engineers on what geometric features of a product will cause difficulty for a certain manufacturing operation and at what cost such feature can be made if it is manufacturable. Chan (2000) proposed an expert knowledge-based integrated DFM system for small and medium-size enterprises (SME) that provides the designer with decision-making capability on material selection and process evaluation. Gifford (1991) also believes that since design engineers are not manufacturing expert, the aid of expert system can improve company's manufacturing capability. Ramaswamy proposes that the DFM is the simultaneous development of product and process design. He further commented on some DFM methods such as DFMA (Boothroyd, 1994), *Lucas DFM method (Molloy et al, 1998)*, and *Nippondenso method and DFM Guidelines (Whitney, 1988)* in which most tools do not have the ability to provide redesign suggestions. Venkatachalam (1992) analyzed common tools and techniques used in the DFM approach such as *Axiomatic approach, Taguchi method,* and *Process-driven design method.* He found that some factors contributed to inefficient implementation of DFM

tool, namely, lack of interdisciplinary expertise in designers, inflexibility in organization structure which hinders interaction between design and manufacturing system, insufficient manufacturing cost analysis at the design phase, and the absence of integrated engineering effort intended to maximize functional and manufacturability objectives.

The DFMA methodology only focuses on individual manufacturing operations, for example, design for injection molding. In real production, once a product design is given, a feasible, and ideally optimal, manufacturing process has to be developed based on available facilities and production capacity. Other issues have to be determined include the number of employees with different skills, suppliers, plant layout, temporary and long-term storage, material handling strategy, machine capacity, and so on. In a word, a product design dictates an optimal production strategy for a given product. To achieve the overall efficiency, a product design should be evaluated together with the process and other production issues, not only from operation perspective alone (Soundar, 1994). Ideally, a product can be optimized at the early design stage from the overall production perspective, given the constraints of the existing production capacity of the company. Thus the *design for production* (DFP) strategy, which extends beyond the DFMA, should be more practical and useful for manufacturers.

2.2 Design For Production Philosophy

DFP is a recently evolved product design methodology. However, its philosophy has been well documented since the 60's (Trucks, 1987; Niebel, 1963). Trucks especially proposed useful design guidelines that many are adopted in Chapter 3 of this thesis. The recent research in this field provides papers presented by Herrmann and Chincholkar.

(2001a, 2001b). They defined DFP as "methods that determine if a manufacturing system has sufficient capacity to achieve the desired throughput and approaches to estimate the manufacturing cycle time." They distinguished the DFM as studies of the feasibility of manufacturing the product while the DFP evaluates manufacturing capacity and measures the manufacturing time. In general, they focus on the reduced manufacturing cycle time that will bring profit to company. They find that DFP requires information about the product designs as well as details of the manufacturing as a whole. Their DFP approach is useful for introducing a new product into an existing manufacturing system already producing other products. One major concern to this approach is the use of cycle time as the measure of productivity. For a given manufacturing line assuming other conditions remain the same, if better equipment and more skillful operators are used, the cycle time will surely be reduced. However, is the company willing to cover the increased cost of the machinery and personnel? Other research on DFP using different name is Govil (2000). He presented an analytic tool that can be used to alter product design, manufacturing processes and assembly techniques to increase production rate. His approach is by simultaneously considering part geometric attribute, material selection, and process selection during the product conceptual stage. However, the desired production rate is the only criteria that are considered in process selection and design modification (Govil 1999).

Locascio (2000) also developed a software program with the concept of DFP. The model he proposed helps a designer in calculating manufacturing costs and aids in related manufacturing and design decision-making. Quantitative tradeoffs between manufacturing cost and material selection can be made. The methodology is based on the

activity-based costing (ABC) method, by which the total cost is derived from activities and resources related to the manufacturing system. Basically, setup time, processing time, and labor cost are the focus of the proposed model. While the shortcomings are the negligence of the consideration of quality and reliability issues, the model can be generalized to other product design and manufacturing scenarios other than the provided case study. Minis (1999) on the other hand not only considered the manufacturability evaluation of product design but also concurrently select potential partners or vendor that best fit the design's manufacturing requirement. This approach is more human oriented that results in lower cost and more efficient production but lacks product design feedback during the product development stage. Another research area that is related to DFP is the link between product design features and manufacturing system performance proposed by Soundar and Bao (1994). They developed Concurrent Engineering Support Tools (CEST) that addressed the issues of the relationship between manufacturing system performance and product design features. The system performance analysis evaluated the output of work-in-process (WIP), scrap, machine utilization, flow time, and throughput. The shortcoming of the system is lack of quantification capability of production cost. In addition, Chen (2001) included an expert system in the design evaluation system, CONDENSE to qualitatively perform design evaluation and quantitatively evaluate the product design performance, assemblability, manufacturability, and costs to facilitate design selection. However, the cost aspect of this system is focused on identifying cost drivers and process constraints and is not intended for production activity based cost estimation.

2.3 Cost Estimation

Whether it is the DFX tool or other DFP, DFM approaches, it is obvious that cost is ultimately the objective of many methods indicated above. This is a common indication for company profit. The cost estimation tools are integrated to provide quantitative analysis of product design for design engineers. Nowadays, this is often done through the use of software tools as the computers are increasingly becoming more reliable and fast. This also helps in reducing time to market of product, which is an important element in every product design. There are many methods used for cost estimation. Duverlie and Castelain (1999) identified some methods, namely, the intuitive method, analogical method, parametric method, and analytical method. Boehm and Abts (1998) categorized some costing approaches into model-based, expertise-based, learning-oriented, dynamic based, regression based, and composite techniques. The costing methods are similar in fundamental principles to find optimum production cost, although different terms are being used. Specifically, there are parametric costing, activity-based costing, target costing, life cycle costing, value engineering, variant-based costing (Brinke et al., 2000, etc.). Esawi and Ashby (1999) further proposed a resource-based method that first estimates the consumption of resources and then the sum of individual costs to get the ranking of the minimum production cost. Charles (1997) also identified a couple of other costing methods that are used in engineering practices such as the average costing, direct method and full absorption costing. Of the many cost estimation methods, four popular and representative approaches will be discussed in the following and they are the parametric costing, activity based costing, target costing and life cycle costing.

2.3.1 Parametric Costing

This approach involves the extensive use of computer aided technology and programming software. The product design is often modeled using CAD software tools such as Pro/Engineer, Solidworks, Unigraphics, CATIA and so on. The feature-based solid modeling implemented in CAD software provides a designer with parametrization capability. The design changes of part or assembly done by parametrization can save time and increase design efficiency. Within the solid modeler, designers' design intents and design variables are carefully established and geometric dimensions are mathematically formulated to establish relations on part and assembly. Thus by changing one dimension, the solid model can be regenerated with new updated product features. In general, this method uses equations to map measurable system attributes into cost. The assumption is that a measurable relationship exists between system attributes and the cost system as documented by Dean (1989). He further describes the use of different formula such as exponential factor, power law factor and the hybrid combination of the two factors to improve accuracy of cost analysis. Chang and Silva (2001) proposed a set of guidelines that are used for parametric product design. This technique provides useful product performance, quality, and manufacturing cost information. Vitaliano (2000) presented the advantage of parametric costing, which enables knowledge-based data to be used to save time and cost. In addition, parametric costing provides nearly real time feedback on the design option and manufacturing cost. Duverlie (1999) and Hollmann (1994) describe it is useful because of its rapidity of execution. Duverlie briefly described three types of the parametric method: the method of scales, statistical models, and cost estimation formulae (CEF). The method of scales generally applies the product

variables to a cost ratio such as $/ft and $/kg. Statistical models are constructed from a set of data such as product technical specifications, constants and variables that formed different domains of activities. The statistical relationship can be formulated through this model with the help of some mathematical formula. The CEF method takes a simple mathematical relationship between design parameters and the cost through a linear regression model. However, he indicates the drawback of this method is that it is hard to justify the result due to the unknown origin of costs. Besides, a user has to estimate missing parameter in order for the model to run and thus the cost uncertainty is increased. Rohm III et al. (2000) in depths described that a modern CAD system can accomplish the parametric function through two methods: the interactive and the programmatic approach. Two concerns were raised about the programmatic approach, which is normally needed for parametric costing to be embedded into a CAD system. First, the engineers have to have high computer programming skills as well as in-depth CAD system database knowledge. Secondly, the process to create the parametric model is time consuming.

2.3.2 Activity-based Costing

The activity-based costing has attracted many cost engineering applications since its development in the 1980s' by Robert Kaplan and Robin Cooper (Brimson 1991, Cooper 1992, Fritzsch 1997/1998). This approach is intended to improve traditional cost analysis methods, providing that costs of product or service are assigned to operation-related "activities" that are carried out to produce the product or service. The method is based on the idea of "activities consume resources and product consumes activities." It uses manufacturing process activities as the basic unit for the accumulation of

manufacturing cost. Then the manufacturing costs are allocated based on utilization of these activities. The application of ABC tends to fall into three categories: diagnostics, reengineering and financial management systems (Corrigan, 1999). ABC can accurately determine product cost from manufacturing process activities and thus helps engineers to make decisions on pricing, estimating, make/buy and design to cost. In addition, it can trace the liquidity of cash flow, such as overhead allocation of direct labor, machine hours, and material that help engineers to have better control over production cost (Brimson, 1991).

However, Yahya-Zadeh (1997) brought up the drawback issue of the assumption about constancy of average activities cost. This assumption for allocating product cost over activities may distort the overall system accuracy. For Charles Curry Jr. (1997), he mentioned that ABC is appearing to be more widely used as a cost management technique nowadays than as a product costing method. Devost and Miller (1995) concerned that human factors and organization behaviors often hinder the success of the ABC implementation. The uncertainty of benefits and high costs can also affect the ABC implementation (Corrigan, 1996). Fritzsch (1997, 1998), on the other hand, points out the limitations of ABC: 1) a failure to distinguish between fixed and variable costs and 2) full absorption of costs that are partially depreciated. A very common criticism is that ABC is superior as a basis for decision-making however that the time involved in establishing ABC is excessive due to large amount of data requirements (Skinner 1998).

2.3.3 Target Costing

The Target costing philosophy is based on the market price, which is the determinant of cost. It originated in the Japanese auto industry at Toyota about 1965 (Tanaka, 1993). This approach is the opposite of many practices in organizations that the production cost drives the product-selling price. It is a profit management technique used to ensure that a company generates sufficient profits in the long run. Cooper (2000) stated that target costing could be divided into three sections, including market-driven target costing, product-level target costing, and component-level target costing. The sequence is to first determine the market driven cost where consumer demands take place, followed by product level costing, whose focus is on the designer's creativity, and finally to component-level costing where the supplier is the main focus, so that the production cost is gradually reduced with more beneficial suppliers. Ansari (1997) further elaborated that target costing consists of six key principles, including price led costing, customer focus, focus on design of product and processes, cross-functional team, life cycle cost reduction, and value chain involvement. He defined the target costing as *"The target costing process is a system of profit planning and cost management that is price led, customer focused, design centered, and cross functional. Target costing initiates cost management at the earliest stages of product development and applies it throughout the product life cycle by actively involving the entire value chain."*

This approach is based on researching the product market price requirement or the price customers can afford within the profit margin, then the potential production cost reduction is estimated. Schemelze (1996) provides the target costing equation as follow:

Target Price – Target Profit = Target Cost

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The target price of a new product is primarily determined from market analysis while the target profit or margin is set based upon company profit expectations, historical results, competitive analysis and computer simulation. The resultant target cost is then used for determining the purchase price of components and raw materials (Cooper, 1994). In addition, the benefit over traditional approaches that estimate the production cost first and then adds the profit margin to obtain the market price. Gagne (1995) briefly described the procedure for the implementation of target costing. Besides, he documented the usefulness of target costing is toward product that has short life cycles and product with diversity. Throughout the product life cycle, the use of this approach is most effective during the product development and design stage (Lee 1994, Gagne 1995).

However, the target costing is just a business philosophy based on market price rather than a costing technique that provides promising production solutions. Furthermore, the definition is not clear enough to justify the implementation for every organization. Since it is a market driven costing approach, the nature of customer and the intensity of competition highly influence its output.

2.3.4 Life-Cycle Costing

A successful cost estimation approach since 1960's in many engineering applications is called the lifecycle costing. This method originated from the Department of Defense of the United States to improve the government's purchasing systems (Lobo 1998, Brown 1985). This method studies the life cycle of a product and its product cost can be determined from the product life span. In addition, a company can focus on the long term planning of the total product cost including the operational cost and support

cost. Since a product's initial cost might not always be cheaper than its operation and maintenance cost, a decision maker can decide whether to increase expenditure during the product development stage and reduce its operational cost or vice versa (Anonymous 1995). Lobo (1998) and Atkinson (1990) documented that the product life cycle consisted of four phases: development, growth, maturity, and decline. Brown (1985) referred this practice as "Design To Cost". Four major factors influence the success of LCC application.

1. Energy consumption partly adds cost to the product and thus the design consideration has to anticipate the energy cost throughout product life span.

2. The product life expectancy can affect the LCC cost. Normally, support and maintenance costs are more important than its initial cost for products of long life, and the initial cost is more significant for products of short life.

3. The efficiency of operation and maintenance is significant to the overall LCC cost.

4. When the investment cost is high, the LCC analysis becomes more important.

LCC analysis normally is used for the product that has a long life span, such as construction equipment, building, heating and air conditioning system, aerospace applications, hospital equipment (Dhillon 1989, Brown 1985). Dhillon also demonstrated the formulation and procedure for LCC within engineering economic perspectives. Ashworth (1989) further outlined the difficulties occurred for the LCC application, including the rapid change in manufacturing technology, product fashion and trends in product costs. These factors are major consideration of LCC analysis because they are subjected to rates of interest, inflation, taxations, and discount rates.

2.4 Operation-Based Costing (OBC) For Design For Production

In general, the four common costing methods discussed above are not suitable for the development of DFP strategy. The parametric costing method is too abstract. It needs support from a detailed cost analysis model to overcome the difficulty in tracing the origin of costs. The activity-based costing method does not sufficiently address the structure of production system analysis, and it is meant for accounting management strategy. The target-costing method focuses more on the business management strategy, while life-cycle costing method addresses the importance of support, service, and recycling costs. In spite of the limitations imposed by these costing methods, their benefits can be realized which give raise to the operation-based costing method.

Operation-based costing method, which will be further discussed in Chapter 3, is considered as an extension to the ABC method that is specially designed to suit manufacturing system applications. It has the advantage of tracing activities that consume resources in a production system without spending excessive efforts by changing the overall corporate cost management system. In addition, product design parameters can be associated to the cost elements of an individual activity of an OBC model through parametric relationships. The parametric aspects of OBC, discussed in Chapter 6, facilitate product design automation and time reduction in product development. As a result, the costing method in DFP methodology comprises of a hybrid of parametric and activity-based philosophies.

Chapter 3 Design For Production (DFP)

3.1 Overview of The Design For Production Methodology

This work proposes a promising approach, Design for Production (DFP), for product design. The proposed DFP methodology refers to a method that leads to the optimal product design with minimum production costs while satisfying all the product functional requirements. This approach simultaneously considers the production planning, manufacturing processes, and product features during the design phase, striving to obtain the optimal product design.

DFP is intended to first measure the productivity of manufacturing systems. An efficient manufacturing system considers a production plan that uses less resource and time. On the other hand, a more efficient manufacturing system indicates less production cost as Deo and Strong (Deo 2000) mentioned that cost is the ultimate measure of productivity. In every organization, cost is considered the common indicator into which all resources throughout the manufacturing system can be translated and measured. Cost is used to quantify all manufacturing systems' performance whether the goal is to increase sales or to reduce production costs. In addition, Fitzgerald (1997) reported that cost reduction was of concern more than any other product design aspects. DFP would use the cost as the measure of the productivity of manufacturing systems. Based on the productivity measurement, the DFP will first feedback the production information to design, identify design alternatives, and search the optimal design that yields the least production costs by varying geometric parameters, material choice, tolerances, design concept, manufacturing process, and manufacturing system. As a result, the DFP methodology will help design engineers examine all the related production issues and

constraints to achieve a minimum-cost product and effective production strategy. Specifically, four elements are being considered essential to the proposed DFP methodology and they are:

1. The use of the operation-based costing method (OBC) to measure productivity and quantify production costs.

2. The relationship and boundaries between product design and production issues are defined to serve as DFP design guidelines.

3. A systematic approach to establish relations between product design variables or parameters and cost elements of OBC model.

4. The use of meta-modeling based design optimization algorithm as an integral ingredient of DFP.

The simultaneous integration of these four elements forms the core of DFP methodology. A DFP software tool is developed to illustrate this methodology depicted in Chapter 4 & 5. The OBC and meta-modeling algorithm are used to search for the minimum-cost design through a clearly defined relationship of product design parameters and production issues. First, engineers identify the product requirements and its functionality, which are related with manufacturing process selection and planning. Such relationship as well as the boundary between production and design should be clearly defined. Some important production information such as the desired production volume should be given beforehand. Then, CAD software is used as the solid modeling tool for the designed product. The parametric capability of the CAD tool can associate product features and parameters to an external programmatic tool. The OBC costing procedure can be

integrated and linked to the designed parameters through the programmatic tool to quantify the production cost. Finally, optimization is carried out to search for the optimum product design within some designated product constraints. The following diagram depicts an overview of the DFP methodology.

Design For Production Methodology Overview

```
┌─────────────────────────────────────┐
│     Product Design Requirements      │
└─────────────────────────────────────┘
                  ⇩
┌─────────────────────────────────────┐
│     Relation and Boundary of Product │
│     Design and Production Information │
└─────────────────────────────────────┘
                  ⇩
```

Solid Modeling of Designed Product

Link Between Design Parameters & Production Costs

Operation Based Costing

Integrated Knowledgebase Manufacturing Processes

Optimization Algorithm Loops

No

Yes

Optimum Design & Minimum Cost

Figure 3.1 Diagram shows the overview of the Proposed DFP methodology

As in Figure 3.1, product requirements are first defined. These requirements can be provided by the customers or through marketing research. Then, the product design

objectives, design constraints, manufacturing processes and related production issues are defined to narrow down to specific problem solving statements. The problem statements are translated into quantifiable mathematical formula to associate the product specifications in the CAD model with the production system information. The OBC model is developed to implement the product information into quantifiable cost information. The optimization iteratively finds the optimum design parameters and minimum production cost. The following sections will discuss the four essential elements respectively. Applications of the DFP methodology will be described in Chapter 4 and 5.

3.2 Assumptions

As production situations can be very complex, this study will focus on basic and important production issues in developing DFP. Some assumptions on the production and design are made as listed below to set a boundary for the study. The developed DFP methodology, however, is expected to be fundamental so that it can be easily extended to accommodate more complicated production situations.

1. **A Single Product**: The analysis of DFP approach is applied to a single product type at a time. For manufacturing systems that have a high product variety, only the utilization of the related production activities by this single product is calculated regardless of how a product family or group is treated. This single product, however, is not limited in any aspects in terms of shape, size, material, and so on, to be representative of any possible product.

2. **Historical Manufacturing Information Based**: The cost and manufacturing information used in DFP are based on the historical data within a manufacturing company. The information on the current production facility, capacity, and practice is the basis for a detailed productivity measurement. Other historical data such as tolerance-cost relationship of each machine will facilitate the quantification of manufacturing costs and the relationship between the design tolerance and the manufacturing cost. This work assumes that the majority of the necessary input information required by the cost analysis and DFP is readily available, or can be easily obtained within the company. It is to be noted that the optimal product design to be obtained using the proposed DFP is accompanied with the minimum-cost production strategy that is based on the existing facilities. Purchasing of new equipment usually represents a high investment cost and is not considered in this study.

3. **Yearly Based Cost Model**: The data used in the OBC cost calculation is yearly based since it is assumed more convenient to this study. A yearly quantity output is estimated for example, 5,000 unit/year. Average value is used such as the interest rate, tied rate or tied cost, and depreciation. One should realize the effect of changing quantity of output towards the production systems.

4. **Fixed Handling and Scheduling**: The variation of a product design is assumed to have less effects on the handling and scheduling. This assumption is made on the observation that for a product having a certain function, the change in design parameters normally are not significant enough to affect the material handling strategy. Scheduling itself is a complex and challenging issue and gradually

grows to be a problem independent to product design. In this study, the scheduling is assumed to be always acceptable and would not cause any constraint on the manufacturing process, if the product design were changed. We do recognize that in some situations, the change of product design does affect the material handling and do cause scheduling difficulties.

5. **Ideal Operation**: The frequency of machine breakdown, maintenance, and setup-time is considered the same as that of the previous year.

6. **Product Producibility**: The designed product whether new or from a redesign process, is considered manufacturable using the provided manufacturing process.

7. **A Good Generation of Process Plan**: This work assumes that for a given product design, an ideal process plan can be generated by the field experts. It is also assumed that the process plan varies with different design concepts, materials, and tolerance but is invariant with the change of geometric dimensions. The generation of a process plan or computer aided process planning (CAPP), has been intensively studied in Refs. (Ahmad et al. 2001). This work does not focus on CAPP, but a CAPP system, on the other hand, can greatly help the proposed DFP methodology in achieving design automation.

3.3 Operation-based Costing (OBC)

The proposed DFP methodology is based on the quantification of detailed production costs. Therefore, a cost estimation method that is tightly related to the production plan is required for an accurate productivity measurement. Section 2.3 has discussed different common cost estimation methods, including parametric costing, life-

cycle costing, target costing, and activity-based costing (ABC) methods. None of these methods is directly applicable for an accurate productivity measurement. Thus, a new costing method, the operation-based costing (OBC) method originated by Strong in 1996 (Strong, 1996), is chosen in this work for accurate cost estimation. OBC provides a manufacturing operation based cost model, in which for every operation, 8 cost elements (Material Cost, Machine Cost, Labor Cost, Space Cost, Incentives, Contract, Tied Cost and Fixture Cost) can be associated and distributed over that particular operation. Because the operation cost is broken down into the 8 cost elements, distribution of costs on each element can be studied explicitly and clearly. A detail illustration of the 8 cost element will be presented in this section using a table example in Appendix A.

The software of the OBC cost analysis model is programmed in Excel as a combination of spreadsheet and macros. This will consider all the manufacturing operations altogether with the cost analysis. Macros are programmed into the cost model. Users just need to manually input some cost and manufacturing information and click on a specific macro button to generate the results. The program consists of several Excel worksheets. Other worksheets can be added depending on the collected product data and manufacturing information, but every product design should contain the major four worksheets as follow:

1) FlowDiagram – a process diagram for description of material and part flow between operations.

2) ElementData – a detail analysis of the 8 cost elements in cost table format.

3) CostTable – a table used for gathering input from ElementData worksheets and programmed to perform iterative cost calculation.

4) Charts – all cost resultants from CostTable worksheet are displayed in chart format for the user to interpret the cost distribution to identify the potential production and design improvements.

The "FlowDiagram" worksheet is meant for the user to plan and outline the production flow. This diagram does not participate in the cost calculation. Users can use this diagram to help establishing the "ElementData" worksheet. The cost information of the "ElementData" worksheet is involved in the cost calculation used by the "CostTable". Thus, the syntax and wording have to be carefully input to avoid compilation error. "FlowDiagram" and "ElementData" are the only two worksheets required for user input for the manufacturing cost and part flow information. The next worksheet, "CostTable" is used to perform the calculations and list out the resultant of the 8 cost elements in a table format. The worksheet of "Charts" is used to show the operation costs in bar charts for the user to visually inspect the results and make decisions on the design change. The following diagram shows the outline of OBC and its integration with solid modeling tool.
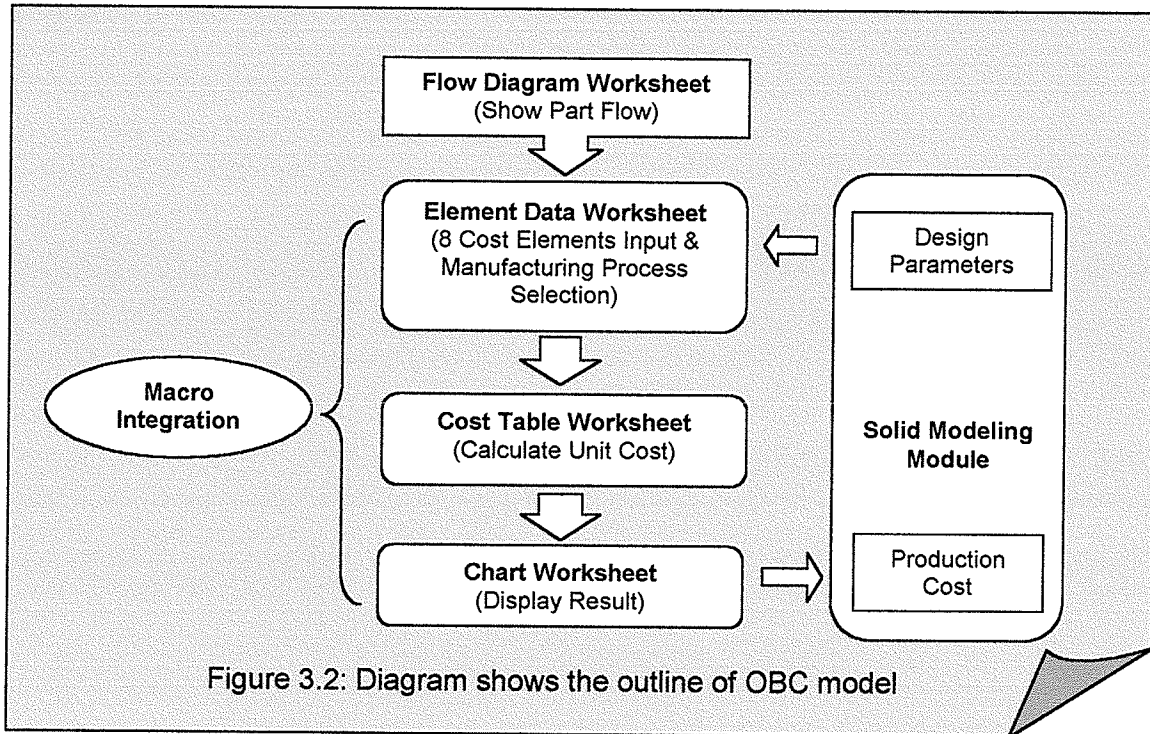
Figure 3.2: Diagram shows the outline of OBC model

For further illustration, an example of the manufacture of a circular wood table is presented with the analysis of the four worksheets depicted in Appendix A. The appendix provides the procedure to construct an OBC model and instruction on the use of it.

3.4 Product Design And Production System

This section continues with the definition of the boundary between product design and production issues. Today's global market generally consists of three industry types; service, producing and distribution industries (Dieter 2000). Dieter (2000) describes that the service industry is a business that involves human service and power to customers such as banking, insurance, and education. The producing industry produces products

out of natural resources and the distribution industry deals with merchandising and transportation that makes product available to consumer as shown in Figure 3.3.

A Hierarchical Classification of Industry
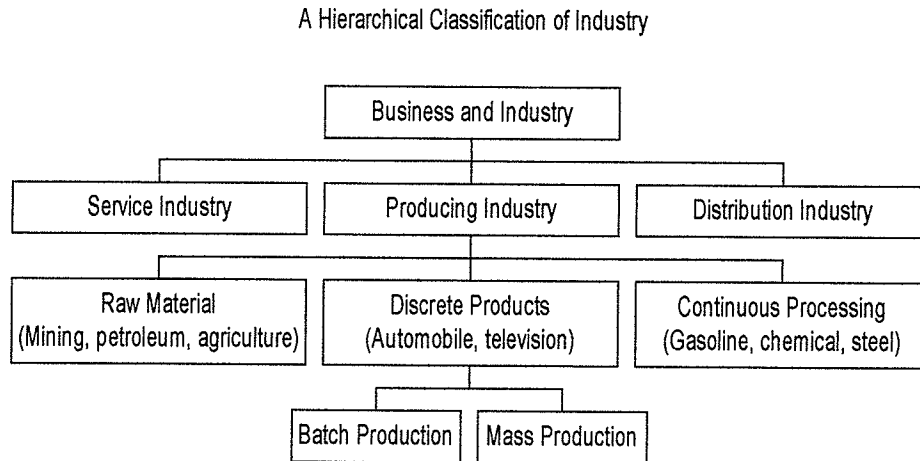
Figure 3.3: Classification of Industry Adopted From Dieter 2000

The producing industry can be further classified into, raw material, discrete product, and continuous processing industries. Within these manufacturing types, the discrete product industry is important to this study as far as DFP concerns, it is the only manufacturing type that converts raw material into products and thus involves both product design and production. The other two manufacturing types involve no product design and therefore the DFP methodology is applicable to the discrete product industry only. One should note that the OBC cost estimation model is applicable to other industrial types if only the cost analysis is of concern. Within the discrete product industry, the major two production systems can be identified are batch or low-volume production and mass production.

DFP can be used for both product reengineering and new product development. Product reengineering may involve change of certain design attributes or incorporate

change to manufacturing planning for existing production systems. New product development can disregard the existing production system in order to implement the new design concept. It is important to clarify the relationship between the product design parameters to production issues. As Govil (2000) emphasized that many enterprises are focusing on production time and cost reduction by improving production planning and scheduling. However, the improvement is limited by constraints imposed by one or more aspects of the product's design. The interrelated relationship of manufacturing processes, material selection, and assembly operations has significant impact on developing feasible production operations. Due to this complication imposed by product design and production systems, DFP is intended to develop a systematic approach that defines boundaries for the two activities. It is obvious that some production issues are considered to have a strong relationship with respect to product design, while some issues might have either little or no effect from the perspective of design. This relationship can be categorizes into two broad relationship functions: direct and indirect functions. Direct function is the relationship that design parameters can be directly assigned to production activities while indirect function is usually related to production activities, which are less subjected to change with design parameters. This distinction often appears in production cost evaluations literatures (Dieter 1983, 2000; Matthews 1983). The production cost is generally separated into direct cost and indirect cost or more widely used as fixed and variable costs. Since DFP measures the manufacturing productivity through its production cost, the distinction between product design and production issues prevents some production issues from being over-emphasized during the product design phase.

This study considers four design parameters: product dimension, design tolerance, material selection, and design concept.

To assure the optimal product design from a DFP standpoint, general Design for Manufacturing (DFM) guidelines, can be applied before DFP. The following is a list of design guidelines developed through the author's experience while some are adopted from Trucks (1987) and Dieter (2000).

1. **Seek design simplicity**: Design for maximum simplicity in functional and physical characteristics.

2. **Minimize production steps**: Design for the minimum number of separate operations in machining, finishing, forming, molding, casting, fabrication, assembly and so on.

3. **Eliminate fixturing and handling problems**: Design for ease of location, setting up and holding parts.

4. **Employ maximum acceptable tolerances and finishes**: Specify surface roughness and accuracy no greater than that, which is commensurate with the type of part or mechanism being designed and production methods.

5. **Automate the production system**: Design for highly automated production system reduces the overall product throughput time.

6. **Minimize the total number of parts**: Eliminating parts resulting in less material used, storage, handling, and assembly complexity.

7. **Minimize inventory**: Eliminating parts' buffer or material in inventory greatly reduces the inventory cost, handling, and storage area.

8. **Synchronize with suppliers and customers**: Ensure the production to run smoothly without delay and with product availability, by establishing mutually beneficial relationships with suppliers and customers.

9. **Minimize redesign cycle**: Design by minimizing the cycle of redesign can reduce significantly design cost and product development time.

The above guidelines are qualitative in nature. However, they all point to the direction of overall production cost reduction. The developed DFP in fact endeavors to turn these guidelines into quantifiable terms and integrate these terms in the cost analysis and optimization. The following sections will discuss different design parameters and their relationship with various production issues. Various approaches will be proposed to build quantitative relationship between design parameters and production cost elements, based on which the optimization becomes possible.

3.4.1 Design Parameters

The chosen design parameters are the factors that affect production costs. To identify the relationship between design parameters and production issues can provide engineers with detail information for making decision in product design to achieve a low-cost production strategy. The chosen four types of design parameters are as follows.

1. **Product Dimension & Shape** – The product dimension determines the size, angle, length, width, height, depth, diameter, volume, and weight of the product. Some dimension related parameters may include the length to depth ratio, diameter to depth ratio or length to thickness ratio. Basic shape elements include

hole, square, round, fillet and so on. Another important aspect is the assemblability of product. The changes made to the component shape, dimension and size might affect the order of assembly sequence and tools used for joining the components together. The product volume and weight often determine the amount of raw material used to make the product. The volume of material is directly related to the size of product. Often the size affects the manufacturing operation time, such as the machining time, and setup time as well. If the product is made by molding, the cost of the mold may vary according to the product dimension.

2. **Design Tolerance** – In general, design tolerance involves the fitting and mating between two parts. Two common types are cylindrical fits for shaft and hole, and location fits for mating parts. The manufacturing cost and design tolerance are often exponentially associated, in which cost will increase for tighter tolerance design (Trucks 1987). It is also related to quality control where inspection and testing are carried out to make sure the product meets the standard set by ISO. Besides, this parameter is important to assembly of components especially for cylinder and shaft that require tight tolerance. Some products might require shrink fit or force fit. This is also important to process planning because each individual machine has a machine tolerance range. So, for product designs that require tight tolerance, engineers have to determine the capability of the machine in order to produce the intended tolerance. Worth considering is the operator's skill and experience. The surface finish is also influenced by the tolerance in which the tolerance often determines whether a finishing process is required or

not. The finishing process often includes sanding, polishing, deburring, painting, and so on. The extra process will increase the time and cost.

3. **Material Selection** – The material selection is often based on the product mechanical properties and its costs. The mechanical properties are normally the focus such as tensile strength, elongation, ductility, hardness, heat treatable, grain size and so on. It is possible that by selecting a different material, cost can be reduced while the product functionality is still met. This parameter can change the process planning where new equipment or fixtures might be needed to operate on the new material. Operator training is sometimes required for different materials.

4. **Design Concept** – The design concept consists of the mix of the product dimension, shape, tolerance, and material selection. The concept change might result in the change of the entire production line.

3.4.2 Relationships To Production Issues

Some study has been done on developing the relationships between the design attributes/parameters to production system attributes (Soundar 1994, Izuchukwu(a),(b) 1991, Thurston 1993). Throughout the manufacturing system, DFP considers a wide range of production issues that either directly or indirectly related to the designed product. To avoid confusion with the word of "direct" or "indirect" relationship with the description in Table 3.1, we set the priority of considerations to the production issues by using a strong or weak relationship. A strong relationship is based on the level of importance for the most critical cost elements that are affected by design parameters.

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Those elements include material, machine, fixture, and labor costs. A weak relationship exists between design parameters and the rest of cost elements, including space, tied, incentives, and contract costs. Other production issues such as scheduling, safety, serviceability, and ergonomics should not be neglected but can be considered depending on the specific product requirements. These weak relationships are often out of the control of designer too since they are mainly production oriented issues. However, in this thesis, 8 production issues will be considered as described in the OBC model.

3.4.2.1 Strong Design To Production Relationship

For the four main production issues listed in Table 3.1, machine, material, operator and fixture, their relationships with design parameters may be established using parametric equations. By forming a mathematical formula, most of their attributes can be directly related to the design parameters. The indirect relationships, however, are ones that cannot directly relate to design parameters through parametric equation. In this situation, the relationship can benefit from knowledge-based, case-based reasoning or other similar approaches as mentioned in Section 2.3. One example is machine attributes; the machine envelope has a direct relationship to product dimension in which the product size is bound by maximum allowable dimensions for that particular machine to handle. For example, in a water-can manufacturing plant, if the maximum width for a sheet metal plate to go through an extrusion machine is one foot, the maximum allowable product height for the process of rolling the sheet and welding the edge together should be at least one foot. In this case, the height of cans could also be less than one foot. On the other hand, the relationship between the shape complexity level and the machine's process

capability cannot be easily established using parametric relationship. It is mostly based on the experience of manufacturing engineers to consider the product's machinability.

Thus, knowledge-based techniques based on certain design rules or logical attributes may capture this type of relationship effectively. The advantage of a knowledge-based system is to provide engineers with manufacturing process and planning solutions without complicated mathematical equations. The listed Table 3.1 is intended to form a general qualitative guideline on developing the relationship of product design and production.

Table 3.1 Relationships Between Product Design and Production Issues

Production Issues	Attributes	Relationship	Product Design Parameters	Comments
Machine (Drilling, Turning, Milling, Grinding, Extrusion, Stamping, Forming, Forging, Casting, Powder Metallurgy)	Machine Envelope	Direct	Dimension	
	Tolerance Range	Direct	Tolerance	
	Life Span	-	N/A	- life of machine, depreciation
	Machine Accuracy	Indirect	Tolerance, Material, Shape	
	Surface Finish	Direct	Tolerance, Material, Shape	
	Shape Complexity Level	Indirect	Dimension, Shape	
	Working Condition	-	N/A	- hot or cold material, force
	Speed, Feed Rate	Indirect	Tolerance, Material, Shape	
	Extra Processing	-	N/A	- surface finish process
	Operation Time	Direct	Dimension, Shape, Tolerance, Material	
	Setup Time	Direct	Dimension, Shape, Tolerance	
Material (Metals, Ceramics, Polymers, Woods, Composites)	Mechanical Properties	Direct	Material	
	Thermal Properties	Direct	Material	
	Electrical Properties	Direct	Material	
	Raw Material Shape	Direct	Dimension, Shape	
	Scrap	-	N/A	- material leftover
	Availability	Indirect	Material	
	Weldability	Indirect	Material	
	Machinability	Indirect	Material	
	Physical State	Indirect	Material	
	Service Environment	Indirect	Material	
Operator (Working on machines & tools)	Operator Skill	Indirect	Tolerance, Shape	
	Available Working Time	-	N/A	- total worker time
	Operation Time	Direct	Dimension, Shape, Tolerance, Material	
	Support Benefit	-	N/A	
Tools (Die, Mold, Pattern, Jigs, Fixtures)	Maximum Size	Direct	Dimension, Tolerance, Material, Shape	
	Tool Storage	-	N/A	- inventory for tools
	Life Span	-	N/A	- tools life depend on part quantity
	Shape Complexity Level	Indirect	Dimension, Shape, Tolerance	
	Material Used	Indirect	Material	
	Setup Time	Direct	Dimension, Tolerance, Material, Shape	
	Wall Thickness	Direct	Dimension, Shape	
	Lead Time	Direct	Dimension, Shape, Tolerance, Material	
	Tooling Cost	Direct	Dimension, Shape, Tolerance, Material	
	Tool Tolerance & Accuracy	Direct	Tolerance, Material, Shape	
	Weight	Direct	Dimension	
	Flexibility	-	N/A	- depend on tools design capability
	Surface Finish	Indirect	Tolerance, Material, Shape	
	Extra Processing	-	N/A	- surface finish process

Identifying the relationships described above can provide designers with insight to construct the design for production optimization model. The four cost elements in the

model are parametrically related with the solid model parameters in a CAD environment. Although relationships exist between design features and production issues, the interrelationship among the design parameters may further make both parametric and logistic relationship become more complex. For example, machine attributes are not just related to design parameters alone but also the attributes of material, labor, and tools. Note that this thesis may not provide every parametric equation associated with production issues for all the manufacturing processes. One example of a parametric equation that shows this interrelationship is documented by Ben-Arieh (2000) for total cost TC of machining process is as below:

$$TC = C_{RM} + \sum_{i-1}^{T} nC_{t_i}.T_{t_i} + C_{mc}.T_{mc} + \left(\sum_{i=1}^{S_n} T_s + \sum_{i=1}^{t_n} T_c \right).C_m$$

where

C_{RM}	is the raw material cost,
C_{ti}	is the cost of using tools i (per time unit),
T_{ti}	is the time of using tool i,
C_{mc}	is the total machining cost per unit time (includes operator and overhead costs),
T_{mc}	is the machining time,
C_m	is the machine idle time cost per unit time (includes operator and overhead costs),
T_t	is the machine idle time due to a tool change,
T_s	is the machine idle time due to setup of work piece,
s_n	is the number of setups required,
t_n	is the number of tool changes required.

The subset of the equation can further breakdown into subcategory function that can associate with design parameters. Table 3.2 listed some commonly used parametric equations that are applicable to many design-to-production relationships.

Table 3.2 Common Parametric Relationship

General Parametric Equation	Example of Equation
Linear Relationship	$f(x) = ax + b$
Exponential Relationship	$f(x) = ae^{bx} + c$
Polynomial Relationship ($2^{nd} - n^{th}$ order)	$f(x) = ax^n + bx^{n-1} \dots + cx + d$
Power Relationship	$f(x) = ax^b + c$
Logarithmic Relationship	$f(x) = Log_a x + c$
Trigonometric Relationship	$f(x) = aSin(x) + bCos(x)$
Combined Relationship	Linear & Exponential
$a,b,c,d = constant; n=integer$	

For example, the material cost C_{RM} is related to the volume or dimensions of the product. The simple linear equation can be formed such as below:

$$C_{RM} = M_C \times M_D \times PD$$

where

M_C is material unit cost (\$/kg)
M_D is material density (kg/m^3)
PD is product designed volume (m^3)

The machining time T_{mc} on the other hand is function of length, design tolerance, and shape. Similarly, labor and tool costs also can be associated with the design parameters depending on product specifications and manufacturing requirements. Sometimes, the data collected are a set of points or values. In this case, the data are curve fitted using the linear regression method in order to obtain the parametric equation. For further illustration of these relationships between product design parameters and production cost, one can refer to the applications in Chapter 4 and 5.

3.4.2.2 Weak Design To Production Relationship

The space, contract, incentives, and tied costs are mostly concerned with production activities; they bear weak relationships with product design. There are quantities based on certain manufacturing activities such as plant utilities expenses, make/buy, inventory layout, etc. as provided in Section 3.3. These production issues are commonly listed under the "overhead cost" in the traditional costing approach.

1. Space Cost: Normally the change of the design parameters will cause little variation on the space cost. The plant layout and scheduling issues are partly contributing the space cost too, which is assumed working in ideal condition. But sometimes, installing new machine or producing a custom made product of enormous size will affect the space area. Such an effect will require knowledge in facilities planning to plan for optimum handling and scheduling procedures. This cost element is basically a fixed cost in the manufacturing overhead.

2. Contract, Incentives, Tied Cost: The Incentive and Tied costs are independent to product design. The incentives or penalties are more related to the aspects of suppliers and customers. It is one of the production considerations that mutually beneficial relationship can improve production efficiency. Tied cost mainly depends on the inventory storage level. The Contract cost, however, is related to the quantity of production and the design concept. The change in product components such as standard parts might affect the buy or make decision, thus affect the contract cost. Besides, this quantity of production, change of product shape, dimension, and concept might influence the shipping costs, which is obviously one example of the contract costs.

3.5 Design Optimization

Among many optimization algorithms (Chong 1996), this study chose Adaptive Response Surface Method (ARSM) as the optimization algorithm, originally developed by Wang (Wang et al. 2001, Wang 2002). It is one of the meta-modeling based design optimization algorithms rooted in the response surface method, a systematic Design of Experiment (DOE) approach. Meta-modeling based optimization methods are developed to solve optimization problems with computation-intensive function evaluations. As one of the meta-modeling based optimization algorithms, the benefits of ARSM over many conventional analytical optimization approaches such as Newton Raphson's and Broyden-Fletcher-Goldfarb-Shanno (BFGS) methods are manifold, including

1) This approach tends to solve for global optimum which avoid being trapped in local optimum,

2) It is applicable to any complicated design functions since no function derivation is involved,

3) Its solution does not depend on the initial design variable input,

4) It reduces computation cost for expensive computer simulation and analysis problems by supporting parallel computation and

5) It is designed to solve a computation intensive design problem that normally requires a large amount of computation memory and iterations.

Adaptive Response Surface Method

Initial Conditions

| Design Variables | Design Objectives & Constraints | Initial Design Space |

Generation of Experimental Designs

Call → Function Evaluation ·······→ Design Library

Function Values → Model Fitting

Global Optimization

Computation -intensive Analysis & Simulation

Call → Function Evaluation at the Optimum

Function Values → Design Space Reduction

Design Criteria Satisfied?   N →

Inherit the optimum if Fall in The New Design Space

Inherit Designs that Fall in the New Design Space

Generate New LHDs if not Saturated

↓ Y

STOP

Figure 3.4 Diagram shows procedure of ARSM algorithm (Wang 2002)

In the ARSM as shown in Figure 3.4 above, a function evaluation is treated as a computer "experiment." The constructed model from computer experiments is called response surface model, or surrogates. The ARSM employs the second order polynomial function as the response surface model and the Latin Hypercube Designs (LHD) for planning experimental designs or points. The LHD points essentially form a stratified random sample set to estimate the output. The algorithm of ARSM takes the design variables,

objective function, constraints, initial design space or design variable range, as well as experimental points to fit a response surface model using the least square method. Then a global optimization method called simulated annealing is carried out to find the design optimum. The resultant original design space is systematically reduced and few more points are added to the new design space, in which a new surrogate is generated. This process iterates until the algorithm converges or a satisfactory design optimum is obtained.

The ARSM has been tested with widely used test problems. This method converges to the global optimum or near global optimum with a relatively small number of function evaluations (Wang et al. 2001, Wang 2002). Since the ARSM starts with planned "samples" (different design points with their respective function values), those samples can be obtained in parallel and simultaneously. For example, if an optimization process needs 1000 function evaluations to get the global optimum and each function evaluations takes 2 hours, a conventional sequential optimization process will need 2000 hours at least. For the ARSM, if the optimization takes about 50 iterations and each iteration needs 20 points to fit the surrogate, assuming those 20 points can be computed in parallel, then the total time the ARSM requires is only 100 hours (50*2 hours). From this perspective, the ARSM can obtain the solution more efficiently because the samples at each iteration are independent to each other. Moreover, due to the independency, various analytical and simulation tools can be distributed to different workstations and be used to perform the analysis on the same product design simultaneously, only the analysis results are needed by the optimizer, with no need to integrate various tools for the optimization purpose. The integration of tools has been found to be a very different and

costly activity by many large companies, because those tools are developed by different vendors with different standards, conventions, intellectual property protection barriers, and so on. The use of the ARSM can overcome the integration difficulty and make the tools work together for the optimization purpose. The proposed DFP strategy needs to integrate the cost concern with other performance perspectives. It will most likely need to integrate various tools such as FEA and CFD for performance evaluation. Computation cost and tool integration are two major concerns for the implementation of the proposed DFP. The ARSM can satisfactorily overcome these two difficulties and thus it is believed that the ARSM, or other meta-modeling based optimization algorithms, should be an integral ingredient for the DFP as its optimization tool. From the industrial applications of the proposed DFP method in later chapters, the optimization efficiency and effectiveness by using the ARSM will be further demonstrated. In the proposed DFP, the ARSM algorithm is embedded within the OBC cost model and the CAD solid modeling tool as shown in Figure 3.5 below.
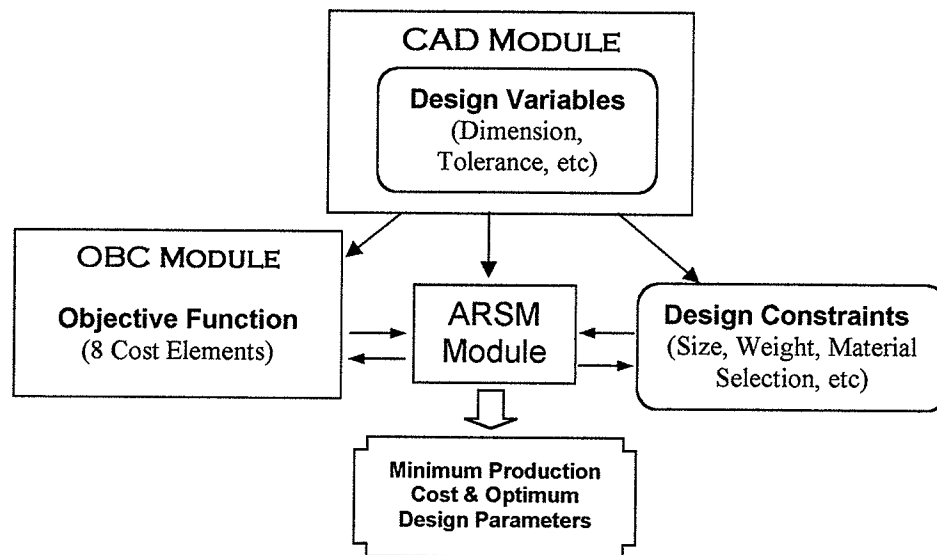
Figure 3.5 Interaction of ARSM with OBC and CAD Modules

The design parameters in the solid model are extracted to fit the surrogate in the ASRM. Since the cost is the design objective, the OBC model is considered as an objective function. The constraints can be either from product design or from the imposed interrelated production activities. The product constraints are the design parameters that deal with functionality and performance such as dimension, size, tolerance, shape, weight, and material properties. The production activities' constraints are mainly those indirect functions depicted in Table 3.1 such as shape complexity level, extra processing and tool storage attributes. This indirect relationship is considered as weak constraints since its parameters are less sensitive to the change of design variables. A knowledge-based system is embedded in the OBC model in which best selections of operations or raw material used depends on design variables as well as other design requirements. During the execution of the ARSM, the objective functions and constraints are simultaneously being evaluated iteratively in order to obtain the optimum output. The constraints are used in the model to control the output result that if any constraints are failed, the penalty function in the model will give an invalid result to the user. The outputs of the ARSM are the minimum production cost and the optimum design parameters, which are sent back to update the CAD model. This process is automatically carried out after all the design requirements are entered to the program. Further explanation of design automation will be discussed in Chapter 6.

3.6 Summary

As a conclusion to this chapter, a clear definition of boundary between product design and production issues can help design engineers to focus on the related production issues

that are impacted by design changes. The design parameters provided can be associated with the OBC model in order to quantify the production cost. The strong design-to-production relationships are developed through parametric and knowledge-based approach for taking account of the complicated manufacturing activities. Change of design parameters causes little variations on the production costs through only the weak design-to-production relationships. The ARSM is introduced into both CAD and OBC module in order to optimize the designed product with minimum production cost. Therefore, the productivity of the manufacturing systems can be identified by examining each operation cost from the associated production activities. DFP methodology in general provides ease of production for today's engineering production system.

Chapter 4 Optimal Design of Industrial Silencer

4.1 Introduction

This industrial silencer case study is an extension of the research carried forward from the thesis project originated by Charles Friesen (Friesen, 2001). The COWL silencer is a product of Phillips and Temro Industries, a manufacturer of exhaust gas silencers. The silencers are used primarily on diesel engines in the marine, generator, construction vehicle, and military vehicle industries. About 40% of the silencer products need to be customized to meet the broad application requirements. The production of a custom silencer normally requires a minimum of one day to create the manufacturing drawings and the relevant MRP information. In addition, the customer must approve the initial drawings before they are sent to the production plant in order to successfully create the COWL unit. The time for this design process varies from a couple of days to a week to complete, depending on the level of customization and the complexity of the customer's design. For this reason, a new design approach is required to speed up the design process as proposed by the DFP methodology. The following diagram depicts an example of a commercial silencer product.
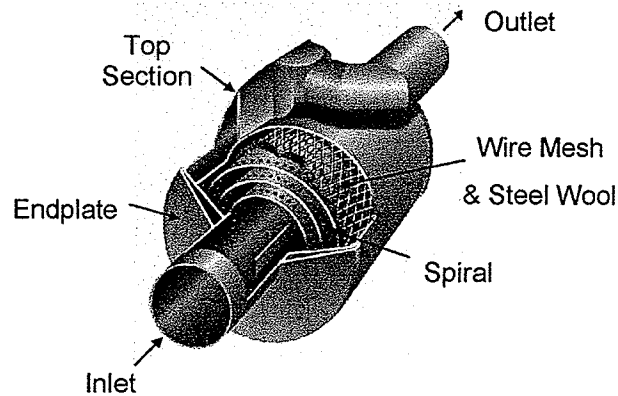
Figure 4.1 Commercial COWL Silencer

The components of the silencer include the spiral section, inlet and outlet tubes, endplates, and top plate section. The wire mesh is welded to the spiral section in order to sandwich the steel wool within the spiral gap. These sound-damping materials provide the silencer with a sound-damping level of between 20 to 40 decibels. The final product is the silencer, which becomes a passive sound-damping device. The existing design has 9 configuration models: PL, PR, PV, PT, TR, TL, SL, SR, and SV as shown in Appendix B. While the most common silencer configuration contains only one inlet and one outlet, some may have two inlets and outlets. For the first letter designation of the models, "P" signifies that the inlet and outlet are perpendicular to each other, "T" signifies that the inlet and outlet are parallel to each other, and "S" signifies that there is no outlet, meaning that the gases enter the atmosphere directly from the spiral section. For the second designated letter, "L" indicates that the inlet is on the left side of the silencer, "R" implies an inlet on the right side, "V" implies both sides, and "T" signifies that the outlet section is exits through the top section. The inlet tube is mounted on the exhaust of the various engines. The exhaust gas from the engine is channeled through the inlet tube, circulates within the spiral section, and then passes out through the outlet tube. In

addition to the choice of configuration, the silencer dimensions and materials can also be customized to fit the functional requirements of the design.

4.2 Proposed Design

The proposed new silencer differs from the original in the design of the top section and the endplates. The figure below shows the solid modeling of a "PV" model silencer. This design change is expected to save manufacturing time and use less material and with less shape complexity. The assumption to this new design is that it is considered manufacturable given the existing manufacturing facilities.
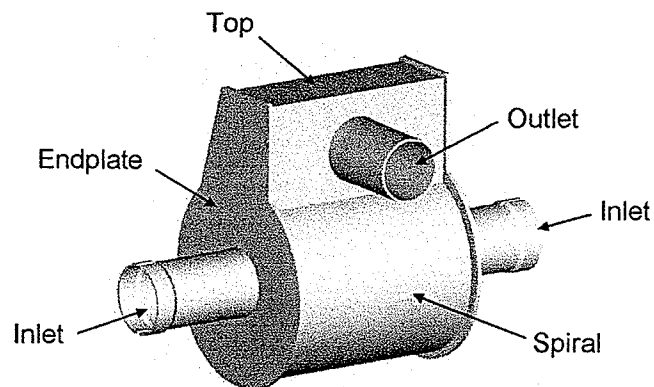
Figure 4.2 New Silencer Design (Friesen, 2001)

Depending on the design model, the inlets and outlets can be attached in a number of ways, with or without the top section. The customer specifications include the flow direction, either standard or reverse flow. For reverse flow, the inlets and outlets are interchanged. In this configuration, the exhaust gases enter the top piece and flow into the center of the spiral. In addition, the silencer can be produced using either stainless

steel or an aluminized steel material, and the product can be either powder coated, or painted silver or black in the painting process. The ultimate working environment of the silencer will determine the selection of the material and paint. For example, in the marine environment, a stainless steel silencer may be chosen for its resistance to corrosion. Each model of silencer can be ordered in a number of sizes. This project will use the COWL catalogue data, with inlet and outlet diameters ranging from 1.5" to a maximum of 12". The overall silencer sizes are determined by the available space of the installation site. The design must produce an allowable gas flow rate and back pressure from the silencer, while satisfying its damping function.

4.3 COWL Program Development

4.3.1 Design Parameters

The COWL program is developed based on the proposed DFP methodology. The design parameters and their relationship to production activities are the first to be identified. In addition, the COWL solid model is constructed using the Pro/Engineer 2000i interface. Then the manufacturing and operation information are gathered and entered into the OBC model. These relationships are then linked to the Pro/Engineer model and an optimization algorithm is carried out to search for the minimum production cost.
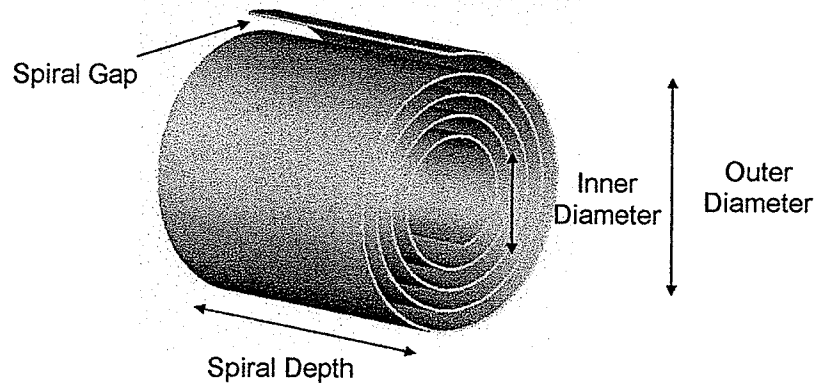
Figure 4.3 Spiral Section (Friesen, 2001)

For the optimization of the silencer, the design parameters of spiral section shown in Figure 4.3 contributes the overall noise damping effect and thus the following variables are optimized:

- Spiral Outer Diameter

- Spiral Gap

- Spiral Depth

As these three variables change, the production cost for each silencer component is modified accordingly. These spiral dimensions are the design parameters, which is directly related to the following production activities:

- Raw Material Used

- Paint Material Used

- Operation and Welding Time

4.3.2 Operation-based Model

The COWL OBC model is shown in Appendix B. The model is constructed based on the manufacturing information gathered and is manually inputted into the 8 cost element tables. The silencer is manufactured using metal plate and long pipe as the raw materials. The major operations involved are stamping, bending, cutting, and rolling. The amount of raw material used will be based on the overall volume of the silencer. Normally, the material purchased is in unit cost/weight, and the silencer volume is linearly formulated by providing the material density. The paint material is dependent on the silencer size, as the surface area is linearly related to the estimated paint cost/unit area. The operation time is based on the size of the silencer, particularly the spiral section. Since the spiral is made using a rolling operation, which transforms a rectangular sheet into a spiral form, the larger designs require more turns and thus increase the operation time. In a similar way, the welding time is dependent on the amount of joint section. The weld length is dependent on the size, which is proportional to the welding time. Both the welding and roll operation time will affect the number of labor hours in the OBC model.

4.3.3 Relationship of Design to Production

The following figure depicts an intermediate data exchange worksheet between the Pro/Engineer model and the OBC model. The number ① shows the information retrieved from the Pro/Engineer model. It consists of the three design variables, silencer area, and welding time. These values are linearly formulated with the material table in area ②. This table consists of the material type, paint and wool material selections. The

relationships are linked to cost elements in the OBC model. Within the model, Excel

macro carries out the cost calculations and gives the unit production cost.

Figure 4.4 Data Exchange Table
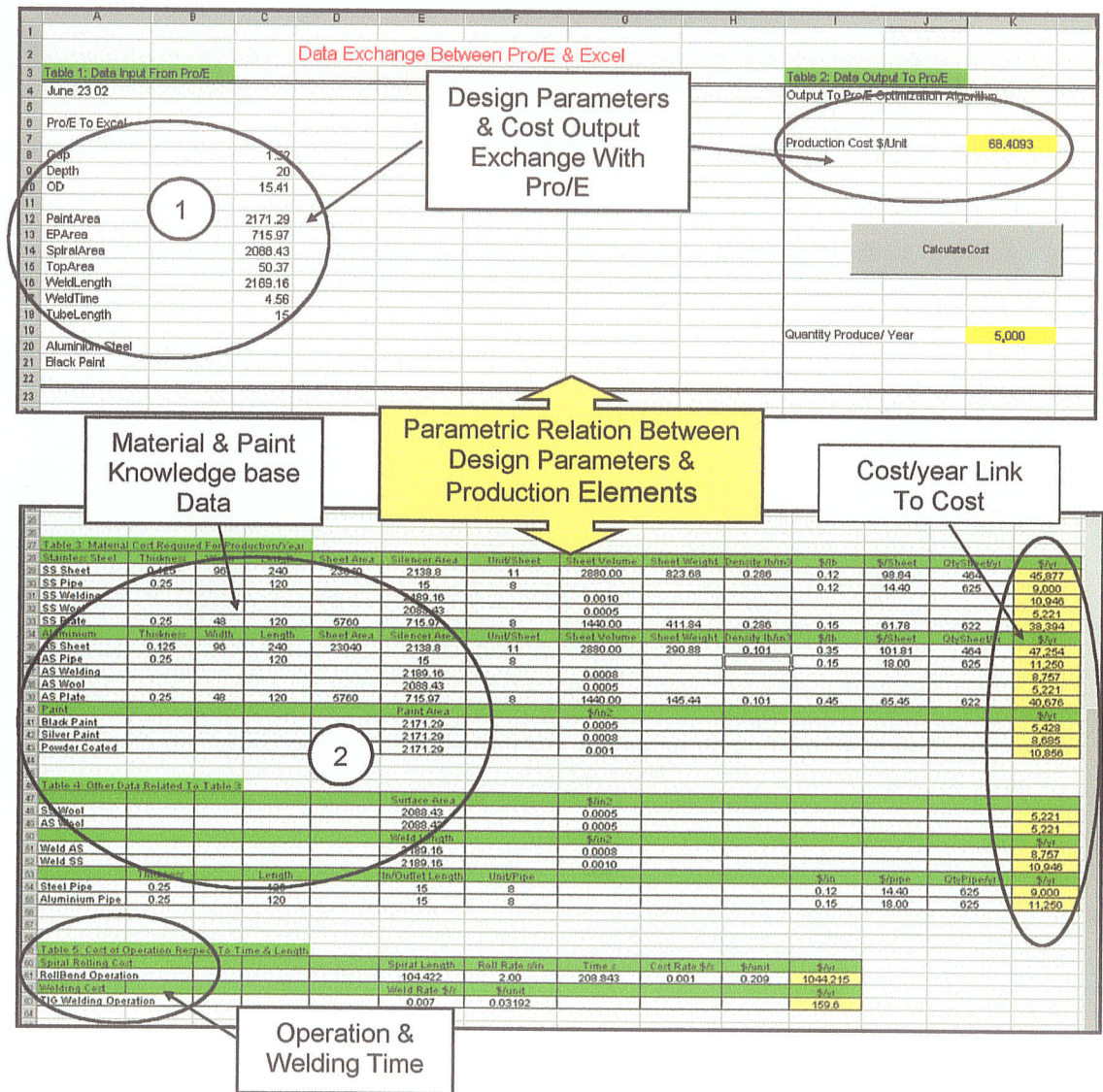
From area ②, the relationships of silencer components and material costs are formed

through a series of parametric equations as shown in Table 4.1. The other dimensions

used in the equations such as *gap*, *ephc*, *epdia*, *eptop*, *ol*, and *il* are directly extracted

from the silencer model.

Table 4.1 COWL Parametric Relationship Table

Silencer Area (in^2)	Parametric Equation
Spiral	$SA = \left[\pi \left(\dfrac{od}{2} \right)^2 - \pi \left(\dfrac{id}{2} \right)^2 \right] \times \left(\dfrac{depth}{gap} \right)$
Top	$TA = 2.35 \left(ephfc - 0.25 - \dfrac{od}{2.5} + gap \right) + eptop + depth$
Endplate (Both Side)	$EA = 2 \left(epdia * \left(\dfrac{epdia}{2} + ephfc \right) \right)$
Tube Length (in)	$TL = ol + il$
Operation Time (s)	
Welding	$WT = \dfrac{wl}{avgrate}$
Rolling (Spiral)	$RT = \dfrac{sl}{avgrate}$

where   *od*   spiral outer diameter
          id   spiral inner diameter
          depth   spiral depth
          gap   spiral gap
          ephc   endplate height from center of endplate axis
          epdia   endplate diameter
          eptop   endplate top section distance
          ol   outlet tube length
          il   inlet tube length
          wl   welding length of joint section
          sl   spiral length before coiling
          avgrate average rate of operation (in/s)

These parametric equations calculate the amount of material used for each silencer components. Then the costs of sheet metal that is required for forming the related silencer components are as follow.

$$Material\, Cost = sarea * t * density * unitprice$$

where   *density*   density of sheet metal (lb/in^3)
          unitprice   price of sheet metal per weight ($/lb)
          t   material thickness (in)
          sarea   silencer component area (in^2)

In addition, the welding and paint material costs are obtained by multiplying the overall silencer area with these material unit costs. The labor cost (operator cost) of welding and rolling operations in Table 4.1 is

$$Operator\,\mathrm{Cost} = opertime * \mathrm{cost}$$

where *cost*   cost of operation per unit time ($/s)
         opertime   time of rolling/welding operations (s)

Ultimately, both material and labor costs are dynamically updated during program execution to change the model's material and operator elements. The other design parameters that are indirectly related to the production activities are the raw material selection, paint material selection and wool material selection. Stainless steel or aluminized steel materials are used for wool and silencer structures, silver, black or powder coated paint material. These material types are selected based on the silencer operation environment, which is less likely to be able determined by scaling methods. Thus, simple knowledge-based material selection is integrated to accommodate these design functions.

Table 4.2 Knowledge-based Material Selection Table

Table 3: Material Cost Required For Production/Year														
Stainless Steel	Thickness	Width	Length	Sheet Area	Silencer Area	Unit/Sheet	Sheet Volume	Sheet Weight	Density lb/in3	$/lb	$/Sheet	QtySheet/yr	$/yr
SS Sheet	0.125	96	240	23040	2138.8	11	2880.00	823.68	0.286	0.12	98.84	464	45,877
SS Pipe	0.25		120		15	8				0.12	14.40	625	9,000
SS Welding					2189.16			0.0010					10,946
SS Wool					2088.43			0.0005					5,221
SS Plate	0.25	48	120	5760	715.97	8	1440.00	411.84	0.286	0.15	61.78	622	38,394
Aluminum	Thickness	Width	Length	Sheet Area	Silencer Area	Unit/Sheet	Sheet Volume	Sheet Weight	Density lb/in3	$/lb	$/Sheet	QtySheet/yr	$/yr
AS Sheet	0.125	96	240	23040	2138.8	11	2880.00	290.88	0.101	0.35	101.81	464	47,254
AS Pipe	0.25		120		15	8				0.15	18.00	625	11,250
AS Welding					2189.16			0.0008					8,757
AS Wool					2088.43			0.0005					5,221
AS Plate	0.25	48	120	5760	715.97	8	1440.00	145.44	0.101	0.45	65.45	622	40,676
Paint					Paint Area		$/in2						$/yr
Black Paint					2171.29		0.0005						5,428
Silver Paint					2171.29		0.0008						8,685
Powder Coated					2171.29		0.001						10,856

The raw material and paint material used for the COWL production is shown in Table 4.2 as a knowledge-based format. Either stainless steel or aluminum based material can be chosen by integrating "if" statement in the macro. Similarly, paint material: black paint, silver paint, and powder coated can be chosen according to the input from data exchange table in Figure 4.4.

4.3.4 Design Optimization

4.3.4.1 Objective Function

Minimizing the production cost of the silencer is the main objective of the design. The total cost is calculated by determining the cost elements of the operations, as discussed in Chapter 3. The program sets the OBC model as the objective function. The return value from the objective function is the production cost. With the proper design variables and constraint inputs, this model will produce the minimum production cost.

4.3.4.2 Subjected Constraints

a) Maximum Size

The first constraint is the maximum size of the silencer. This refers to the silencer's overall width, depth, and height. This size constraint is imposed by the installation space available for the silencer to be fit in. If any of these dimensions is violated, a trigger is set within the constraint function. The purpose of the trigger will be discussed later.

b) Sound-Damping Performance

The sound-damping performance of the silencer is a constraint with respect to the silencer surface area. This is to ensure that the design silencer meets the sound-damping criteria. It would be ideal if a CFD model can be constructed to simulate the damping effect. However, it is a rather complex problem and is out of the scope of this research. Therefore, it is assumed that the larger the spiral surface area, the better is the damping effect. The COWL catalogue contains the dimension information for calculating the surface area. This value can be plotted according to the inlet diameter as shown in the figure below. With respect to the new design, the assumption is made that the designed surface area should be larger than the current catalogue data for a given inlet diameter.

Figure 4.5 Required Spiral Surface Area Function
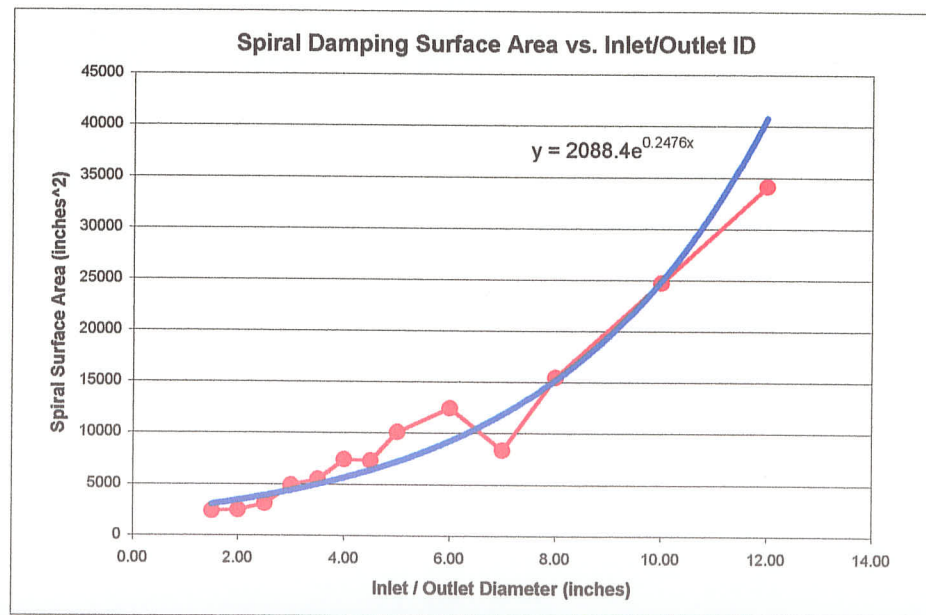
The trend line shown in red is derived from COWL catalogue data, and is exponentially fit to the blue curve. This equation is used to calculate the catalogue spiral's surface area

based on the desired inlet diameter input. Therefore, the sound damping performance constraint should satisfy the following equation:

$$Design\ Surface\ Area \geq Graph\ Function\ f(x)$$

When this constraint is violated, a trigger is set in the constraint function.

c) Maximum Back Pressure Performance

The designed silencer must meet the performance requirements specified by the customer. Customer inputs include gas flow rate, operating temperature, and the maximum allowable back pressure. The exhaust gas back pressure produced in the design silencer should be lower than that specified by the customer. This relationship is shown in the following two equations:

$$Current\ Velocity = \frac{Volumetric\ Flow\ Rate}{Cross\ Sectional\ Area\ of\ Exhaust\ Gas\ Flow}$$

$$Maximum\ Velocity = Velocity\ (Backpressure) * Exhaust\ Gas\ Temperature\ Correction$$

The "Current Velocity" is based on the flow rate entered by the user and the cross sectional area the exhaust gases flow through in the spiral gap. The "Maximum Velocity" is determined from the velocity function shown in the figure below, and the gas temperature correction. The figure plots the relationship between the exhaust gas velocity at 900°F and the back pressure in the silencer. The red trend line is determined using performance data from the COWL catalogue. The blue curve is formed using the

fitted line equation that will be used in the constraint function. Figure 4.7 depicts the equation that determines the temperature correction factor for silencer temperatures other than 900°F.

$$Current \quad Velocity \leq Maximum \quad Velocity$$

The constraint function of the back pressure performance shows that if it is violated, a trigger is set.

Figure 4.6 Velocity Trend Line Function
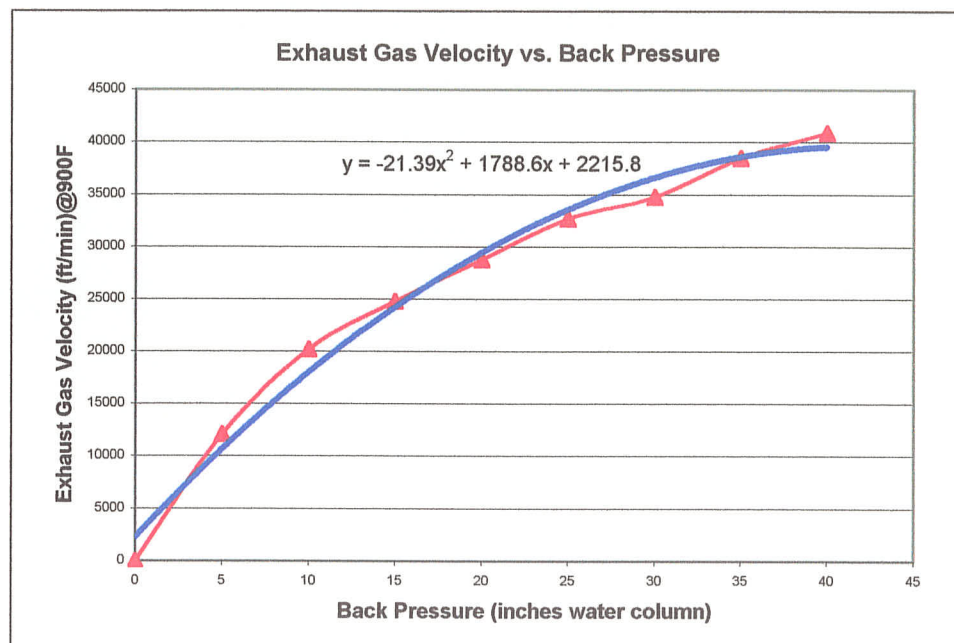
Figure 4.7 Temperature Correction Function

Temperature Correction Graph

$y = -1.22E\text{-}09x^3 + 3.56E\text{-}06x^2 - 4.12E\text{-}03x + 2.74E\text{+}00$
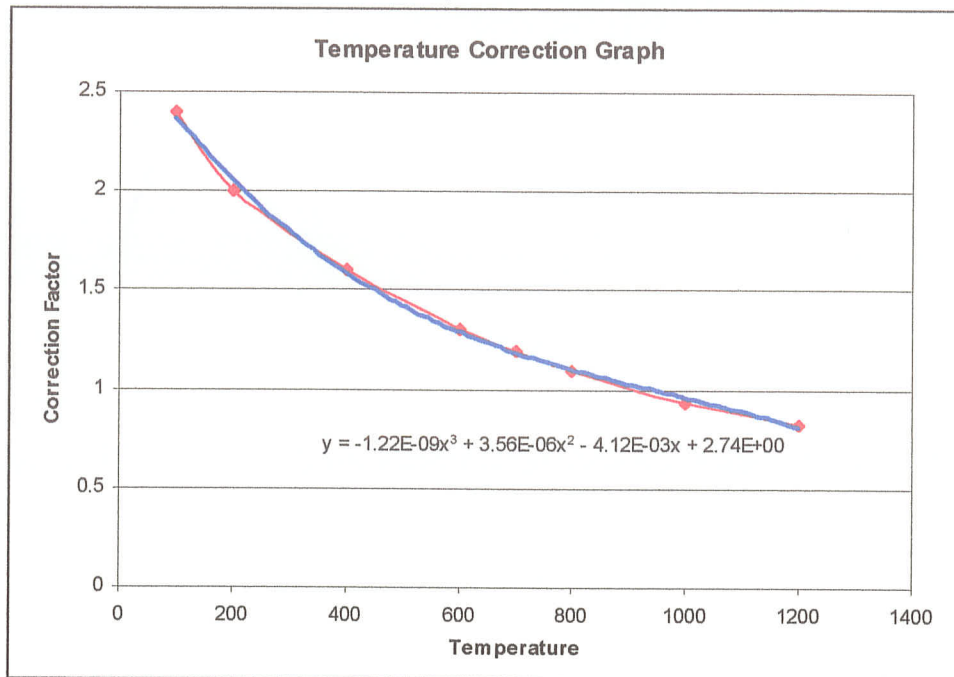
4.3.4.3 Final Optimization Function

The final optimization function is based on the penalty method, which is in the form:

$$Total\ Production\ Cost = Total\ Cost + 1x10^8 * (constraint\ function)$$

where the *constraint function* is a function of the size, damping surface area, and back pressure performances. If any of the triggers in the constraint function is set, the *Total Production Cost* will increase significantly due to the penalty value of $1x10^8$. Thus, invalid results are obtained. In summary, the optimization model can be formulated as below:

$$\min_{w.r.t.\ \bar{x}} \quad cost(\bar{x}) \quad \bar{x} = od, depth, gap$$

subject to

Spiral surface area $\geq$ Graph Area Function

Current exhaust velocity $\leq$ Maximum velocity

Overall size $\leq$ Maximum Given space

$$x_i \in [x_{l,i}, x_{u,i}], \quad i = 1, 2, 3$$

where, $x_{l,i}$ and $x_{u,i}$ are lower and upper bounds for each design variable, respectively.

4.4 COWL Program

The silencer design program is called "COWL". This program is basically developed using the C language. The silencer model is in the Pro/Engineer environment, where the Pro/Engineer programmatic tool, Pro/Toolkit, is used to extract and control the solid model display. The c programming reads the dimensions and material parameters in the Pro/Engineer database, and then sends information to the OBC and ARSM models. Within the OBC model, these parameters are used to calculate the amount of material used, the type of material used, and the operation time based on length. ARSM then carries out the optimization procedure by utilizing the OBC model to determine the minimum cost. The design constraints are simultaneously checked to ensure that the design is satisfactory. Figure 4.8 depicts the Pro/Engineer design environment and the main menu created through Pro/Toolkit. In Figure 4.9, the main menu provides the user with many design parameters inputs and modification options for the silencer. The menu sequence is as follows:

1. Silencer Configuration: When the program starts, the Pro/Engineer window is blank. The user can select the desired model, inlet/outlet diameters, and type of flow.

2. Set Silencer Option: This menu allows the user to select the material and paint types for the OBC to calculate the total cost. Maximum silencer size (height, width, depth) and silencer performance parameters (maximum back pressure, required flow rate, temperature) are manually entered for used by the constraint functions.

3. Show: The model is displayed after the data is entered from steps 1 and 2. Figure 4.8 shows this model.

4. Modify: This menu allows the user to modify the design parameters and change the overall silencer design if required.

5. Optimize Silencer: This menu gives user the opportunity to select either the BFGS or the ARSM algorithm. The BFGS algorithm is an optional algorithm carried forward from previous work. Figure 4.10 shows the output screen for the BFGS algorithm. This thesis is focused on the ARSM procedure, as mentioned in Chapter 3.

6. Display Cost: The production cost of the silencer is displayed, as shown in Figure 4.10 and 4.11 respectively. The information on the silencer costs before and after helps the user to justify the results. During this process, the model is also updated automatically for the user to see the updated optimum design. If the ARSM procedure is chosen, the procedure is slightly different, as the production cost is displayed in an Excel worksheet window as shown in Figure 4.11.

Figure 4.8 COWL Pro/E Environment

Main Menu

Silencer Type
Configuration
Menu

Silencer Design
Model
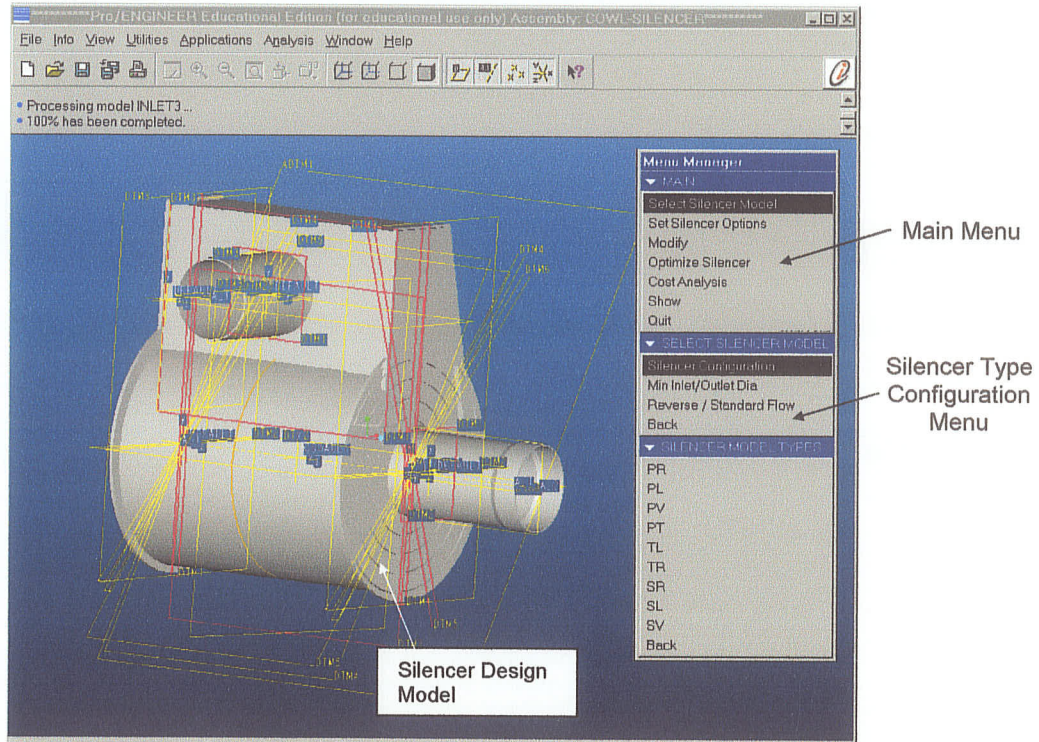
Figure 4.9 COWL Program Menu Bar

Figure 4.10 BFGS Display Output (Left)

Figure 4.11 ARSM Cost Output Display

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4.5 Test Results

The results of the COWL program are shown in Table 4.3. The user inputs are shown in the first 7 columns, and the cost results are shown under the BFGS and ARSM columns. This result is tested through various user inputs of silencer configurations.

Table 4.3 Comparison Table of BFGS and ARSM Cost

Model	Inlet/Outlet Diameter	Flow Direction	Material	Paint	Max. Dimension	Performance	BFGS			ARSM		
							Initial	Final	% Change	Initial	Final	% Change
PR	5	Standard	Aluminum	Black	20,20,20	3000,30,500	47.85	43.77	8.53	114.21	68.44	40.08
PR	8	Standard	Aluminum	Black	30,30,30	3000,30,500	78.19	55.07	29.57	177.47	78.12	55.98
PR	10	Standard	Aluminum	Black	40,40,40	3000,30,500	122.36	71.23	41.79	276.33	90.16	67.37
TL	5	Standard	Aluminum	Black	20,20,20	3000,30,500	47.08	43.02	8.62	113.38	67.80	40.20
TL	5	Reverse	Stainless	Black	20,20,20	3000,30,500	56.65	51.71	8.72	112.11	66.61	40.59
SR	5	Reverse	Stainless	Black	20,20,20	3000,30,500	44.23	39.62	10.42	102.39	58.93	42.45
SR	5	Reverse	Stainless	Silver	20,20,20	3000,40,800	44.49	39.87	10.38	102.73	58.95	42.62
SR	6	Reverse	Stainless	Powder	25,25,25	4000,40,800	52.61	40.92	22.22	123.87	59.43	52.02
Average Value For BFGS & ARSM							61.68	48.15	17.53	140.31	68.56	47.66

Note: The cost calculation is done in yearly basis at 5,000 units of production output and is based on the assumptions made in Section 3.2.

The averages cost reductions are different for both algorithms. BFGS shows approximately 18% in cost reduction, while ARSM gives 48%. This variation is partly due to the algorithm approach, where BFGS allows for local optimization, and is sensitive to initial design inputs. BFGS requires a derivative of the cost objective function to calculate the cost. In addition, the OBC model is not implemented for the BFGS optimization. Alternatively, ARSM is a global optimization algorithm that does not require derivative functions that use an approximation-based approach, and is not sensitive to initial inputs. The difference in the overall initial and final cost outputs is due to the fact that BFGS only partially considers the production activities, such as the

material and the labor costs. ARSM is a more detailed analysis procedure in which the 8

cost elements in the OBC model are all considered.

4.6 Discussion

The case study on the silencer design has shown the successful DFP application.

By simultaneously integrating CAD modeling of the designed product, cost modeling,

and the optimization algorithm, the minimum production cost can be achieved. The

development of the DFP methodology also reduces the product design cycle time. The

optimum product design can thus be manufactured faster, since the cost and customer

satisfaction are met. The COWL program development phase is time consuming, but the

program execution and procedure only takes minutes to complete. Therefore, in

comparison with initial design work that takes weeks to complete, this approach has

significantly reduced the time used in the product design phase. This program also gives

instant production cost evaluation, which helps product designers to justify the results

before the silencer production is initiated.

Advancements in COWL Program development have also allowed for the option

of a web-based application. The web-based silencer design will be briefly discussed later

in Chapter 6.

Chapter 5 Linear Air Diffuser

5.1 Introduction

The second case study is performed on a linear air diffuser unit. The focus of this study is a linear bar grille type of air diffuser. It is a product line among various air distribution products by E.H. Price, Ltd. The product line is referred to as the LBMH series, as shown in Figure 5.1. LBMH is an air distribution device, which is usually installed in floors, in windowsills or in high sidewall locations. It is designed for durability, and for the purpose of distributing air efficiently. It can be designed for both supply air or return air applications.
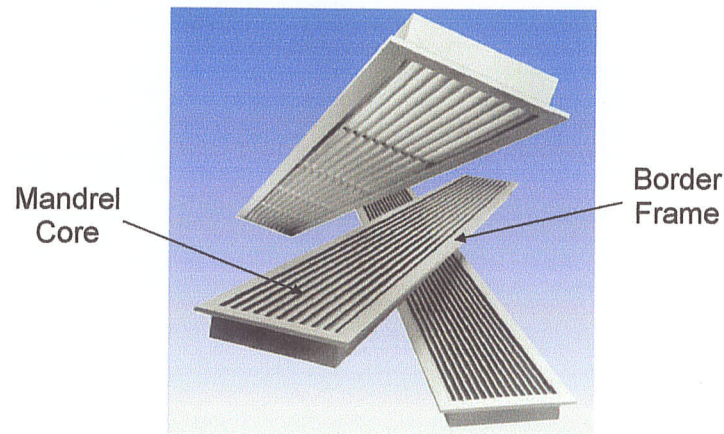
Figure 5.1 LBMH Linear Bar Grilles

LBMH is constructed using heavy-duty aluminum material. It consists of a rectangular border frame and support bar for the mandrel core to place on top of the frame. Core clips are used to secure the mandrel core to the support bar. This mechanism is installed to allow for the mandrel core to become detachable, so that to ease duct cleaning and maintenance. The mandrel core consists of bars aligned in parallel, and tubes that are

inserted through the holes on bars, to prevent the bars from shifting. There are wide varieties of sizes, core style, fastening type, and border width selections depicted in Appendix C. Basically, the model selection is denoted by 15A, 16A, 15B, 16B, 25B, 26B, 27B, 25C, 26C and 27C. The first number "1" indicates 1/8" bar nominal thickness and "2" represents 3/16". The second number represents bar deflection, where "5", "6", and "7" represent 0°, 15°, and 30° respectively. The deflection angle is chosen to determine air flow pattern, depending on its application. The letter designation A, B, and C represent the between-bar spacing 1/4", 1/2", and 7/16" respectively. LBMH model selection is determined by the installation space, location, air flow rate, and noise level specifications required by customers. This product mostly involves manual assembly, and thus the production time is largely determined by the size of the product, and operator skill. Larger sized units require more mandrel bars and tubes, and thus increase the assembly time. It is also noticeable that the assembly time doubles for inexperienced operators. There is an optional painting process, normally in white. The existing production rate for typical 6"x 12" sized LBMH is approximately 20 units/day.

5.2 Problem Statement

The analysis of LBMH series production showed that the mandrel core assembly process alone utilized 25% of total production time. Figure 5.2 shows a picture of this assembly process. Two aluminum tubes are inserted through the two holes on each side of the mandrel bars. The mandrel bars are aligned with equal spacing using the notch fixture. A 1-inch long pin, with a larger diameter than that of the inner diameter of the tube, is then pushed through the tube, in the direction shown. The machine uses a long

rod to force the pin through and expand the overall diameter of the tube. A typical tube expansion is from 0.312" to 0.318" of its outer diameter. This operation is used to expand the tube diameter, in order to tightly hold the mandrel bars together.
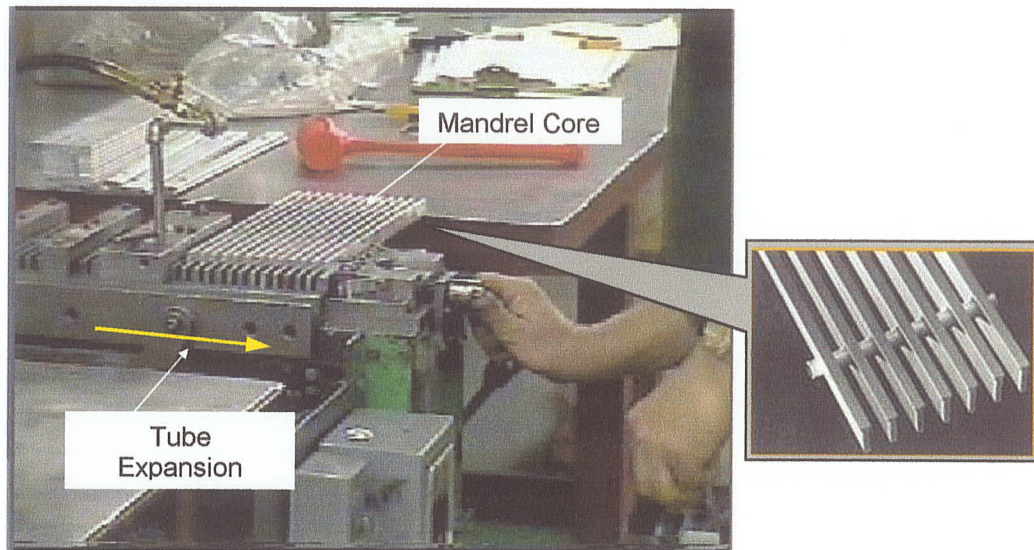
Figure 5.2 Mandrel Core Assembly Process

The main problem with this operation is the long setup and operation time. It takes approximately 5 minutes for a skilled worker to complete a 6"x 12" mandrel core. The number of tubes required is linearly increased with the length of the bars. For example, 4-12" requires 2 tubes whereas 14-24" requires 3 tubes. The core width is linearly related to the number of bars required, such that 4" requires 12 bars, 5" requires 16 bars, and so on. Therefore, generally speaking, increase in size results in increased assembly time. In addition, the pushing rod is easily bent for larger width cores, thus resulting in the pin becoming stuck within the tube. The damaged part is often disassembled and some of the undamaged bars are then reused. Therefore, extra time and effort are used for repairing and recycling the damaged parts.

5.3 Proposed Design Change

The DFP methodology is applied to the proposed new design. The following design requirements are chosen to be customer design inputs: the width of the core, maximum noise criteria (NC) value, and the airflow rate (CFM) requirement according to room volume i.e. 3000 ft^3. The grille length and hole tolerance are design variables which are required to satisfy the minimum production cost for design in Section 5.3.3. As stated in Section 5.2, the solution to the existing problem is to eliminate the costly core assembly process by implementing a design concept change to both the product specification and the manufacturing process. The new proposed design should satisfy the following requirements:

- The new design should not significantly alter the existing manufacturing processes.

- The tube expansion process should be eliminated, as it contributes most of the existing design difficulties.

- The use of raw material should be kept to a minimum.

- If possible, introduction of extra weight to the current design should be avoided.

- The existing core assembly time should be cut in half.

- In spite of the requirements listed above, minimum production cost can still be achieved.

5.3.1 Notched Bar Support

As shown in Figure 5.3, the first proposed design change is to introduce the notched bar at the end of the core. The notched bar support can provide the rigidity of bar spacing, while the tube is kept as the support for distributing vertical force if installed on the floor area, and for clip support to attach on to the frame.
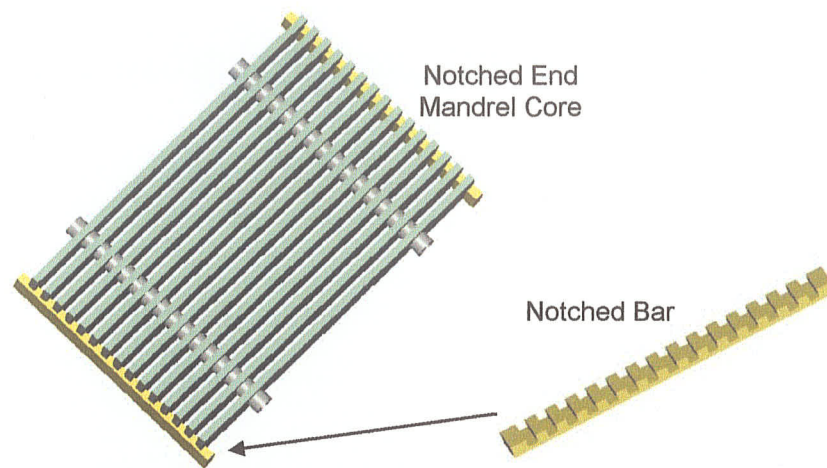
Figure 5.3 Mandrel Bar Tightened By Notched Bar

In this situation, the core tube diameter need not be press expanded with tight tolerance fit while the tube end is secured using a pin clip to prevent sliding movements. This design is rejected for the following reasons: 1) introducing an extra bar might add both weight and material cost; 2) a new cutting machine would likely be required to perform the notch-cutting process; and 3) with increasing number of core bars and different bar thicknesses, processing time might increase gradually.

5.3.2 Sleeves On Core Tube

The second proposed design is depicted in Figure 5.4. This is done by inserting constant length sleeves in between core bars, and then fitting the end cap at the end of the tube to secure the mandrel bars. The inner diameter of the sleeves is equal to the outer diameter of the tube. The outer diameter of the sleeves should be larger than the hole diameter of the mandrel bars, in order to prevent the sleeves from slipping into the holes.
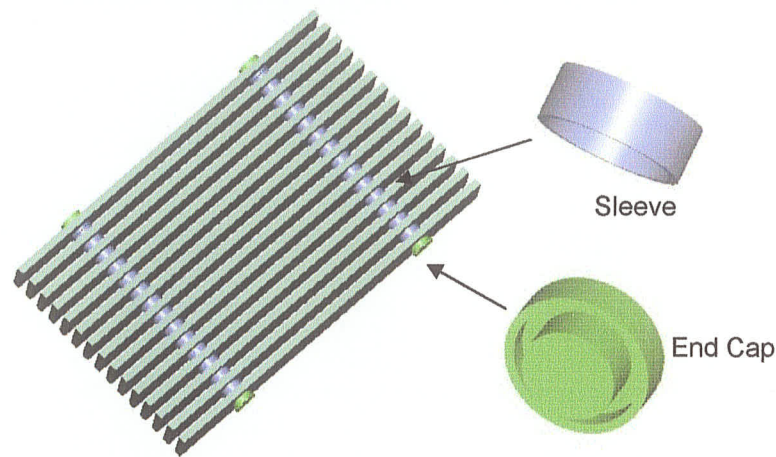
Figure 5.4 Mandrel Bar Tightened By Sleeves in Between Bars

This is a very simple design that can eliminate the use of the tube expansion machine. The sleeves can be cut using any existing hacksaw equipment, which only requires a larger sized aluminum tube. However, this design is rejected for the following reasons: 1) extra materials are added to the design, which increases both the material cost and weight of the mandrel core; 2) an extra operation is needed to manufacture the end cap, either by a casting or by machining process; and 3) there is increased cutting operation time for the sleeves alone.

5.3.3 Improved Hole with Tolerance Fit

The third proposed design is shown in Figure 5.5. This design follows the assumption that other manufacturing issues remain the same, while changes are made specifically for the mandrel bars. Instead of a circular hole, which exists in the original LBMH model, the hole is improved to enable a locking mechanism of the tube. This improved hole consists of two overlapping holes with differences in radii, as shown in Figure 5.5. The larger hole, with a radius of 0.165", is for the tube to slide through and align with the other mandrel bars. When the bars have been properly spaced, the tube can be knocked into the smaller radius hole using a hammer. The smaller hole radius is 0.156", following the assumption that a design tolerance of between ±0.005-0.01" is satisfactory to provide the locking mechanism. The nominal tube outer diameter is currently listed at 0.313". The design distance at the edge of the arc for two holes is 0.03".

Improved Hole Section
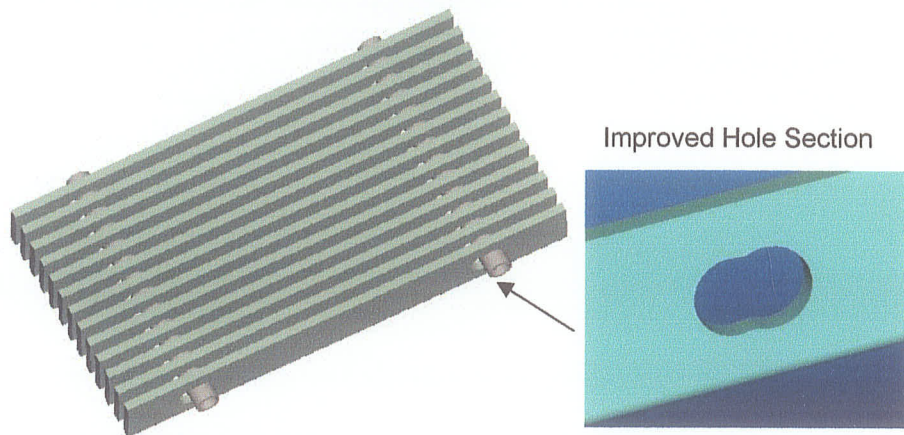
Figure 5.5 Mandrel Bar Tighten By Hole Tolerance Fit
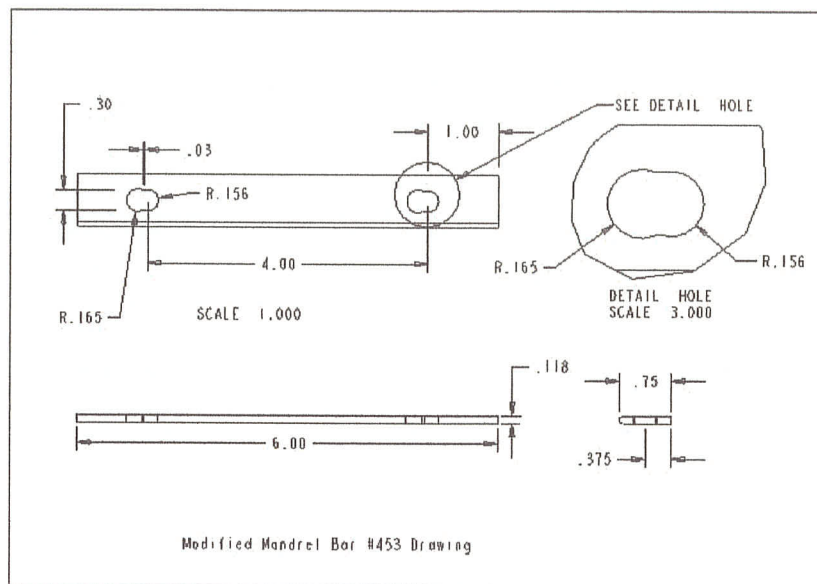
Among the three proposed designs, this thesis chose the third design for the DFP application. The advantages of the improved hole design are as follows: 1) no extra material has been added to the mandrel core, but rather a small amount of bar material was removed to add to the weight benefit; 2) no extra process is needed, while the extrusion machine can be eliminated, and the fixture for holding the mandrel bars can still be used; 3) the core assembly time is estimated to be reduced by half; and 4) the estimated damage from the assembly process is considerably less. The only change

needed for implementing the new design is for the punch die to make the two holes. The hole punching process can be done by two step circular hole punching, or by a one-step punch with the die designed to fit the dimensions as shown in Figure 5.5. Assuming that the second option can be used in the current punch machine, only a new die is required to accomplish the improved design.

5.4 LBMH Program Development

5.4.1 Introduction

Program development of the LBMH series of air diffuser requires product design specifications and information on the manufacturing processes. The LBMH program is a partially developed program that is intended to show the application of DFP methodology, similar to Chapter 4. This LBMH program is developed with an integrated cost model and optimization algorithm, but without direct linking to Pro/Engineer and Pro/Toolkit. In other words, the design parameters in the CAD model are manually entered into the LBMH program. Therefore, in this chapter, only the LBMH cost model and ARSM algorithm will be discussed in detail. The program is created using the C language under the Microsoft Visual C++ interface. As for the new LBMH design, there is an extra knowledge-base table, which will select the proper manufacturing process for the punch machine die, depending on the design tolerance requirements specified by the hole-tube locked mechanism.

5.4.2 LBMH OBC Model

In this case study, the OBC cost model is first developed with all the cost information and manufacturing processes. The ARSM algorithm is then linked to this model, and with the input of proper design parameters, the program will search for optimum design and production cost. The 8 cost element tables are shown in Appendix C. This new design information is incorporated into the OBC model, based on the sales quantity of 1500 units in the year 2001. The following modifications are made to the model:

- The percentage of damaged parts from the core assembly operation is reduced from 3% to 0.5% of total quantity that is from 45 units to 8 units.

- The tube expansion machine, which contributed an annual machine element cost of about $2000, is eliminated.

- An extra fixture cost is estimated at $3000, due to the new die design that should meet the specified design tolerance requirements.

- The operator assembly time is expected to be cut in half, with respect to the size of the mandrel core.

5.4.3 Relationship of Design to Production

During the program execution, the DOS prompt window requires the user to input the LBMH design specifications. The user inputs information include LBMH design length, width, static pressure, control temperature, maximum NC value, and minimum air flow rate. This section only describes the LBMH design length and width and their

physical relationships to production cost while other performance design features will be discussed in a later section.

Figure 5.6 Design Parameters Data Exchange Worksheet
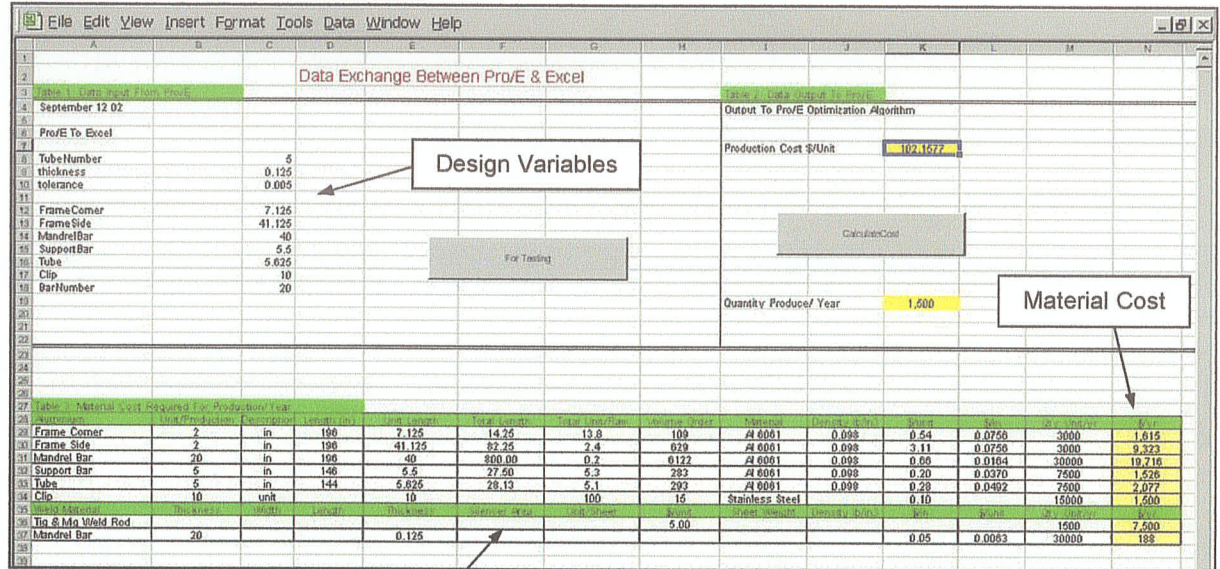
Added tolerance design for manufacturing the punch die in the new improved LBMH

Die Process	Tol Range	Tolerance	Initial $	Setup $	$/Operation	Qty/Die	Qty/yr	Die Number	Die Needed	$ for Qty Die	$ Formula	Relative $	$/Die
Die Casting	0.001 - 0.02		1000	200	300	50000	12000	0.2	1	300	27.44	2.2618	2,762
Investment Casting	0.002 - 0.02	0.005	1000	175	250	42000	12000	0.3	1	250	33.40	2.7536	3,179
Machining	0.002 - 0.02		1000	250	500	20000	12000	0.6	1	1000	18.11	1.4929	2,243
General Curve	Formula	12.13											

After entered the design data, the design parameters are transferred along to the OBC Data Exchange worksheet as shown in Figure 5.6. The production cost is calculated using an Excel macro in the OBC model. This process is done with the relationship defined using a parametric equation, similar to that in Chapter 4. The length of core bar, L, is defined as a design parameter. Then, the length of other LBMH components can be determined through the following equation in Table 5.1.

Table 5.1 LBMH Parametric Relationship Table

LBMH Component Length (in)	Parametric Equation
Frame L Side (both side)	$FL = L + 1.125$
Frame W Side (both side)	$FW = w + 1.125$
Support Bar	$SB = w - 0.5$
Tube	$T = w - 0.375$
Other Specifications	
Number of Core Bar	$NB = 4 * w - 4$
Number of Clips	$NC = 2 * nhole$
Number of Tube/Support Bar	$NTS = nhole$

where L design length of mandrel core (LBMH length)
       w design width of LBMH
      $nhole$ number of holes extruded on mandrel bars (depend on L)

The number of holes, $nhole$, in the table depends on the design length. For example, a length that is between 4 and 12 inches needs two holes while from 14 to 24 requires 3 holes and etc. This approach is integrated with a simple "if" statement in the programming. Then, for the amount of material cost needed, the total length of each components is multiplied by its material unit cost, ($/in). For a detailed formulation of these relationships, one can refer to Appendix C and the CD for its programming structure. Another aspect of this relationship is regarding of the core assembly time. The following equation is implemented in the LBMH model.

$$t = 1.2 * NTS + 0.3 * L + 0.1 * NB$$

where t core assembly time (min)
       L length of mandrel core bar (in)
     NTS number of tube
     NB number of mandrel core bar

The core assembly time is considered as a function of the number of tubes and mandrel bars, and the mandrel bar's length. The multipliers are estimated to convert the

measurement units into measurable time units.   In reality, the multiplier is obtained through a series of case studies during a real time assembly operation.   The assembly time is linked to the operator time element of the OBC model.   Thus, these parametric relationships will always drive and update the entire model for calculating production cost during the program execution.   In addition, optimization algorithm, which will be discussed in detail in later section, also requires this information on design/production relationships to establish its modeling process.

5.4.3.1 Tolerance Design

The tolerance design of the core bar assembly, on the other hand is done through a knowledge-based approach.   The tolerance design focuses on the selection of a proper manufacturing process in producing the die that is used in the hole-punch machine.   The die selected is assumed capable of punching holes in the mandrel bar, as described in Section 5.3.3.   The knowledge-based data in the LBMH cost model provides a selection of three processes: die casting, investment casting, and machining process, assuming that these processes are applicable in this case.   The cost tolerance relationship is obtained from the reference by Zoumin Dong (Dong, 1994).   The curve provided shows relative cost versus design tolerance.   In general, the tighter the tolerance, the higher is the cost. During program execution, the user can input a desired value of design tolerance.   Since the proposed design has not been tested, the current design tolerance is set at 0.005".   The following is an example of an equation for calculating the relative cost (RC) of die casting process.

$$RC = 64.914e^{-172.24*Tol}$$

where   *Tol*   design tolerance specified by the user.

This relative cost is assumed with references to the base cost of $1000. Therefore, for this specific die casting process, the processing cost is about 2.3 times with respect to the base cost i.e. about $2300. The "if" statement in the macro will choose a proper process based on minimum die processing cost, as shown in Table 5.1 that will ultimately lead to lowest production cost. Other information such as machine setup cost, die processing cost and die life are also included in this table. The cost of producing one die is listed on the right hand side of the table with yellow highlighted table cell.

Table 5.2 Tolerance Selection Table

Die Process	Tol Range	Tolerance	Initial $	Setup $	$/Operation	Qty/Die	Qty/yr	Die Number	Die Needed	$ for Qty Die	$ Formula	Relative $	$/Die
Die Casting	0.001 - 0.02		1000	200	300	50000	12000	0.2	1	300	27.44	2.2618	2,762
Investment Casting	0.002 - 0.02	0.005	1000	175	250	42000	12000	0.3	1	250	33.40	2.7536	3,179
Machining	0.002 - 0.02		1000	250	500	20000	12000	0.6	1	1000	18.11	1.4929	2,243
General Curve	Formula	12.13											

Thus, for the table example above, machining process will be chosen and the die cost is entered into the fixture cost element section of the OBC model.

5.4.4 Optimization Procedure

5.4.4.1 Design Variables

The design variables for the LBMH program are the active length, ambient air temperature requirement and die design tolerance. From the data provided by E.H. Price, Ltd, the active length is designed to fit specific design requirements, such as sufficient amount of airflow and desired room temperature, either to cool or heat the room. This thesis only considers the 15A LBMH model. The width of the LBMH is selected based

on the available sizes specified in the catalogue. Therefore, the designed open area of the LBMH should allow sufficient air flow through it. The LBMH length and air flow rate are directly associated with LBMH performance, and are thus used as design constraints. The value of design tolerance is determined by the die size use in the hole-punch machine. The die size is assumed to have the same diameter as the hole on the bars after the punching process. The locking mechanism of the aluminum tube and hole are dependent on this design tolerance. In the assembly process, the hole tolerance specified on the newly design mandrel bar should sufficiently tighten the bars without shifting.

5.4.4.2 Objective Function

The objective function in this program is the production cost, which consists of the 8 cost elements. The material and labor costs contribute the majority of the production cost. The design variables determine the amount of material used and the operation time.

5.4.4.3 Design Constraints

Two design constraints are set in the program. These are based on the design conditions, such as location of the device to be installed and structure of the room. The selection of size and type should result in acceptable noise levels, room temperature, and air velocity. These conditions are termed the noise criteria (NC) and comfort criteria. The NC value is generally related to the acoustical design of the linear grille. The air velocity and room temperature are related to the comfort criteria, where the criteria should satisfy at least 80% of the acceptable level of space occupants. In other words,

only 20% or less of the room occupants may object to the room conditions. Further information on these criteria can be obtained from the ASHRAE Handbook and Engineering Guidelines provided by Titus (Titus Website, 2002). Thus, both of these criteria represent the linear grille design performance, for which these constraints should be satisfied for every selected design specification.

a) Comfort Criteria

The comfort of an occupant is determined by both occupant variables and the conditions of the space. Occupant factors include activity level and metabolic rate, as well as occupant clothing levels. The factors that influence space comfort conditions include the dry bulb and radiant temperatures, relative humidity and air velocity. This indication is measured by local effective draft temperature, as shown by the equation below.

$$\phi = (t_x - t_c) - 0.07(V_x - 30) \quad where \begin{cases} -3F \leq \phi \leq 0 & feeling\ coldness \\ 0 \leq \phi \leq 2F & feeling\ warmth \end{cases}$$

where $\varnothing$ effective temperature
t_x local air temperatures, °F
t_c ambient temperature (average room temperature or control temperature, °F)
V_x local air velocity, fpm

The local temperature, t_x, the local air velocity, V_x, and the control temperature have significant effect on the draft temperature. It is considered that a $\varnothing$ value between –3 and +2 will satisfy the ADPI (Air Diffusion Performance Index) criteria. ADPI is a method of relating the space conditions of local transverse temperatures and velocities in the

occupied zone to occupants' thermal comfort. It is one comfort index for a given space, derived by Nevins and Ward. This ADPI criterion is rated by percentage, where higher values represent the higher comfort levels.

For this case study, the effective temperature equation will be used as the constraint. The limit is set between −3 and 0 for a cooling effect. This is assuming the design is applicable for heating purposes as well due to heating condition requires lower air velocity. Therefore, as long as the cooling design is satisfied, which normally requires a higher air velocity, it can be used for a heating environment. The temperature difference $(t_x - t_c)$ is kept between −5 and 0 for a cooling effect. t_x is the local supply air temperature to the diffuser that is maintained at a certain value, for example 70°F. t_c, on the other hand, is set as a design variable, which is the control temperature set on the thermostat. For example, if the local supply air temperature is maintained at 75°F in order to reach an 80% acceptance level of occupant comfort, the control temperature can be set at 77°F and air velocity at 70 fpm. From the equation above, the resulting effective temperature is −2.28, and is considered a satisfactory value. The air velocity V_x can be obtained from the designed air flow rate (CFM). For every selected LBMH size, its airflow rate should be greater than the room design requirements. For example, in order to cool a 3000 CFM room, 600 CFM air supply is required, therefore one can use two units of LBMH, which each supply air at 300 CFM. For the equation shown below,

$$Current\ airflow\ rate \geq Minimum\ Specify\ airflow\ rate$$

$$Current\ airflow\ rate = (0.3639w^2 + 12.341w - 8.9601 + Correction(static\ pressure)) * L$$

The current airflow rate can be obtained from the flow data listed in the LBMH catalogue, available from E.H. Price. This data is then curved fitted, as depicted in Appendix C. In general, the current airflow rate is a function of width w, length L, and static pressure. The constraint is set that the designed air flow rate should be greater than the minimum user specified value. Since the general equation of airflow rate is

$$Q = VA$$

where Q is airflow rate (CFM)
       V is the air velocity (FPM)
       A is the open area (ft^2)

The LBMH open area,

$$A = (w - nt) * L$$

where n is the number of mandrel bar
       t is the thickness of bar

Thus, the air velocity in the effective draft temperature can be obtained through the relationship

$$V_x = \left(\frac{Current\ airflow\ rate}{LBMH\ open\ area} \right)$$

b) Noise Criteria

The noise criteria level often determines the device size and supply air pressure. This value should be considered properly, in order to select a desired air diffuser to be installed. The sound level in an occupied space can be measured directly with a sound

level meter, or estimated from published sound power after accounting for room volume and other acoustic factors. The measurement more widely used is the sound power level, in decibel (dB) units. Either way, this measurement provides the maximum NC in a typical space, which can be used in selecting a proper LBMH device. According to the constraint shown by the equation below,

$$Current \ \ NC \leq Maximum \ \ NC$$

$$Current \ \ NC = f(width) + f(length) + f(static \ \ pressure)$$
$$= (4.566Ln(sp) + 11.645) + (13.922w^{0.3234}) + (4.601Ln(L) - 17.595)$$

where sp is the static pressure

The current NC value should be less than the maximum NC value. The current NC value is basically determined from the listed data in the LBMH catalogue. This data is curved fitted to obtain the relationship with design variable L, which is depicted in Appendix C. Similar to the airflow rate equation, the NC value is the function of width, length, and the static pressure.

In summary, the optimization model can be formulated as below:

$$\min_{w.r.t. \ \bar{x}} \ \ \ \ \ cost(\bar{x}) \ \ \ \ \ \ \bar{x} = L, Tol, t_c$$
subject to
     Current airflow rate $\geq$ Required airflow rate
     Current NC $\leq$ Maximum NC
     $x_i \in [x_{l,i}, x_{u,i}], \ \ \ i = 1, 2, 3$

where, $x_{l,i}$ and $x_{u,i}$ are lower and upper bounds for each design variable, respectively.

5.5 Program Test Results

The program is tested using a few different design configurations. Figure 5.7 depicts

the output graph of the cost elements for all the operations involved in the production of

the LBMH. It is obvious from the chart that the operator (Oper) contributes the highest

production cost. The detailed cost element information can be obtained from Appendix C.

Table 5.3 shows the resultant production cost reduction from the program simulation.

Figure 5.7 Graph Indicates Distribution of Element Cost
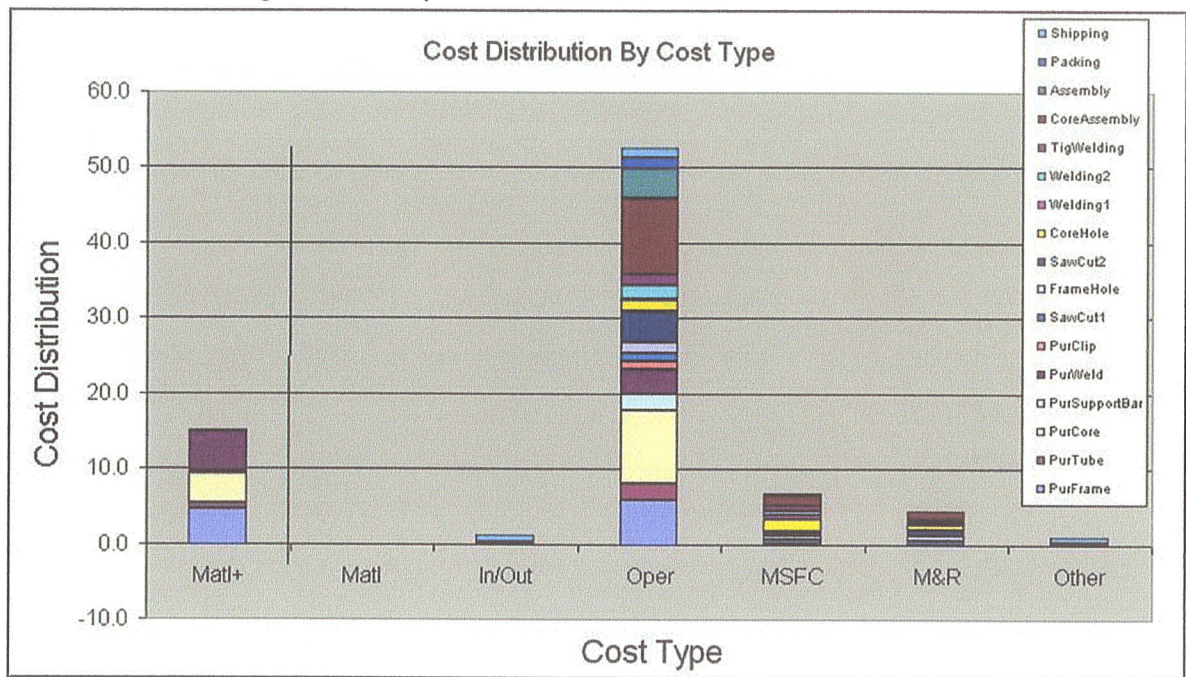
Table 5.3 LBMH Production Cost

Input Parameters							Test Output				
Room Temperature (°F)	Length (in)	Width (in)	Tolerance (in)	Noise Criteria (NC)	Air Flow Rate (CFM)	Static Pressure (in H2O)	Optimum Length	Initial Cost ($)	Final Cost ($)	% Change	Die Processing Method
70	4	1.5	0.005	20	5	0.2	3.74	33.94	33.60	1.00	Die Casting
70	12	2	0.005	30	20	0.2	9.32	39.50	37.85	4.18	Machining
70	20	3	0.005	20	50	0.2	13.28	53.78	47.26	12.12	Machining
70	40	6	0.005	30	300	0.2	31.07	102.16	86.54	15.29	Machining
70	50	5	0.005	30	350	0.2	46.81	107.44	96.27	10.40	Die Casting
70	96	6	0.005	50	800	0.2	89.87	180.15	159.96	11.21	Machining
							Average % Cost Reduction			9.03	

Note: The cost calculation is done in yearly basis at 1,500 units of production output and is based on the assumptions made in Section 3.2

5.6 Discussion

The results shown in Table 5.3 depict an average of 10% reduction in production cost. In addition, the best die processing method has been selected, which results in minimum die production cost with respect to the improved LBMH design. It can be seen that for smaller grille sizes, the cost reduction is less compared to the larger sized grilles. This is due to the fact that the labor hours and cost incurred may not be linearly associated with grille size. Therefore, smaller sized grilles have less potential cost saving, since the material cost that is directly related to size does not significantly affect the entire production cost. The cost table that represents average core assembly time is also reduced by 50%, as shown in Table 3 of Appendix C. In the example of the 40 x 6 configuration, the core assembly time recorded is reduced from 31.50 minutes to 15.11 minutes. The LBMH program has shown the potential design improvement that can be achieved through the implementation of the DFP application. The result implies that by

looking at production cost, one can tell about the efficiency of a production system. In general, a successful design improvement can be indicated by its less production cost.

Chapter 6 Design Automation

6.1 Introduction

As part of the DFP methodology, the integration of the design automation system into the DFP software tool is to significantly shorten the design process cycle. In this chapter, the use of Pro/Engineer and Pro/Toolkit is introduced together with the programming part of the DFP preliminary software. The design automation discussed here only refers to the silencer design in Chapter 4. Section 6.6 discusses some extended work to move this design into a web-based environment. The following figure depicts an overview of design automation system. This system integrates the ARSM and OBC models that dynamically change the Pro/Engineer database. Thus, one can obtain optimal product design and minimum production cost.

Figure 6.1 Design Automation System
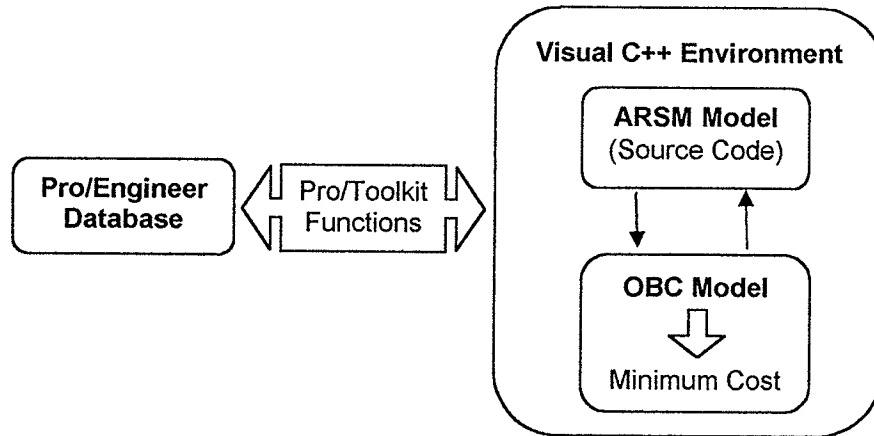
6.2 Pro/Engineer Background

Pro/Engineer is a parametric solid modeler developed by the Parametric Technology Corporation (PTC). Pro/Engineer allows the user to create a solid, three-

dimensional model that can be easily modified and analyzed. This solid model has a variety of uses such as for creating manufacturing drawings, motion analysis, checking fit tolerances, part assembly and finite element analysis. In the accompanying CD, both the COWL and LBMH projects directory contain the product model files with extension "prt" for part, "asm" for part assembly and "drw" for 2D drawing.

Pro/Engineer is a feature-based, associative, and parametric solid modeler. The feature based modeling process within Pro/Engineer allows the user to construct solid models, one feature at a time. Protrusions and cuts are examples of these features. The associativity of Pro/Engineer implies that all instances of a modeled part refer to a common database. The manufacturing drawings, assemblies, and part models that incorporate a common part will change accordingly to any modification of the part. Associativity within Pro/Engineer allows the user to made modifications to an assembly or part and have those modifications reflected in the manufacturing drawings and other associated applications. Pro/Engineer is parametric because its features are interrelated to one another. Any modification to one feature will have an impact on the features that refer to it. The parametric nature of Pro/Engineer allows a part design to retain its design characteristics while remaining highly flexible during design modifications. The interrelations between features are commonly referred to as "parent/child relationships". The feature based, associative and parametric aspects of Pro/Engineer form the fundamental basis on which successful and efficient model development occurs. Further Pro/Engineer documentations can be referred to the accompanying CD.

6.3 COWL Silencer Model

The solid modeling of the silencer is developed using Pro/Engineer 2000i CAD software. The silencer components are first being created individually and then assembly to form the silencer model. Similar components, such as the front and rear endplates, are developed using a single part file. The part file can then be repeatedly used to create the assembly if part similarity is found. The "resume" and "suppress" functions in Pro/Engineer are quite heavily used, such that some features can be suppressed when they are not needed for the designed model. Silencer dimensions are mandatory for setting, as design parameters will later be used by the program. The "relation" function in Pro/Engineer provides the user with control over the dimensions. By changing the driving dimension, the associated dimension established through the relation will be changed according to the specific implemented formula.

6.3.1 Front and Rear Endplate

The front and rear endplates are constructed using features of the protrusion cylinder. The cylinder diameter forms the outer diameter of the endplate and cylinder depth forms the thickness of the endplate. In the middle of the cylinder is a hole, which represents the inner diameter of the endplate. This inlet hole diameter is similar to the inlet tube diameter. Both the diameter of the hole and cylinder can be modified to change the size of the endplates. The endplate without the top feature configuration is designed for the SL, SR, and SV silencer models. For the remaining silencer configurations, a top section must be added to the endplate as shown in the figure below.
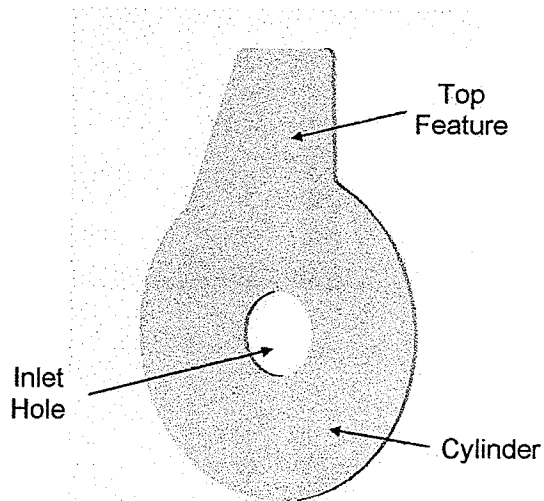
Figure 6.2 Silencer Endplate (Friesen, 2001)

Another hole is created in the middle of the top section for the TR model design. The hole is referenced to the axis of the endplate cylinder. This allows the center-to-center distance from the hole to the cylinder to be modified, as well as the diameter of the hole.

6.3.2 Spiral Section

The spiral component, shown in Figure 4.3, is modeled using a curve feature through a set of equations. A spiral curve is created with coordinates that were changed from the normal Cartesian coordinate system (x,y,z) to cylindrical coordinates (r,θ,z). The equation set for the spiral is as follows:

$$r = \left(\left(Outer\ Radius - Inner\ Radius\right) \cdot t\right) + Inner\ Radius$$
$$\theta = t \cdot 360 \cdot \left(\left(Outer\ Radius - Inner\ Radius\right) \div Spiral\ Gap\right)$$
$$z = 0$$
$$where\ "t"\ increases\ from\ 0\ to\ 1$$

90

In the equation, the outer radius, inner radius, and spiral gap are design parameters, which can be modified to generate new spiral sizes. A rectangle feature with the cross section of the sheet metal is swept along the spiral curve by modifying its depth and thickness. The spiral shape construction can be viewed as rolling a rectangle sheet into a swirl formed along an axis.

6.3.3 Inlets and Outlets

The inlet and outlet are created by revolving 360° from a cross sectional sketch around a centerline or axis. The dimensions used to create the sketch are used to modify the dimensions of the inlet and outlet. The dimensional parameters involved are:

General Diameter: The inner diameter for inlets; the outer diameter for outlets

Length: The overall length of the inlet

Flange Diameter: The diameter of the inlet that is welded to the silencer
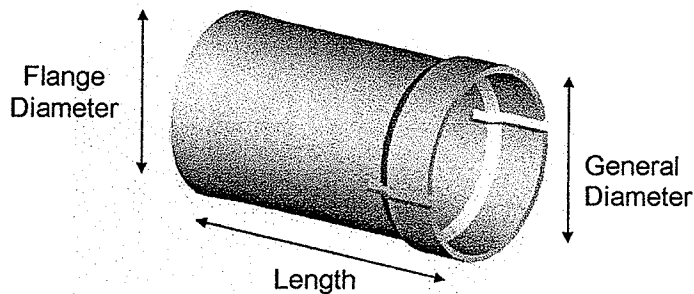
Figure 6.3 Inlet/Outlet (Friesen, 2001)

The general diameter is made equivalent to the inlet and outlet holes in the endplate and top section. This diameter range is based on the data in the COWL catalogue.

6.3.4 Top Section

The top piece was created by protrusion through a cross sectional sketch. The plate thickness, depth, and outlet hole dimensions are subjected to design changes. The angle, top and height value are related to the three dimensions. A hole is also created from the top area specifically for the PT model.
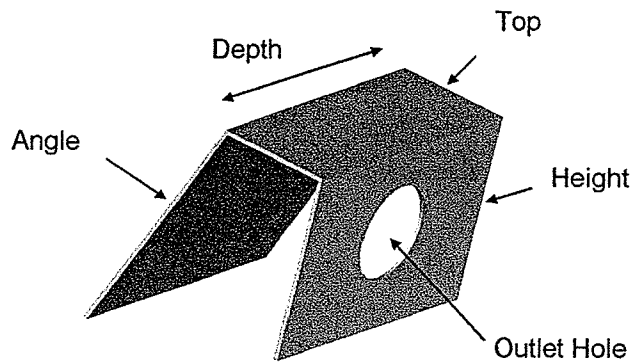
Figure 6.4 Top Section (Friesen, 2001)

6.3.5 Silencer Assembly

The silencer is assembled from the components to form an assembly file. The silencer components must be assembled in sequence to ensure that regeneration of the assembly is successful. The sequence is as follows:

1. Front Endplate

2. Spiral Section

3. Rear Endplate

4. Top Section

5. Inlets and Outlets

The regeneration of the model in the program will follow this sequence to show the model on the screen. This is important due to the parent/child relationship in Pro/Engineer. For example, the front endplate is the first to be executed; therefore, it is the "parent" of other features. Other components joining on top of the parent feature are considered "child", whose dimensions and references are based on the parent features. For this reason, Pro/Engineer will prompt regeneration failure if the reference is missing.

6.4 Pro/Toolkit Background

The additional PTC software package included with Pro/Engineer is an object orientated application programmers interface (API) called Pro/Toolkit. Pro/Toolkit is a library of C functions that are available to the user for fully automating design tasks within Pro/Engineer. By using these C functions, the ability of Pro/Engineer can be customized and expanded on that allows user for the creation of external and internal programs to interact with the Pro/Engineer environment and model database. The environment of Pro/Engineer includes the display and menu commands. The development of the customization program is based on the coding of the C programming language by using any applicable text editor. However, for more efficient coding Microsoft Visual C++ 6.0 has been used. The coding format is created with source files and header files. C source code files usually have an extension such as ".c" while header is ".h". To further understand the abilities of Pro/Toolkit some essential topics will be briefly discussed here while the detail Pro/Toolkit functions is located in Appendix D and the accompany CD.

The source files contain the functions, variables, declarations, and procedures that are used to communicate with Pro/Engineer. When the source file is completed, the C++ complier will convert the codes into machine language to form an executable program. By executing the program, it will run a user defined application and perform the tasks as described in the source file.

6.4.1 Source Code And Header File

In order to use the Pro/Toolkit functions, the source file need to access their header files. The header files contain the necessary information to execute the Pro/Toolkit functions. For example the Pro/Toolkit functions "ProMdlRetrieve()" is used within the source code, then the header file "ProMdl.h" must be included. This is done by placing "#include <ProMdl.h>" at the beginning of the C source file. The Pro/Toolkit function in the header file often begins with the letters, "Pro"; this signifies that the file or function belongs to Pro/Toolkit. The later abbreviated word represents what section of Pro/Engineer function the header file is applied to, such as the letters, "Mdl" represents the word "Model". So the model is referred to "ProMdlRetrieve()" which is the "retrieve" function. The model retrieve command allows the user to open a solid model that is stored on the computer.

Other than the Pro/Toolkit function, user defined structure class is heavily used in the program. The dimensions, materials, costs, and configuration of each silencer component must be modified and recorded. Therefore, the structure class declaration can provide efficient data management for objective-oriented programming. For example, the following is a shortened version of the spiral structure class.

```
typedef struct spiralparams {
        int status;              /* Display status */
        double od;               /* Outer diameter */
        double id;               /* Inner diameter */
        double gap;              /* Gap between coils */
        double depth;            /* Depth of the spiral */
        double thickness;        /* Thickness of the coil */
        double cost;             /* Material cost */
} SpiralParams;
```

The structures are also created for other silencer components such as inlet/outlet, top, endplates sections. The structure class above is declared as (in the program code):

SpiralParams spiral;

This declaration creates a variable *spiral*. Then, in the COWL Program code, the depth of the spiral can be accessed by, *spiral.depth*, and so on for the other variables.

As mentioned earlier in this chapter, Pro/Engineer feature "Relations" is also heavily used within the COWL Program. The majority of dimensional parameters are calculated from relations. The relations retain the design characteristics for each silencer component and the complete silencer assembly. During the customization of the silencer design, a small number of parameters, usually driving dimension, are directly modified by the users input. The majority of modified parameters are calculated from a complex set of interdependent relations based on the user's modifications. As each modified parameters can calculate a new set of parameter values that will update the model with new values. The following is an example of dimensional parameters (D0, D1, D2) that have been created within Pro/Engineer:

D0 = height   D1 = width   D2 = depth

With the parameters defined, user can create the following relations,

$$IF\ D0 == D1$$
$$D0 = D2 * 2$$
$$D1 = D2 * 2$$
$$END\ IF$$

This relation shows that D2 is the driving dimension. When the "if" statement is true, the coding will set D0 and D1 equal to the twice value of D2.

6.4.2 Compiler and Make File

Once the source code is completed, the source file must be compiled. This process has been done from the DOS command prompt under the Visual C++ 6.0 environment. Under the DOS prompt, command is entered as "nmake –f makefile". The make file is created to link the "included" header files and source files together for creating a complete package. This package can be compiled into two forms, either an EXE or a DLL file. These files both contain the user program but execute it in different ways. The user program can be compiled into a DLL (Dynamically Linked Library). In this mode, Pro/Engineer calls the DLL file to complete tasks. This method is noticeably faster when many functions are making to the Pro/Engineer model database. The other user program is called EXE (executable file). This mode allows the EXE program to call functions within Pro/Engineer, which allows for more customization of the user program at the cost of speed.

6.4.3 Running the Program

After source code compilation, the file with ".exe" or ".dll" extension is created depending on user preference. To run the program, a Pro/Toolkit data file named "protk.dat" must be present together with the program file in the working directory from which Pro/Engineer is executed. The instructions within this file determine which external programs should be executed during the startup of Pro/Engineer. In addition, several options can be set to tailor different execution mode of the program. With this step complete, the program can be executed into Pro/Engineer environment and accessed by the user to customize external design commands. During the program execution, menu toolbar such as shown in Figure 4.9 will be loaded. User can input parameters such as dimension and select desired design configurations to initialize a silencer model. The design process is iteratively performed to find an optimal design.

6.5 Automate Product Design Process

The product design automation features in the program can significantly benefit design cycle time and cost saving. For this section, only the silencer program in Chapter 4 will be discussed since it is fully integrated into Pro/Engineer environment. To further illustrate the design automation, the COWL program is created within VC++ 6.0 environment. This serves the main programming interface that is done using C language. The Pro/Toolkit functions are then linked to Pro/Engineer model. The functions are linked to the database of Pro/Engineer, thus all the Pro/Engineer parameters, variables and strings can be read by this external program. The OBC model, on the other hand, is created under Microsoft Excel. Within this model, some macro functions are created to

run the tasks of calculation for the production cost. In order for the COWL program to automatically call the macro within the Excel table, the limitation of C language prevents the direct control over the macro function since the macro function is based on Visual Basic language. Therefore, an executed file is created using Visual Basic 6.0 that has ActiveX Control over the Excel macro function. The control is used to open the Excel file, run the macro, and then close the file. Within COWL program, now C can be used to call the executed file to perform the Excel macro tasks. The ARSM algorithm is written using the C language and is inserted into the COWL program. After the COWL program is created, all the parameters and values can be linked to Excel and Pro/Engineer automatically. The figure below shows the related files and commands used in the COWL program.

Figure 6.5 COWL Program Files
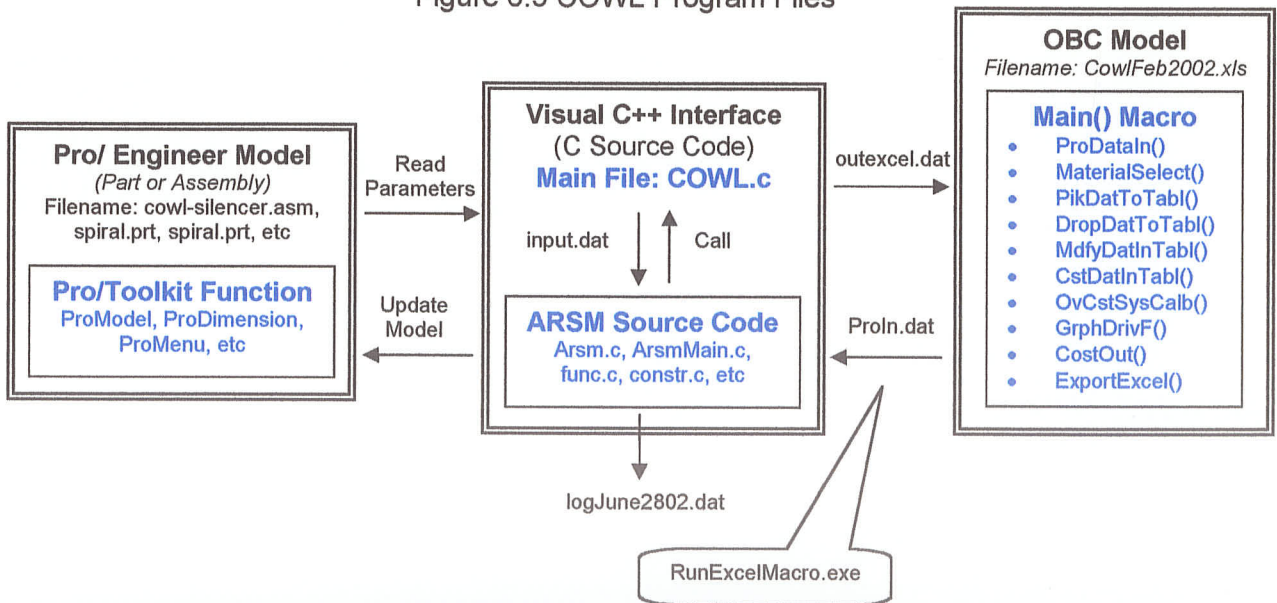
During the execution of the COWL program under the Pro/Engineer interface, the design parameters are fitted into "input.dat" and "outexcel.dat" data files. Both these files

contain values and texts to be used in the cost analysis and optimization procedures. Pro/Toolkit functions as a tool to create a user defined menu under the Pro/Engineer interface as well as control over the silencer assembly model that is loaded to Pro/Engineer. When the ARSM is being called, it sent the design parameters to update the "outexcel.dat" file and "RunExcelMacro.exe" is executed to open the "CowlFeb2002.xls" file and run the "Main()" macro within the file. The "Main()" will drive the function command to perform the required calculation to produce the resultant production cost. For example "ProDataIn" function will read the values in the "outexcel.dat" data file and based on the data, "MaterialSelect()" is used to select the user preference material type. Then from "PikDatToTbl" to "GrphDrivF()" are series of element cost calculation commands as described in those of Chapter 3 table example. Finally, "CostOut" command will display the result in the Excel file as well as to the output file called "ProIn.dat". The "ProIn.dat" file is used to serve as the objective cost function value that is required for the ARSM iteration sequence. After the procedure, "RunExcelMacro.exe" will then close the Excel file and return to the Pro/Engineer interface. The optimum values such as dimension that is obtained from the ARSM algorithm is finally sent back to update the model value and display to the user. The output data file "logJune2802.dat" record all the values during the execution of the ARSM procedure. User can check the final cost value in the Excel file that similarly opened by another executed file "ExcelOpen.exe" but only without closing it. At some point during the procedure, the design constraints including the silencer maximum size and performances are checked at the background. Appendix D shows these functions in a flow chart format.

As the result, design automation has efficiently improved the design process in which time and cost saving can be realized. The COWL program has been tested to show that the whole design process took minutes to complete. The DFP CD contains the demonstration video files for the COWL design, COWL web-based design, and LBMH design. The silencer design in Chapter 4 shows that an optimal design can be reached within 2 minutes time. Furthermore, the OBC model provides detailed manufacturing costs to support design improvement. In case problem arises, the cost element analysis module can provide graphical information on which operation or process requires attention for design change.

6.6 Web-Based Design

A part of the product design automation, the COWL program has been extended to a web-based design approach. This project research is part of undergraduate thesis by Ken How and Lucas (Ken How & Pang, 2002). The program is modified to fit into World Wide Web application. This project is intended to show that the product design process can be done on distributed design environment where customers are not locally available. The application is done by using CGI interface and then loaded onto the server for internet used. Figure 6.6 and 6.7 shows the customer input interface and the display output screen respectively. The result has shown a time saving for the silencer design process and be more accessible by customers at different location. For further information can be referred to their thesis project.

Figure 6.6 Customer Input Interface

Silencer Configuration: [PR ▼]

Reverse / Standard Flow: [Reverse ▼]

Min Inlet / Max Outlet: [_____]

Material: [Aluminized Steel ▼]

Paint: [Black ▼]

Max Silencer Depth: [_____]

Max Silencer Width: [_____]

Max Silencer Height: [_____]

Required Flow Rate: [_____] (CFM)

Max Back Pressure: [_____] (inch. w. c)
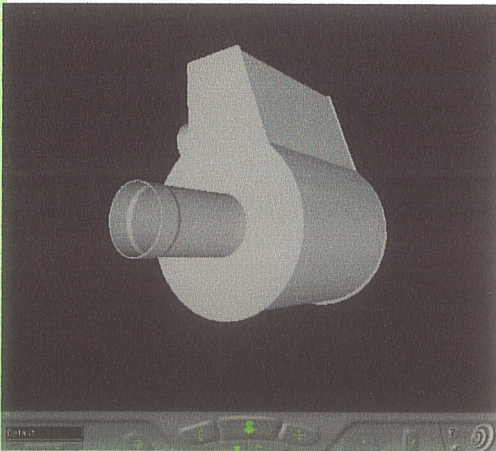
Exhaust Gas Temperature: [_____] (F)

Other Special Requirements:

[_____]

[Submit Data]   [Clear Entries]

Figure 6.7 COWL Web Output Display

Performance:	
Back Pressure	200Psi
Surface Area	19.5 meter square
Performance Satisfied	Yes
Overall Dimension	1m x 0.6m x 0.5m
Other Special Requirements:	
(i) Corrosion	None
(ii) Weight	None

Price: CAN 102

[Order Now]   [Later]   [Back]

Chapter 7 Conclusions

7.1 Summary

In this work, the design for production (DFP) methodology has been developed and its applications presented. The core features of the DFP comprise of the definition of product/production relationship, systematic formulation of the defined relationship, using operation-based costing approach for cost estimation, and using the ARSM as the design optimization strategy. In addition to the developed DFP methodology, design automation has been achieved to further reduce the design cycle time. The first contribution of DFP is the use of the OBC as the tool to quantify production costs. In addition, the definition of product/production relationship during early product design stage can reduce the amount of effort in search of a feasible design solution. A preliminary DFP software tool was developed to demonstrate its application in industry. Two industrial projects, the designs of industrial silencer and linear grille air diffuser were used to test and demonstrate the effectiveness of the DFP methodology. The outcome presents a potential saving in production cost and time. It has shown that the proposed DFP methodology can be applied to other product.

7.2 Limitations

1. The current practice only considers one product design, which in reality is hard to implement into companies with a high variety of products.

2. The product design and production relation is conceptually defined. Though general formulas are given for various types of relationships, it is normally difficult to form a

parametric relationship between design features and costs. Specific equations for many of the relationships are product dependent.

3. Currently, only some production issues are considered in this thesis. Other contributors such as supplier, handling and scheduling and safety issues might be significant in certain situations and thus they should be taken into account.

4. The quantity of production in a certain period is currently fixed for the cost analysis. The effect of changing the demand, and thus the quantity towards the entire production system needs to be further investigated.

5. The development of the design automation system demands extensive programming and is currently product dependent.

7.3 Future Work

The capability of the developed DFP methodology needs to be further assessed in more complex manufacturing systems. Currently, the DFP methodology is applied to a research project with the collaboration of Vansco Electronics Ltd. This research project is about the design of an electronic instrument cluster. The result should promise an optimal final product with minimal production costs. In addition to this research, a more solid design guideline still needs to be explored to accommodate the complex relationship of product design and production cost issues. Future research is required especially for incorporating the entire production concerns and manufacturing processes into the product design phase that will reduce the design cycle time and ultimately reduce production costs.

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Appendix A

Operation-based Costing Analysis Example: Circular Table

Operation-Based Costing Excel Worksheet

Operation-based Costing Analysis Example: Circular Table

This section describes the procedure and analysis of an operation-based costing method by using a circular table as an example. The following Figure A.1-A.4 depicts the pictures of a table and its parts. The table consists of a top wood section, a support plate, a chrome bottom section, and screws. For every unit of table production, the raw materials required are two units of ½" thick 40" diameter circular wooden board, one thin 40" diameter plastic cover, one long 2 1/4" width plastic strip to cover table perimeter, one 8"x 8" 1/2" thick square plate, 8 screws, a 20" long 2" diameter pipe, and a 25" base diameter 1/4" thick cone based plate. The predicted sale for a particular year is 10000 units. This material information will be used for the four worksheets in the operation based cost model.

Figure A.1: Table Top Section   **Figure A.2: Table Bottom Section**

Figure A.3: Cone Based Plate   **Figure A.4: Support Plate**
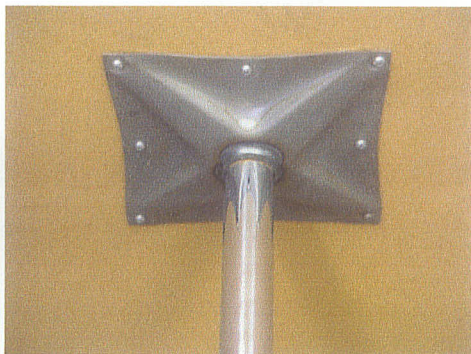
A.1 Flow Diagram: Material & Part Flow In Manufacturing Line

The FlowDiagram worksheet shows the material and parts flow in a diagrammatic representation for the table manufacturing system. The diagrams specifically outline the bill of materials (BOM) and manufacturing processes from the purchasing department to the shipping department. Users can breakdown the system into individual operations that are required for producing the table. Then the operations can be further grouped into a few categories such as the pipe section and the bottom plate section as shown in the figure below. The category division and operations outline depend mostly on the preferences of the user and are often product oriented.
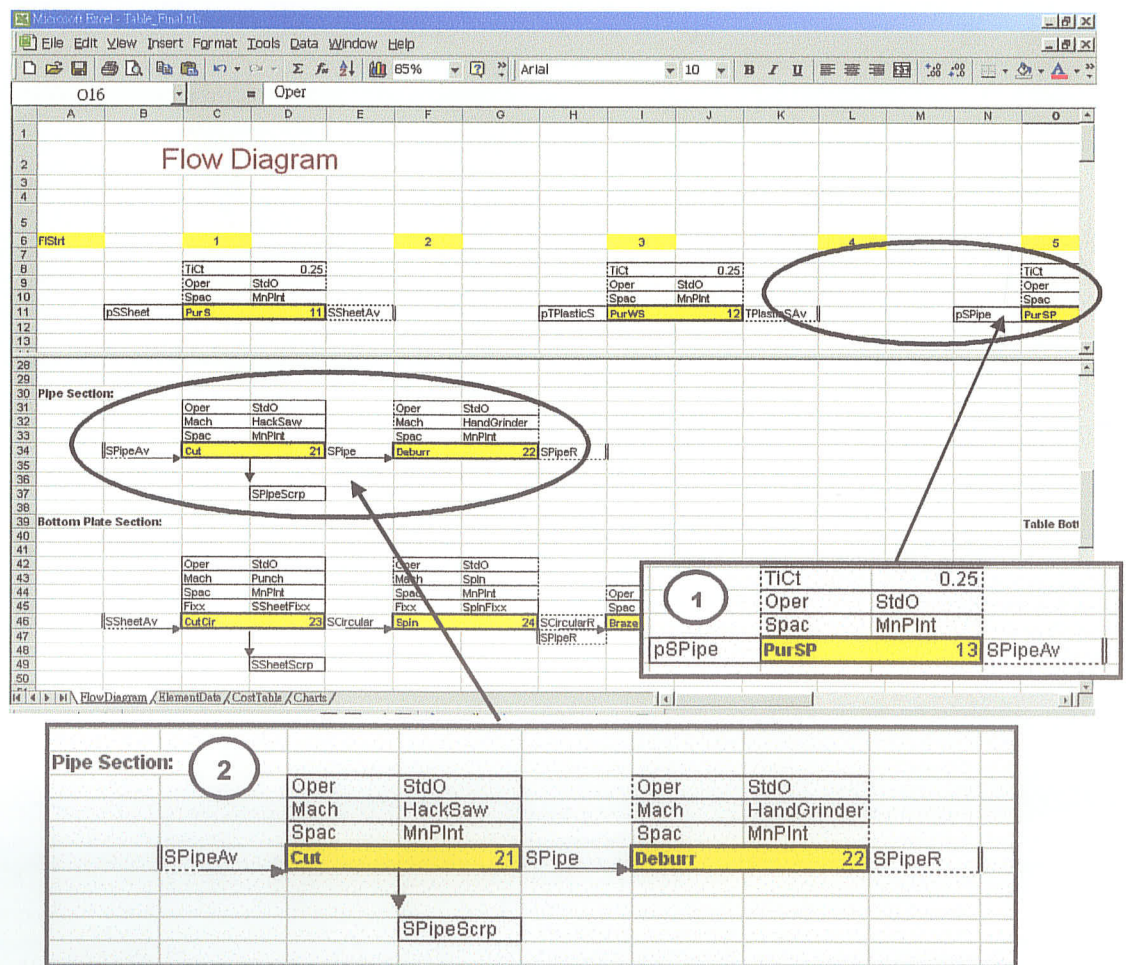
Figure A.5: Pipe Section With Cutting And Deburring Operations

In Figure A.5, the small box, labeled 1, depicts a "capsule" of an operation. An operation capsule groups the material flow in and out together with the cost elements that are associated to the operation. Box 1 is an example of a capsule showing a purchase operation. The highlighted cell shows the name of this operation, "PurSP", and the operation number is "13". The rows on top of the operation name list the cost elements associated with this operation. There are 8 cost elements in total of which the user only includes those that are required in the operation, such as TiCt – tied cost, Oper – operator, and Spac – space. Other cost elements are Mach - machine cost, Fixx – fixture cost, Ctrt – contract, Incv – Incentives. The material cost is not directly shown in one of these rows but rather as the part flow through the operation. The right column next to the cost element column shows the "value" of the cost element. For example, "StdO" is the value (type) of the operator; this value represents the whole cost package for this type of operator. Tied cost is given a numerical value of 0.25 as above because 25% of the cost is assumed being tied up to the material in storage. The materials or parts "pSPipe" entering the system are shown in the cells to the left and parts "SpipeAv" are leaving the right cell either as finished parts or parts ready for the next operation. Box 2 shows a part flow from one operation to the next operation. The small box, "SpipeScrp", below the "Cut" capsule indicates scrap or damaged parts during the operation. Damaged products, dead or obsolete products are represented by "PdDd" as material or products that are in storage, but because of changes in the product line or other reasons, they will never be used or sold. During the product delivery, sometimes there are products returned from consumers as bad product, named "BadPd". For some situations, there is a late delivery charge "LateDl" for products that do not meet the deadline. Different labels are given to

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materials and parts as they leave an operation and as they move between operations, even if they are not physically changed. The double line to the right of the material indicates that the material does not go to the next step but goes elsewhere; the double line to the left indicates that it comes from somewhere else. For example, the material "SpipeAv" in Box 1 goes into the "Cut" operation in Box 2. It is recommended that a brief description is to be given on the right section of the sheet about each abbreviation and the size and shape of the materials such as "pSPipe" can be described as purchase 12 feet steel pipe with 11/2" thickness.

A.2 Data Sheet: Description of Operations and Cost Elements

The data table is used to describe the capsules or operations and quantify all their cost elements related to the production. All the element cost data are inputted by user and are converted into yearly basis. The operation name and number, cost element type and name, and part name are moved either by copying and pasting from the flow diagram sheet or are inputted manually. It is particularly important to keep this information exactly the same throughout this data sheet otherwise the Excel macro will prompt that a syntax error exists. The highlighted cells in the first column are internal keywords used by macros to identify the position of table cells. For example in Table 1, "StrtQtOut" means the beginning of the table and "StopQtOut" means the end; the rows in between the two cells will be processed by macros. The "fctr" column in all the tables refers to the factor assigned to every cost element indicating the percentage of usage or utilization of the resources such as materials, machines, or an operator's time. For example in the "nMach" column of Table 3, the "HackSaw" factor is 0.1, which means only 10% of the

total operation time of the Hacksaw is used for the assigned operation throughout the year. The value of the factors is usually 1.0, but in some cases, it means unit of usage. For example in Table 2, the "Assem" operation needs 8 units (screws), and thus 8 is input as the factor for the variable "ScrewAv". The "Qctrl" column in Table 5, 6 and 7 describes the effect of cost output per year due to a change of labor or machine input in the operations. This column applies mostly to operator and machine, sometimes to fixture and space as well. For example, if 5 operators are used for a group of jobs in the plant and the production rate is projected to increase by 20%, the number of operators may be increased by 1. If this is the case, the "Qctrl" is assigned to 1 otherwise 0. However, this issue is not implemented in this research. The data worksheet is separated into a few tables as follows:

1) Annual product quantity output,

2) Part relation in operations,

3) Operation relation with cost elements,

4) Material cost,

5) Cost of operator,

6) Cost of machine and fixture,

7) Manufacturing space cost,

8) Contract and incentives cost,

9) Tied cost.

Table 1 shows the estimated yearly product output. Tables 2 and 3 describe the parts in and out of operations and the related cost elements for each operation. These two tables

are used to show the material or part flow relationship in which the green highlighted columns indicate "Oprn", "Oprn#", "Out Dim" and "OprnRw#" as operation name, operation number, operation description and operation row number count respectively. Tables 4 to 9 list the 8 cost elements in relation to Tables 1 to 3. The highlighted cells, in pale yellow, are driven by the Excel formulas, whose values are calculated automatically. Pale blue columns are user input for the collected cost information for the manufacturing plant. All the tables' green-highlighted columns are "Type", "Name", and "Desc", which is the type of operation or cost element, the name, and the description respectively.

Table 1: Annual Product Output

This cell indicates the yearly production output in quantities of the product. It is the projected delivered product to the customer without any defective product return.

Table 2: Part Relation in Operations

For the column "Oprn", the operations are listed according to the operation reference number. The "OprnRw#" column helps users keep track of all operations involved in the production system. This information only appears once throughout the data sheet. The next few columns describe all of the capsules inputs, outputs and all cost elements for each operation group. These are designated by name "in" and "out" for material and supplies entering or leaving the capsule group as well as components and assemblies moving from one capsule to another. The "in" or "Matl+" column shows the material added to the production line or operations; while the "Out" column indicates material leaving the operations. The "Matl-" column indicates the scrap material,

damaged parts, and old or obsolete parts in store, which is added to material cost in terms of disposal and recycling handling fees. If there are 2 "Out" columns, 3 "In" columns and 3 "Matl-" columns, as in Table 2, it indicates that for an operation there are possible 3 inputs, 2 outputs, and 3 types of waste materials, respectively. Table 2 re-organizes the information in the flow diagram to show the material flow between operations.

Table 3: Operation With Cost Elements

This table shows the distribution of cost elements for each operation. The table allows two columns of "nMach" or three columns of "nOper" for each operation. These extra columns leave some room for operations that involve more than one identical cost element. For example, "nOper", which means the number of operators, can be a maximum of 3 who work for a particular operation. Note that the symbol "nMach" means the type of the machine; "nSpac" is the type of the space; "nFixx" is the type of the fixture; "qCtrt" is the type of contract cost; "qIncv" is the type of incentive cost; and "oTiCt" is the percentage of the tied cost. The "Qref" column is for the user to add a description or reference for the operations. For example, the "LatDl" refers to products that are acceptable to the customer but are delivered late in Table 2. The customer may be given a price discount for the late delivery, which is referred as "LatFee". The late fee is documented in Table 8 as an incentives element. Similarly, if the customer does not accept the late product due to damage in handling, it would be shown as a bad product; "BadPd" indicates that a product has been rejected or scrapped or sold at a significant loss in value. Possibly two costs can incur due to the bad product. One is referred as

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"BadRet," which is the cost of shipping and handling. The other is referred as "BadFee", which is the possible penalty that is charged by the customer for the damaged product.

Table 4: Material Cost

This table considers the annual material cost for making the product. The "Matl+" under the "Type" column indicates material added to the production while "Matl-" is the material out of the production system as mentioned before such as scrap, damaged parts and obsolete parts. The "base$/yr" and "added $/prt" or "added $/unit" columns are the main statements of costs. The first gives the base cost of material usage regardless of its level of use. The second cost is the added cost for its use. The material cost per year is the sum of these two quantities that can be seen as a linear equation below:

$$material\ cost/year = base\$/year + added\$/unit * quantity\ unit$$

The "base$/year" is considered as the fixed cost while the "added$/unit" is depend on the quantity produced. In some cases, a volume discount is offered when the quantity required exceeds the normal quantity. As shown in Table 4, "$ for qty 1.0" is the price for a normal quantity, and "$ for 1.5" is the price for a 1.5 times the normal quantity. The volume discount reduces the "added$/unit" and hence the "material cost/year". This example did not consider the volume discount and therefore the cost/unit remains, for example, $3.00 for "pSSheet". If the material scrap is significant, the cost of scrap is listed under the "Matl-" column. In this table example, the scrap produced is considered insignificant however other "Matl-" items are added as damaged or obsoleted parts. The

unit production value under the "units/yr" column for each component should be at least equal or larger than the predicted unit production per year for the product.

Table 5: Operator Cost

This table lists the operator costs for 1 shift year, representing 2,080 hours with 40 hours a week. Usually there is no added operator cost/part. The cost per shift year of the operator is found by adding the salary for a year of operation to the costs of fringe benefits and support. This is then divided by the actual working hours including rest breaks, and then multiplied by 2,080 hours to get 1 shift year of actual at work time as shown by the following equation,

Operator Cost/Shift Year = 2,080 hours*(salary + other pay + fringe1 + support)/(shift hours/year)

where, "fringe1" will be explained later.

A worker working no overtime will actually be on shift about 1,700 hours per year, i.e., 2,080 hours minuses sick leave, training time, and holidays. For some cases, a worker working overtime may be on shift as much as 2,500 hours per year, assuming this is legal. By referring to the table and the headings related to the operator costs:

Salary and other pay: "sal, $/y" shows hourly or weekly salary. "oth pay, $/y" includes the overtime payment; piecework incentive; yearly bonuses, and any other payment for time spent or work done.

The fringe benefits: The fringe benefits are categorized to "Fringe1" and "Fringe2". The "fring1" column lists all money spent on behalf of the operator to make his life better in some way, and can include a medical plan including out-of-country medical insurance,

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dental plan, pension, unemployment insurance, and long term disability insurance. The "fring2" column, covers all paid time-off including sick leave, statutory holidays, summer holidays, maternity leave, and the special and bereavement leave.

Support Cost: The "supprt, $/y" column covers all money spent to keep the operator in a workable state in the plant. This support includes washrooms, first-aid stations, and any aisles for operators that are not used for goods transport, direction from a foreman, personnel department, payroll clerk, worker's compensation, continuous training, and hire-train-terminate average yearly. If any support takes the operator away from the work place for a period of time such as training time, the time is entered into "supprt, hrs/y" column.

Shift hours/year: The "shft hrs/yr" column is the time that the worker is actually on shift and is equal to

$$Shift\ hours/years = nominal\ hours/year + overtime\ hours/year - fringe2\ hours/year - support\ hours/year$$

For simplicity, this table only involves one operator called "StdO", who does all the jobs related to the product in the plant. The utilization of the operator factor in Table 3 is obtained from the following equation:

$$Operator\ factor = (time\ per\ operation * multiplier * quantity\ parts/year)/(total\ hour/year)$$

The time per operation is the actual time that an operator works directly on the product. The multiplier or adjustment factor is for the time lost due to rest break or time delay on setup, breakdown, and so on by the operator. The quantity part per year is the output of the production system and the total hours per year is normally 2080 hours.

Table 6: Machine & Fixture Cost

This table includes the machine and fixture costs in one table since these two elements are often closely related in the manufacturing operations. Normally, the cost of the machine is one of the most complex cost elements for modeling due to many related capital costs, wear cost and other related utilities and services. The following will describe these costs in detail.

1) <u>Capital Related Costs</u> of a machine over a year include:

- The cost of interest on the value of the machine

- The loss of value of the machine over a year caused by the elapse of time or depreciation of machine

- The cost of installation and training amortized over the time of the machine's use

- The cost incurred from taxes amortized over the years of use. This assumes that the company makes a profit and the capitalization of the machine increases the apparent profit.

- <u>Capital Related Cost</u>: The cost of interest, loss of value and installation per year:

$$Capital\ Cost/year = [interest\ on\ average\ value/year] + [average\ loss\ in\ original\ cost/year]$$
$$= [Interest * ((Purchase\ Cost + Install\ Cost) + Sell\ Value)/(2)] +$$
$$[((Purchase\ Cost + Install\ Cost) - Sell\ Value)/(Quantity\ Years\ of\ Use)]$$

- <u>Cost of Taxes</u>: Generally, the cost of interest on taxes is occurred to the machine as it is depreciated. Since this value involves a complex set of calculations, details will not be provided here and for simplicity the approximated 10% interest is subjected to the purchase price as shown by equation below:

% Increase On Tax Of Purchase Price = 10%

Therefore, the total tax per year:

Tax/year = {[Interest* ((Purchase Cost + Sell Value)/(2)) +
[((Purchase Cost - Sell Value)/(Quantity Years of Used))]}* % Increase On Tax Of Purchase Price

2) <u>Wear Related Costs</u> of a machine per year are caused by its use and include:

- The cost of maintenance and repair

- The cost of complete overhaul if this is a machine type that is routinely overhauled to an as-new condition. An aircraft engine is an example.

- The loss in value of the machine caused by wear if this is a machine type that is not routinely overhauled to an as-new condition. A police car is an example.

- The cost of maintenance and repair includes the cost of parts and labor, which are stated by the maintenance department. The cost of wear to capital cost is similar to the calculation of Capital Cost/year shown above but with a slight change to the sell value,

Wear Capital Cost/year = [Interest* ((Purchase Cost + Install Cost) + Wear Sell Value)/(2)] +
[((Purchase Cost + Install Cost) – Wear Sell Value)/(Quantity Years of Use)]

Thus, the loss of value caused by wear is the difference between the calculated Capital Cost/year and Wear Capital Cost/year

Wear Cost/year = Capital Cost/year - Wear Capital Cost/year

3) <u>Other Costs</u> of a machine include:

- The cost of services, e.g. water, electricity. Note that if a significant cost of a resource occurs as the machine operates, this cost is separated from the machine and considered a cost of supply or material, so that it can be more accurately tracked. The service cost calculation is rather straightforward. For example, service cost/year equals to $500 as a summary of yearly charges.

Therefore, the machine cost per year can be obtained as the equation shown:

$$\textit{Machine Cost/year} = \textit{Capital Cost/year} + \textit{Cost of Taxes on Capital} + \textit{Cost of Services}$$
$$\textit{Machine Extra Cost/unit} = (\textit{Maintenance \& Repair Cost/year} + \textit{Wear Cost /year})/(\textit{unit/year})$$

The fixture cost per year is a subset of the machine cost per year and its calculation is basically the same as machine cost. However, costs of installation, wear and services, and selling value are usually not significant quantities to be included in the calculation. The following is the information required for the machine calculation, including:

- The estimate of number of years the machine is to be used before it is resold or put into long-term storage.

- The cost of purchase and an appropriate addition to the cost if the machine has worn and is to be rebuilt during its time in the plant.

- The cost of delivery to the plant, installation, and training of operators and maintenance and repair personnel.

- The salvage value of the machine. Two conditions of sale are of interest: the value considering no additional wear on the machine from the time of purchase, and the

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value considering the projected wear on the machine for machines that are not regularly rebuilt.

- Interest rate

Table 7: Space Cost

This table shows the space costs per year of use, which include the cost of rental, heat, electricity and standard cleaning costs, which are not directly related to production. If the cost of space must be calculated, standard industrial real-estate rental guidelines should be used. The space cost per meter square per year, "$/sq m/y" column, can be obtained by dividing the sum of utilities cost and rent with total manufacturing area in meter square. Thus, cost/year is obtained from the following equation:

$$Space\ Cost/year = cost/sqm\ for\ year * sqm$$

In this table example, the "$/sq m/y" can be obtained from the $100,000 utilities cost and rent, divided by 1000 m^2 of manufacturing plant area. The "sq m" column shows the space area in m^2 while the "$/yr" depicts cost/year for 1m^2 area. This space cost is assigned to the "nSpac" column in Table 3 where the factor, "fctr", of 2.00 means 2m^2 of "MnPlnt" area is used for the operation.

Table 8: Contract and Incentives

This table combines the contract and the incentives cost elements into one table. The calculations are usually similar to the material cost calculations. The contract costs are usually very clear and easy to calculate. For example, the cost of transport is the most

common contract cost, and is based on the amount of production, the distance between points, and the number of deliveries in the year showed by "DlvTrk". Sometimes extra costs are added for special delivery trips and for a significantly different quantity of product to be delivered than projected. Some special manufacturing operations that require expensive specialized equipment, such as electroplating in "Plating", are sometimes subcontracted. Another contract is dealing with customers through a retailer or other third party. If product returns are handled at an extra cost such as "BadRet", this can be considered a contract cost as well.

In addition, penalties or incentives are paid to customers to either appease them for suffering related lost in quality or timing issues. Penalty relationships can also be worked with the manufacturers' own sales department, or between departments such as manufacturing to distribution. This money relationship is used a lot between two companies, especially when Just-In-Time (JIT) is a part of the process. This cost is usually based on the number of parts affected.

Incentive or penalty cost/part = cost charged in year / qnty parts/year

For example, in the "Out" column in Table 2, "LateDl" shows 5% of late delivered products. In Table 8, "LatFee" shows under the "$/unit" column, a $10 is added to each late product.

Table 9: Tied Cost

The table only shows the yearly interest for the tied cost. Normally the tied cost is usually very small and is the cost of money tied up in inventory, insurance on

inventory, and taxes on the inventory value. If the inventory is stored for half a year or more, or interest rates go above 12%, or if the costs are to be extremely detailed, this cost is worth considering. Usually the inventory that is obsolete, spoiled, and pilfered, creates much greater costs. This example uses 8% of yearly interest and the "oTiCt" column in Table 3 shows that 25% of inventories are subjected to this cost.

A.3 Cost Table Sheet: Calculation and Show Result

This table worksheet mainly involves computation of the element cost. It will calculate the total cost per product. It also breaks down the element costs to cost per operation group. The first few columns from the left basically shows the quantity produced in every operation as listed under "Qnty" and "qnty prdt" columns. The individual operation cost is shown under "OprnTot" column, which is the sum of all cost elements excluding material cost. The material cost is listed separately since it is usually the most significant production cost. The terms used for the costs to the right side are: the material cost ("Matl" column), operator cost ("Oper" column), material or parts through the operations ("In/Out" column), machine, fixture, space and contract costs ("MFSC" column), maintenance and repair cost ("M&R" column) for the machine and fixture and other tied and incentives cost ("Other" column). Other columns such as "$/unit", "C/yr" and "+ C/unit" shows the cost/unit, cost/year and added cost/unit production respectively.

The yellow highlighted top cell and bottom cell in the first column are the control start and end called "OprnStrt" and "OprnStop" respectively. Basic iteration is used to search for quantity of inputs required in order to obtain the desired output of 10000

unit/year. The result of the table unit production cost can be seen in the last operation number 36, "StrDlvr," where the delivered product "DeliveredPd" row shows cost/unit is $67.59. Thus, the production cost for this table example is $67.59/unit.

A.4 Charts Sheet: Graphical Interpretation Of Cost Element

This worksheet shows the results of the "CostTable" in more understandable charts format. The data are presented in bar charts so that the user can interpret the resultant cost elements effectively and identify an operation that can be potentially improved either through design or through manufacturing process changes. The following describes the charts used in this worksheet.

1) <u>Total Cost For Each Operation</u>: shows the total cost for each operation group.

2) <u>Fixed & Per Unit Costs</u>: shows the $/unit of product in each operation group.

3) <u>No Loss Costs & Costs From Loss</u>: shows the difference in cost with no loss and loss due to inefficient operations. The table example did not consider the chart and data information relevant to the results and therefore is not used here whatsoever throughout the entire research.

4) <u>Added Cost For Each Operation</u>: shows the cost added to each operation group.

5) <u>Cost Distribution By Cost Type</u>: shows the total cost distribution for each capsule or operation group in every cost element. This chart is important for users to identify which cost element contributes most to the final production cost. For example "MSFC" has a brown color bar that corresponds to the "Plating" operation. This value is 23.39, which in fact has the highest value for the contract

cost and thus the user can seek improvements to this operation. The final production cost can be seen from the table under the "final out" column and "Oprn #" number 36, which is $67.59.

A.5 Running the Excel Macro

This section continues on describing the function of the macros used in the table example. The "CostTable" and "Charts" worksheets are created automatically using macro buttons. Users only need to press the designated macro button and the information will be displayed to the user within the "CostTable" worksheet. The following describes the macro names used in the program. The "PikDatToTabl" button is located in the "ElementData" worksheet and "GrphDrivF" is in the "Charts" worksheet while the other buttons are within the "CostTable" worksheet. These buttons are pressed according to the sequence as shown below:

1) PikDatToTabl: Pick the data from Tables 1 to 9. Note that for Tables 4 to 9, only the data between columns 2 and 8, counted from the left, will be picked and used in the cost calculation.

2) DropDatToTabl: Collect data from Tables 1 and 2.

3) MdfyDatInTabl: Collect data from Table 3.

4) CstDatInTabl: Collect data and equations from Tables 4 to 9.

5) OvCstSysCalb: Test and calculate the possible savings.

6) GrphDrivF: Plot graphs to show the results.

Note that these buttons can be categorized into a single button to facilitate design automation, which will be discussed in Chapter 6. The cost tables used in the silencer and air diffuser projects are similar to the above with only slight modifications that integrate the optimization and design parameters. Both projects are discussed in Chapter 4 and 5 respectively.

Operation-Based Costing Excel Worksheet

Section 1: Flow Diagram Worksheet

File Edit View Insert Format Tools Data Window Help

Section 1: Flow Diagram

	1		2		3		4		5

TiCt 0.25 | Oper StdO | Spac MnPlnt

pSSheet PurS 11 SSheetAv

TiCt 0.25 | Oper StdO | Spac MnPlnt

pTPlasticS PurWS 12 TPlasticSAv

TiCt 0.25 | Oper StdO | Spac MnPlnt

pSPipe PurSP 13 SPipeAv

Oper StdO | Spac MnPlnt

pScrew PurSB 14 ScrewAv

TiCt 0.25 | Oper StdO | Spac MnPlnt

pWBoard PurWB 15 WBoardAv

TiCt 0.25 | Oper StdO | Spac MnPlnt

pSPlate PurP 16 SPlateAv

TiCt 0.25 | Oper StdO | Spac MnPlnt

pPStrip PurStrip 17 PStripAv

Pipe Section:

Oper StdO | Mach HackSaw | Spac MnPlnt

SPipeAv Cut 21 SPipe

Oper StdO | Mach HandGrinder | Spac MnPlnt

Deburr 22 SPipeR

SPipeScrp

Bottom Plate Section:

Table Bottom Section:

Oper StdO | Mach Punch | Spac MnPlnt | Fixx SSheetFixx

SSheetAv CutCir 23 SCircular

Oper StdO | Mach Spin | Spac MnPlnt | Fixx SpinFixx

Spin 24 SCircularR | SPipeR

Oper StdO | Spac MnPlnt

Braze 25 Tsmooth

Oper StdO | Spac MnPlnt

Smooth 26 TStand

Ctrt Plating

Plate 27 TStandR | SPlateAv

Oper StdO | Spac MnPlnt

Press 28 Tbottom

SSheetScrp

BrazeDg

TBottomDg

TiCt 0.25 | Oper StdO | Spac StrSpc | Ctrt DlvTrk | Ctrt BadRet | Incv LatFee | Incv BadFee

Wood Cutting Section:

Table Top Section:

Oper StdO | Spac MnPlnt

TPlasticSAv | WBoardAv GlueTop 31 Gboard

Oper StdO | Mach JigSaw | Spac MnPlnt | Fixx JigsawFixx

Saw 32 GBoardR | PStripAv

Oper StdO | Spac MnPlnt

GlueEdg 33 Tedge

Oper StdO | Spac MnPlnt

Trim 34 TTop | TBottomAv | ScrewAv

Oper StdO | Spac MnPlnt

Assem 35 Table

StrDlvr 36 Delive | LateDl

GBoardScrp

PdDd BadPd | DamagePd

Part Flow Descriptions

Section 2: ElementData Worksheet

Table 1: Quantity Out

YrlyOut	Qnty
DeliveredPd	10,000

Table 2: Part Relations

Oprn	Oprn#	Out Dim	OprnRw#	Out	fctr	Out	fctr	In+	fctr	In	fctr	In	fctr	Sc Matl-	Scrap fctr	Dg Matl-	Damage fctr	Od Matl-	Old fctr
PurS	11	coil form,kg	1	SSheetAv	1.00			pSSheet	1.00										
PurWs	12	5'x12' sheet	2	TPlasticAv	1.00			pTPlastic	1.00										
PurSP	13	5' long,2.5in dia	3	SPipeAv	1.00			pSPipe	1.00										
PurSB	14	box	4	ScrewAv	1.00			pScrew	1.00										
PurWB	15	5'x12' sheet	5	WBoardAv	1.00			pWBoard	1.00										
PurP	16	5"x5" square feet	6	SPlateAv	1.00			pSPlate	1.00										
PurStrip	17	1.5 in x 5 ft long	7	PStripAv	1.00			pPStrip	1.00										
Cut	21	18" length	8	SPipe	1.00			SPipeAv	1.00					SPipeScrp	0.00				
Deburr	22		9	SPipeR	1.00			SPipe	1.00										
CutCir	23	20" dia	10	SCircular	1.00			SSheetAv	1.00					SSheetScrp	0.00				
Spin	24		11	SCircularR	1.00			SCircular	1.00										
Braze	25		12	Tsmooth	1.00			SCircularR	1.00	SPipeR	1.00					BrazeDg	0.05		
Smooth	26		13	TStand	1.00			Tsmooth	1.00										
Plate	27		14	TStandR	1.00			TStand	1.00										
Press	28		15	TBottomAv	1.00			TStandR	1.00	SPlateAv	1.00					TBottomDg	0.05		
GlueTop	31		16	GBoard	1.00			WBoardAv	1.00	TPlasticAv	1.00								
Saw	32	40" dia	17	GBoardR	1.00			GBoard	1.00					GBoardScrp	0.00				
GlueEdg	33		18	Tedge	1.00			GBoardR	1.00	PStripAv	1.00								
Trim	34		19	TTop	1.00			Tedge	1.00										
Assem	35		20	Table	1.00			TTop	1.00	TBottomAv	1.00	ScrewAv	8.00						
StrDlvr	36		21	DeliveredPd	0.95	LateDl	0.05	Table	1.00							DamagePd	0.05	PdDd	0.05

Table 3: Operation

Oprn	Oprn #	nOper	fctr	Qref	nMach	fctr	Qref	nSpac	sq m Fctr	nFixx	Fctr	qCtrt	Fctr	Qref	qIncv	Fctr	Qref	oTiCt
PurS	11	StdO	0.06					MnPlnt	2.00									0.25
PurWs	12	StdO	0.06					MnPlnt	2.00									0.25
PurSP	13	StdO	0.06					MnPlnt	2.00									0.25
PurSB	14	StdO	0.06					MnPlnt	1.00									
PurWB	15	StdO	0.06					MnPlnt	2.00									0.25
PurP	16	StdO	0.06					MnPlnt	2.00									0.25
PurStrip	17	StdO	0.06					MnPlnt	2.00									0.25
Cut	21	StdO	0.12		HackSaw	0.10		MnPlnt	4.00									
Deburr	22	StdO	0.12		HandGrinder	0.10		MnPlnt	4.00									
CutCir	23	StdO	0.60		Punch	0.10		MnPlnt	6.00	SSheetFixx	1.00							
Spin	24	StdO	0.60		Spin	1.00		MnPlnt	6.00	SpinFixx	1.00							
Braze	25	StdO	0.60					MnPlnt	4.00									
Smooth	26	StdO	0.30					MnPlnt	3.00									
Plate	27	StdO	0.00									Plating	1.00					
Press	28	StdO	0.18					MnPlnt	3.00									
GlueTop	31	StdO	0.60					MnPlnt	2.00									
Saw	32	StdO	0.60		JigSaw	1.00		MnPlnt	3.00	JigsawFixx	1.00							
GlueEdg	33	StdO	0.60					MnPlnt	3.00									
Trim	34	StdO	0.18					MnPlnt	3.00									
Assem	35	StdO	1.20					MnPlnt	5.00									
StrDlvr	36	StdO	0.60					MnPlnt	10.00			DlvTrk	1.00		BadFee	1.00	BadPd	0.25

Table 4: Cst: Matl/ Yr+ /Unit

Type	Name	Desc	base $/yr	add $/prt	unit	units/yr	$ for qty 1.0	$ for 1.5	$/unit/yr	$/unit/yr
Matl+	pSSheet	Kg, sheet steel in coil form	0	3.00	table	10,000	30,000	45,000	3.00	
Matl+	pScrew	ship boxes for 5 units ea	0	0.13	Qnty	80,000	10,000	15,000	0.13	
Matl+	pWBoard	m, Wood Board	0	5.00	table	10,000	50,000	75,000	5.00	
Matl+	pTPlastic	m, plastic thin sheet	0	3.00	table	10,000	30,000	45,000	3.00	
Matl+	pSPipe	m, steel pipe	0	1.00	table	10,000	10,000	15,000	1.00	
Matl+	pPStrip	m, plastic edge	0	1.00	table	10,000	10,000	15,000	1.00	
Matl+	pSPlate	m, square plate	0	1.00	table	10,000	10,000	15,000	1.00	
Matl-	SPipeScrp	Unt, scrap from cutting	0	0.00	table					
Matl-	SSheetScrp	Unt, scrap from punch	0	0.00	table					
Matl-	BrazeDg	Unt, damaged from blazing	0	1.00	table					
Matl-	TBottomDg	Unt, damaged from Press fitting	0	1.00	table					
Matl-	GBoardScrp	Unt, damaged from sawing	0	0.00	table					
Matl-	OldPd	Old Prod scrap value	0	10.00	table					
Matl-	DamagePd	Bad Prd Sc Value	0	5.00	table					
Matl-	PdDd	Obselete product	0	1.00	table					

Table 5: Cst: Oper/ sh yr

(1 sh yr = 2,000 hrs, 8hrs* 5 says * 50 wks)

Type	Name	Desc	Qctrl	$/sh yr	sal, $/y	oth pay, $/y	frng1, $/y	supprt, $/y	supprt, hrs/y	nom hrs/y	ovtm h/y	fring2 h/y	shft hrs/yr
Oper	StdO	for all jobs	1	34,524	20,000	2,000	2,000	5,000	100	2,080	50	350	1,680

Table 6: Cst: Mach, Fxx /yr

| | | | | | approx | install incl in Pur Cst | | | | (inc. time spent) | | | | | | Calc, (/Yr) | | |
| | | | | | | Cap | Cap | Cap | Wear | Cap | Cap | Cap | Wear | Othr | | not used | used | |
Type	Name	Desc	Qctrl	$/yr	$/unit	unit	units/yr	Pur Cst	Install Cst	Sell val, N	Sell val, W	Qty yr use	Qty yr dep	int %	M&R	srvc cst	Tax	cap,int	cap,int	diff
Mach	HackSaw	cutting steel	0	1,132	0.01	prt	100,000	5,000	500	3,000	1,000	10	5	8	1,000	500	42	590	710	120
Mach	HandGrinder	smoothing	0	651	0.01	prt	10,000	1,000	0	0	0	10	5	8	200	500	11	140	140	0
Mach	Punch	metal circle shape	0	6,396	0.03	prt	100,000	50,000	2,000	30,000	20,000	10	5	8	2,000	500	416	5,480	6,080	600
Mach	Spin	spinning	0	1,266	0.03	prt	10,000	5,000	1,000	2,000	1,000	10	5	8	200	500	46	720	780	60
Mach	JigSaw	Jigsaw	0	1,331	0.05	prt	10,000	5,000	1,000	1,000	500	10	5	8	500	500	51	780	810	30
Fixx	JigsawFixx	cutting board	0	151	0.00	prt	10,000	1,000	0	0	0	10	5	8	0	0	11	140	140	0
Fixx	SSheetFixx	sheet fixture	0	6,048	0.00	prt	10,000	40,000	0	0	0	10	5	8	0	0	448	5,600	5,600	0
Fixx	SpinFixx	spin fixture	0	756	0.00	prt	10,000	5,000	0	0	0	10	5	8	0	0	56	700	700	0

Table 7: Cst: Spac /yr

Type	Name	Desc	Qctrl	$/yr		$/sq m/y	sq m
Spac	MnPlnt	in main plant plant has 1,000 sq m	0	100		100	1

Table 8: Cst: Ctrt, Incv /yr

| | | | (always =0) | | | | approx |
Type	Name	Desc	Qctrl	base $/yr	$/unit	units	units/yr
Ctrt	DlvTrk	truck delivery on contract	0	100	0.004		10,000
Ctrt	BadRet	returns effort by retailer	0		20		200
Ctrt	Plating	Contract with plating co.	0		20		10,000
Incv	LatFee	reduced price if prdct late	0		10		1,000
Incv	BadFee	reduced price to customer of bad product	0		30		200

Table 9: Cst: TiCt

Type	Name	Desc		Int %
TiCt		fctr yr prdctn stored, yrly int %		8

Section 3: CostTable Worksheet

Overview Cost Table

Instructions for this page

1) Make a copy of this page and give it another name
2) Do "ElementData" sheet first
3) Clear everything below green highlighted line
4) Hit "DropDAtToTabl" button and wait for finish
5) Hit "MdfyDatInTabl" button
6) Hit "OvCstSysCalb", this might a while

7) Go to the "Charts" sheet and hit "GrphDrv"

Part Flow side ← → Element Cost Side

[DropDatToTabl]   [MdfyDatInTabl]   [CstDatInTabl]   [OvCstSysCalb]

OprnStrt

Oprn #	Type	Name	Desc	Qctrl	Dim	Qnty	q/prdt	qnty prdt	OprnTot	Matl	In/Out	Oper	MSFC	M&R	Other	$/unit	C/yr	+ C/unit
				nomVol	base Qnty for Oper, Mach, Fixx, Spac								Contract Space Fixture Machine	Space Fixture Machine	TiedCost Incentive			
11	Oprn	PurS						-12,311	3,072	0	0	2,071	200	0	800	0.25	204	0.23
	Matl+	pSSheet	Kg, sheet steel in coil form	12,311		12,311.5 1.00		12,311		36,934							0	3.00
	Oper	StdO	for all jobs	1	0.06	0.1 1.00				2,071		2,071					34,524	
	Spac	MnPlnt	in main plant	0	2.00	2.0 1.00				200			200	0			100	
	Out	SSheetAv				1.00		-12,311		-40,006						3.25	204	3.23
	TiCt		0.25 fctr yr prdctn stored, yrly int %					3,078	800						800		8	
12	Oprn	PurWs						-11,111	2,998	0	0	2,071	200	0	727	0.27	204	0.25
	Matl+	pTPlastic	m, plastic thin sheet	11,111		11,111.1 1.00		11,111		33,333							0	3.00
	Oper	StdO	for all jobs	1	0.06	0.1 1.00				2,071		2,071					34,524	
	Spac	MnPlnt	in main plant	0	2.00	2.0 1.00				200			200	0			100	
	Out	TPlasticAv				1.00		-11,111		-36,331						3.27	204	3.25
	TiCt		0.25 fctr yr prdctn stored, yrly int %					2,778	727						727		8	
13	Oprn	PurSP						-12,311	2,569	0	0	2,071	200	0	298	0.21	204	0.19
	Matl+	pSPipe	m, steel pipe	12,311		12,311.5 1.00		12,311		12,311							0	1.00
	Oper	StdO	for all jobs	1	0.06	0.1 1.00				2,071		2,071					34,524	
	Spac	MnPlnt	in main plant	0	2.00	2.0 1.00				200			200	0			100	
	Out	SPipeAv				1.00		-12,311		-14,881						1.21	204	1.19
	TiCt		0.25 fctr yr prdctn stored, yrly int %					3,078	298						298		8	
14	Oprn	PurSB						-88,889	2,171	0	0	2,071	100	0	0	0.02	100	0.02
	Matl+	pScrew	ship boxes for 5 units ea	88,889		88,888.9 1.00		88,889		11,111							0	0.13
	Oper	StdO	for all jobs	1	0.06	0.1 1.00				2,071		2,071					34,524	
	Spac	MnPlnt	in main plant	0	1.00	1.0 1.00				100			100	0			100	

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Sc	Type	Name	Description	Qty			m	Cost								Ratio		
	Out	ScrewAv					1.00	-88,889				-13,283				0.15	100	0.15
	15Oprn	PurWB						-11,111	3,452	0	0		2,071	200	0	1,180 0.31	204	0.29
	Matl+	pWBoard	m, Wood Board	11,111		11,111.1	1.00	11,111	55,556								0	5.00
	Oper	StdO	for all jobs	1	0.06	0.1	1.00		2,071				2,071				34,524	
	Spac	MnPlnt	in main plant	0	2.00	2.0	1.00		200					200	0		100	
	Out	WBoardAv					1.00	-11,111				-59,007				5.31	204	5.29
	TiCt	0.25	fctr yr prdctn stored, yrly int %					2,778	1,180						1,180		8	
	16Oprn	PurP						-11,696	2,556	0	0		2,071	200	0	285 0.22	204	0.20
	Matl+	pSPlate	m, square plate	11,696		11,695.9	1.00	11,696	11,696								0	1.00
	Oper	StdO	for all jobs	1	0.06	0.1	1.00		2,071				2,071				34,524	
	Spac	MnPlnt	in main plant	0	2.00	2.0	1.00		200					200	0		100	
	Out	SPlateAv					1.00	-11,696				-14,252				1.22	204	1.20
	TiCt	0.25	fctr yr prdctn stored, yrly int %					2,924	285						285		8	
	17Oprn	PurStrip						-11,111	2,545	0	0		2,071	200	0	273 0.23	204	0.21
	Matl+	pPStrip	m, plastic edge	11,111		11,111.1	1.00	11,111	11,111								0	1.00
	Oper	StdO	for all jobs	1	0.06	0.1	1.00		2,071				2,071				34,524	
	Spac	MnPlnt	in main plant	0	2.00	2.0	1.00		200					200	0		100	
	Out	PStripAv					1.00	-11,111				-13,656				1.23	204	1.21
	TiCt	0.25	fctr yr prdctn stored, yrly int %					2,778	273						273		8	
	21Oprn	Cut						-12,311	4,794	0	0		4,143	513	138	0 0.39	513	0.35
Sc	In	SPipeAv				0.0	0.00		0			0						1.19
	In	SPipeAv		12,311		12,311.5	1.00	12,311				14,881					204	1.19
	Oper	StdO	for all jobs	1	0.12	0.1	1.00		4,143				4,143				34,524	
	Mach	HackSaw	cutting steel	0	0.10	0.1	1.00		251					113	138		1,132	0.01
	Spac	MnPlnt	in main plant	0	4.00	4.0	1.00		400					400	0		100	
	Out	SPipe					1.00	-12,311				-19,674				1.60	717	1.54
	Matl-	SPipeScrp	Unt, scrap from cutting				0.00	0	0			0					0	0.00
	22Oprn	Deburr						-12,311	4,670	0	0		4,143	465	62	0 0.38	465	0.34
	In	SPipe		12,311		12,311.5	1.00	12,311				19,674					717	1.54
	Oper	StdO	for all jobs	1	0.12	0.1	1.00		4,143				4,143				34,524	
	Mach	HandGrinder	smoothing	0	0.10	0.1	1.00		127					65	62		651	0.01
	Spac	MnPlnt	in main plant	0	4.00	4.0	1.00		400					400	0		100	
	Out	SPipeR					1.00	-12,311				-24,344				1.98	1,182	1.88
	23Oprn	CutCir						-12,311	28,322	0	0		20,714	7,288	320	0 2.30	7,288	1.71
Sc	In	SSheetAv				0.0	0.00		0			0						3.23
	In	SSheetAv		12,311		12,311.5	1.00	12,311				40,006					204	3.23
	Oper	StdO	for all jobs	1	0.60	0.6	1.00		20,714				20,714				34,524	
	Mach	Punch	metal circle shape	0	0.10	0.1	1.00		960					640	320		6,396	0.03
	Spac	MnPlnt	in main plant	0	6.00	6.0	1.00		600					600	0		100	
	Fixx	SSheetFixx	sheet fixture	0	1.00	1.0	1.00		6,048					6,048	0		6,048	0.00
	Out	SCircular					1.00	-12,311				-68,328				5.55	7,492	4.94
	Matl-	SSheetScrp	Unt, scrap from punch				0.00	0	0			0					0	0.00
	24Oprn	Spin						-12,311	23,657	0	0		20,714	2,622	320	0 1.92	2,622	1.71
	In	SCircular		12,311		12,311.5	1.00	12,311				68,328					7,492	4.94

	Type	Code	Description	Qty											
	Oper	StdO	for all jobs	1	0.60	0.6	1.00		20,714		20,714			34,524	
	Mach	Spin	spinning	0	1.00	1.0	1.00		1,586			1,266	320	1,266	0.03
	Spac	MnPlnt	in main plant	0	6.00	6.0	1.00		600			600	0	100	
	Fixx	SpinFixx	spin fixture	0	1.00	1.0	1.00		756			756	0	756	0.00
	Out	SCircularR					1.00	-12,311			-91,985			7.47 10,114	6.65
	25Oprn	Braze						-11,696	25,750	-616	5,252 20,714	400	0	0 2.20 400	2.17
Sc	In	SPipeR				615.6	0.05		1,158		1,158				1.88
	In	SPipeR				11,695.9	1.00	12,311			23,186			1,182	1.88
Sc	In	SCircularR				615.6	0.05		4,094		4,094				6.65
	In	SCircularR		12,311		11,695.9	1.00	12,311			87,891			10,114	6.65
	Oper	StdO	for all jobs	1	0.60	0.6	1.00		20,714		20,714			34,524	
	Spac	MnPlnt	in main plant	0	4.00	4.0	1.00		400			400	0	100	
	Out	Tsmooth					1.00	-11,696			-136,827			11.70 11,696	10.70
	Matl-	BrazeDg	Unt, damaged from blazing				0.05	-616	-616	-616				0	1.00
	26Oprn	Smooth						-11,696	10,657	0	0 10,357	300	0	0 0.91 300	0.89
	In	Tsmooth		11,696		11,695.9	1.00	11,696			136,827			11,696	10.70
	Oper	StdO	for all jobs	1	0.30	0.3	1.00		10,357		10,357			34,524	
	Spac	MnPlnt	in main plant	0	3.00	3.0	1.00		300			300	0	100	
	Out	TStand					1.00	-11,696			-147,485			12.61 11,996	11.58
	27Oprn	Plate						-11,696	233,918	0	0 0	0 233,918	0	020.00 0	20.00
	In	TStand		11,696		11,695.9	1.00	11,696			147,485			11,996	11.58
	Oper	StdO	for all jobs	1	0.00	0.0	1.00		0		0			34,524	
	Ctrt	Plating	Contract with plating co.	0	1.00	1.0	1.00		233,918			233,918			20.00
	Out	TStandR					1.00	-11,696			-381,403			32.61 11,996	31.58
	28Oprn	Press						-11,111	25,102	-585	19,173 6,214	300	0	0 2.26 300	2.23
Sc	In	SPlateAv				584.8	0.05		702		702				1.20
	In	SPlateAv				11,111.1	1.00	11,696			13,550			204	1.20
Sc	In	TStandR				584.8	0.05		18,470		18,470				31.58
	In	TStandR		11,696		11,111.1	1.00	11,696			362,932			11,996	31.58
	Oper	StdO	for all jobs	1	0.18	0.2	1.00		6,214		6,214			34,524	
	Spac	MnPlnt	in main plant	0	3.00	3.0	1.00		300			300	0	100	
	Out	TBottomAv					1.00	-11,111			-401,585			36.14 12,501	35.02
	Matl-	TBottomDg	Unt, damaged from Press fitting				0.05	-585	-585	-585				0	1.00
	31Oprn	GlueTop						-11,111	20,914	0	020,714	200	0	0 1.88 200	1.86
	In	TPlasticAv				11,111.1	1.00	11,111			36,331			204	3.25
	In	WBoardAv		11,111		11,111.1	1.00	11,111			59,007			204	5.29
	Oper	StdO	for all jobs	1	0.60	0.6	1.00		20,714		20,714			34,524	
	Spac	MnPlnt	in main plant	0	2.00	2.0	1.00		200			200	0	100	
	Out	GBoard					1.00	-11,111			-116,253			10.46 608	10.41
	32Oprn	Saw						-11,111	23,086	0	020,714	1,782	589	0 2.08 1,782	1.92
Sc	In	GBoard				0.0	0.00		0		0				10.41
	In	GBoard		11,111		11,111.1	1.00	11,111			116,253			608	10.41
	Oper	StdO	for all jobs	1	0.60	0.6	1.00		20,714		20,714			34,524	
	Mach	JigSaw	Jigsaw	0	1.00	1.0	1.00		1,920			1,331	589	1,331	0.05

Spac	MnPlnt	in main plant	0	3.00	3.0	1.00		300		300	0		100	
Fixx	JigsawFixx	cutting board	0	1.00	1.0	1.00		151		151	0		151	0.00
Out	GBoardR					1.00	-11,111		-139,338			12.54	2,391	12.33
Matl-	GBoardScrp	Unt, damaged from sawing				0.00	0	0	0				0	0.00
33Oprn	**GlueEdg**						**-11,111**	**21,014**	**0**	**020,714**	**300**	**0**	**0 1.89**	**300**	**1.86**
In	PStripAv				11,111.1	1.00	11,111		13,656				204	1.21
In	GBoardR		11,111		11,111.1	1.00	11,111		139,338				2,391	12.33
Oper	StdO	for all jobs	1	0.60	0.6	1.00		20,714		20,714			34,524	
Spac	MnPlnt	in main plant	0	3.00	3.0	1.00		300		300	0		100	
Out	Tedge					1.00	-11,111		-174,008			15.66	2,895	15.40
34Oprn	**Trim**						**-11,111**	**6,514**	**0**	**0 6,214**	**300**	**0**	**0 0.59**	**300**	**0.56**
In	Tedge		11,111		11,111.1	1.00	11,111		174,008				2,895	15.40
Oper	StdO	for all jobs	1	0.18	0.2	1.00		6,214		6,214			34,524	
Spac	MnPlnt	in main plant	0	3.00	3.0	1.00		300		300	0		100	
Out	TTop					1.00	-11,111		-180,523			16.25	3,195	15.96
35Oprn	**Assem**						**-11,111**	**41,929**	**0**	**041,429**	**500**	**0**	**0 3.77**	**500**	**3.73**
In	ScrewAv				88,888.9	8.00	11,111		13,283				100	0.15
In	TBottomAv				11,111.1	1.00	11,111		401,585				12,501	35.02
In	TTop		11,111		11,111.1	1.00	11,111		180,523				3,195	15.96
Oper	StdO	for all jobs	1	1.20	1.2	1.00		41,429		41,429			34,524	
Spac	MnPlnt	in main plant	0	5.00	5.0	1.00		500		500	0		100	
Out	Table					1.00	-11,111		-637,318			57.36	16,295	55.89
36Oprn	**StrDlvr**						**-10,000**	**100,647**	**-3,333**	**62,10220,714**	**1,144**	**0**	**20,019 10.06**	**1,495**	**9.92**
Sc	In	Table			1,111.1	0.10		62,102		62,102					55.89
	In	Table		11,111		10,000.0	1.00	11,111		575,216				16,295	55.89
	Oper	StdO	for all jobs	1	0.60	0.6	1.00		20,714		20,714			34,524	
	Spac	MnPlnt	in main plant	0	10.00	10.0	1.00		1,000		1,000	0		100	
	Ctrt	DlvTrk	truck delivery on contract	0	1.00	1.0	1.00		144		144			100	0.00
	Out	DeliveredPd				0.95	-9,500		-642,070			67.59	16,901	65.81
	Out	LateDl		-500		0.05	-500		-33,793			67.59	890	65.81
	Incv	LatFee	reduced price if prdct late	0	1.00	1.0	1.00		5,000			5,000			10.00
	Matl-	DamagePd	Bad Prd Sc Value			0.05	-556	-2,778	-2,778				0	5.00
	Matl-	PdDd	Obselete product			0.05	-556	-556	-556				0	1.00
	TiCt		0.25 fctr yr prdctn stored, yrly int %				2,778	15,019				15,019		8
1,000Oprn	**Total**						**0**								
	In	DeliveredPd				10,000.0	1.00	10,000		675,863				17,791	65.81
1,010Oprn	**END**											**5.00 987,065**	**871.18**
												5.00	

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Section 4: Charts Worksheet

Cost Element Charts

GrphDrivF

		Total Prdct/Yr Output		10,000	WorkSheet Name		CostTable										
		Gives added cost for each Oprn		0.00						Gives total Cost for each Oprn							
ChrtStrt		Added cost for each operation								Tot Cost, Each Oprn			Fixed,/Unit Costs		NoLoss, Loss Cst		
		Cost by types for operations								(Mtl thru, Mtl Scp,Other)							
Oprn #	Name	Matl+	Matl	In/Out	Oper	MSFC	M&R	Other	OprnTot	MtlThru	MtlScp	Othr	PerUnit	Fixed	NoLoss	LossSect	final Out
11	PurS	3.6934	0.0000	0.0000	0.2071	0.0200	0.0000	0.0800	0.3072	3.6934	0.0000	0.3072	3.9802	0.0204	3.2533	0.7473	4.0006
12	PurWs	3.3333	0.0000	0.0000	0.2071	0.0200	0.0000	0.0727	0.2998	3.3333	0.0000	0.2998	3.6127	0.0204	3.2719	0.3613	3.6331
13	PurSP	1.2311	0.0000	0.0000	0.2071	0.0200	0.0000	0.0298	0.2569	1.2311	0.0000	0.2569	1.4676	0.0204	1.2125	0.2755	1.4881
14	PurSB	1.1111	0.0000	0.0000	0.2071	0.0100	0.0000	0.0000	0.2171	1.1111	0.0000	0.2171	1.3183	0.0100	1.1964	0.1318	1.3283
15	PurWB	5.5556	0.0000	0.0000	0.2071	0.0200	0.0000	0.1180	0.3452	5.5556	0.0000	0.3452	5.8803	0.0204	5.3127	0.5880	5.9007
16	PurP	1.1696	0.0000	0.0000	0.2071	0.0200	0.0000	0.0285	0.2556	1.1696	0.0000	0.2556	1.4048	0.0204	1.2215	0.2037	1.4252
17	PurStrip	1.1111	0.0000	0.0000	0.2071	0.0200	0.0000	0.0273	0.2545	1.1111	0.0000	0.2545	1.3452	0.0204	1.2311	0.1345	1.3656
21	Cut	0.0000	0.0000	0.0000	0.4143	0.0513	0.0138	0.0000	0.4794	1.4881	0.0000	0.4794	1.8957	0.0717	1.6115	0.3559	1.9674
22	Deburr	0.0000	0.0000	0.0000	0.4143	0.0465	0.0062	0.0000	0.4670	1.9674	0.0000	0.4670	2.3162	0.1182	1.9995	0.4348	2.4344
23	CutCir	0.0000	0.0000	0.0000	2.0714	0.7288	0.0320	0.0000	2.8322	4.0006	0.0000	2.8322	6.0836	0.7492	5.6906	1.1422	6.8328
24	Spin	0.0000	0.0000	0.0000	2.0714	0.2622	0.0320	0.0000	2.3657	6.8328	0.0000	2.3657	8.1871	1.0114	7.6614	1.5371	9.1985
25	Braze	0.0000	-0.0616	0.5252	2.0714	0.0400	0.0000	0.0000	2.5750	11.1077	0.4636	2.1114	12.5131	1.1696	11.3835	2.2993	13.6827
26	Smooth	0.0000	0.0000	0.0000	1.0357	0.0300	0.0000	0.0000	1.0657	13.6827	0.0000	1.0657	13.5488	1.1996	12.2990	2.4495	14.7485
27	Plate	0.0000	0.0000	0.0000	0.0000	23.3918	0.0000	0.0000	23.3918	14.7485	0.0000	23.3918	36.9406	1.1996	32.2991	5.8412	38.1403
28	Press	0.0000	-0.0585	1.9173	0.6214	0.0300	0.0000	0.0000	2.5102	37.6482	1.8588	0.6514	38.9084	1.2501	34.0819	6.0765	40.1585
31	GlueTop	0.0000	0.0000	0.0000	2.0714	0.0200	0.0000	0.0000	2.0914	9.5339	0.0000	2.0914	11.5645	0.0608	10.4689	1.1564	11.6253
32	Saw	0.0000	0.0000	0.0000	2.0714	0.1782	0.0589	0.0000	2.3086	11.6253	0.0000	2.3086	13.6948	0.2391	12.5644	1.3694	13.9338
33	GlueEdg	0.0000	0.0000	0.0000	2.0714	0.0300	0.0000	0.0000	2.1014	15.2994	0.0000	2.1014	17.1114	0.2895	15.6897	1.7111	17.4008
34	Trim	0.0000	0.0000	0.0000	0.6214	0.0300	0.0000	0.0000	0.6514	17.4008	0.0000	0.6514	17.7328	0.3195	16.2790	1.7732	18.0523
35	Assem	0.0000	0.0000	0.0000	4.1429	0.0500	0.0000	0.0000	4.1929	59.5390	0.0000	4.1929	62.1023	1.6295	55.3360	8.3959	63.7318
36	StrDlvr	0.0000	-0.3333	6.2102	2.0714	0.1144	0.0000	2.0019	10.0647	57.5216	5.8769	4.1878	65.8072	1.7791	58.4839	9.1024	67.5863

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Section 5: Graph of Cost Element

Cost Distribution By Cost Type

Legend:
- StrDlvr
- Assem
- Trim
- GlueEdg
- Saw
- GlueTop
- Press
- Plate
- Smooth
- Braze
- Spin
- CutCir
- Deburr
- Cut
- PurStrip
- PurP
- PurWB
- PurSB
- PurSP
- PurWs
- PurS

Y-axis: Cost Distribution (-5.0, 0.0, 5.0, 10.0, 15.0, 20.0, 25.0, 30.0)

X-axis: Cost Type (Matl+, Matl, In/Out, Oper, MSFC, M&R, Other)
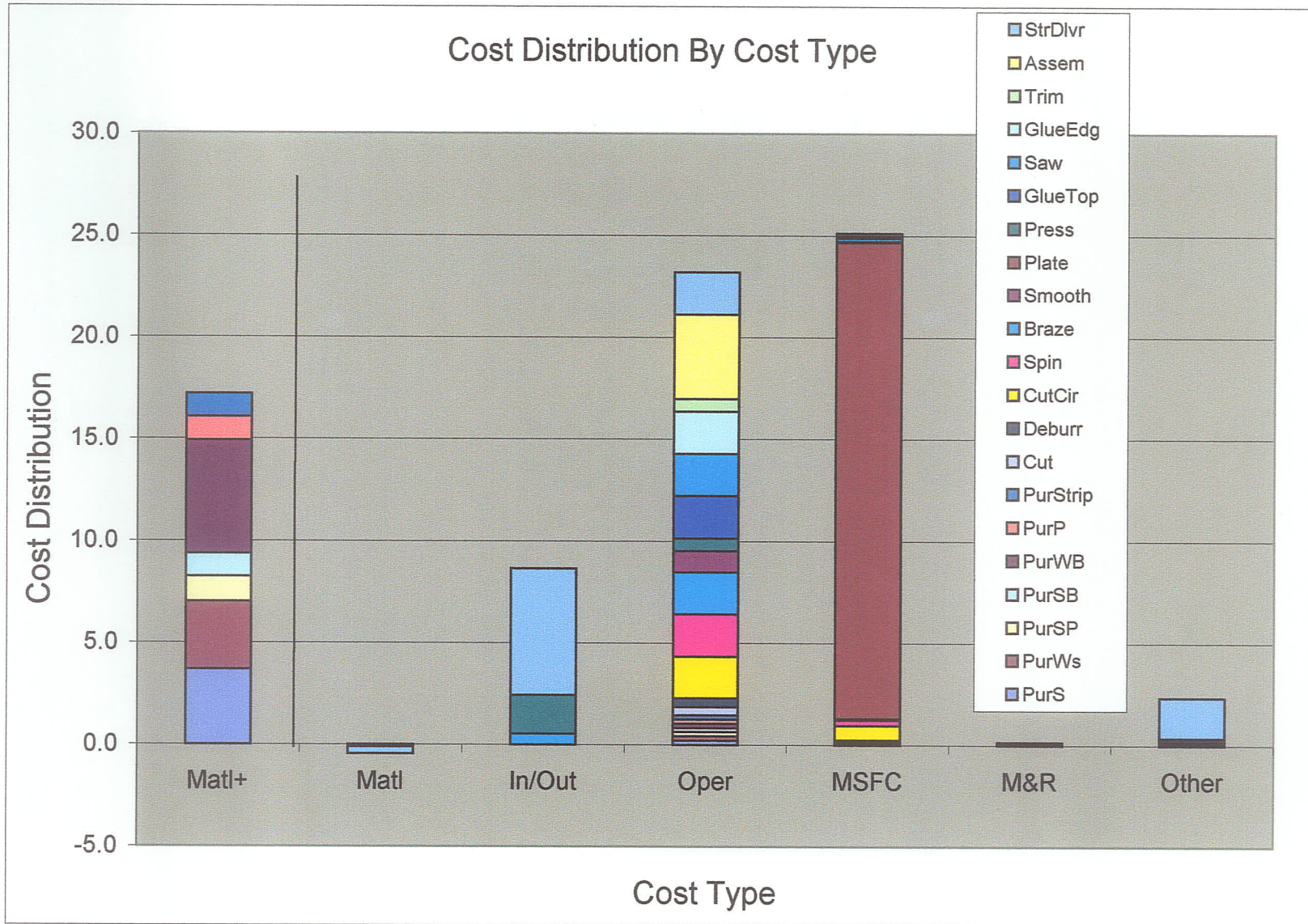
APPENDIX B

COWL Industrial Silencer Project

Silencer Model Configurations (Friesen, 2001)

PL: Inlet attached to left endplate.
Outlet attached to vertical face of top piece.
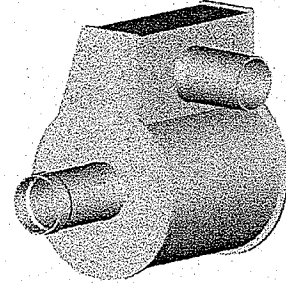
PR: Inlet attached to right endplate.
Outlet attached to vertical face of top piece.
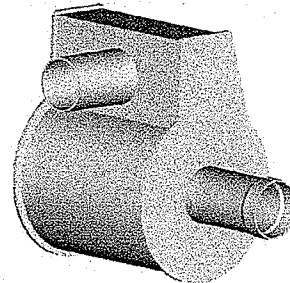
PV: Inlets attached to right and left endplates.
Outlet attached to vertical face of top piece.
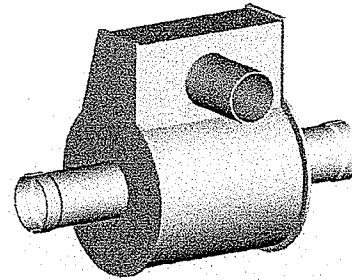
PT: Inlet attached to either endplate.
Outlet attached to horizontal face of top piece.
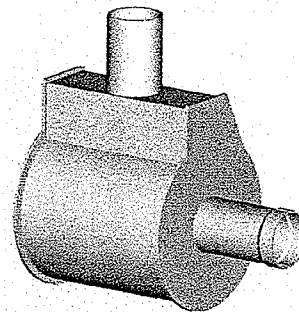
TR: Inlet attached to right endplate.
Outlet attached left endplate.
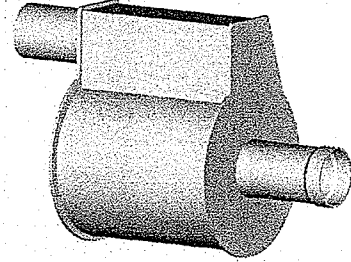
TL: Inlet attached to left endplate.
Outlet attached to right endplate.
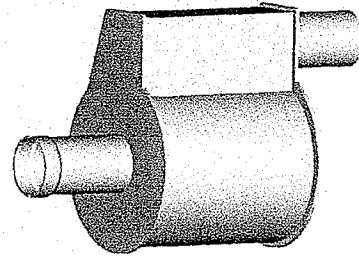
SL: Inlet attached to left endplate.
No top piece. Circular endplates.
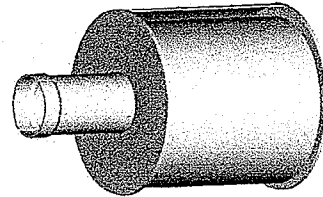
SR: Inlet attached to right endplate.
No top piece. Circular endplates.
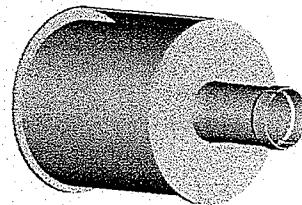
SV: Inlets attached to left and right endplate.
No top piece. Circular endplates.
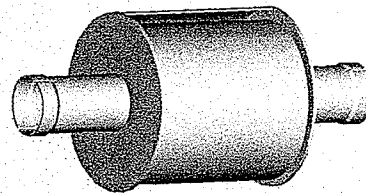
Cowl Cost Element Worksheet

Table 1: Quantity Out

YrlyOut	Qnty
DlvrCowl	5,000

Table 2: Part Relations

Oprn	Oprn#	Out Dim	OprnRw#	Out	fctr	Out	fctr	In+	fctr	In	fctr	In	fctr	In	fctr	Sc Matl-	Scrap fctr	Dg Matl-	Damage fctr	Od Matl-	Obselete fctr
PurSteel	11	coil form,kg	1	RollSteelAv	1.00			pRollSheet	1.00												
PurPipe	12	long pipe stack, kg	2	SPipeAv	1.00			pSPipe	1.00												
PurWeld	13	boxes weld rod	3	WeldMatAv	1.00			pWeldMat	1.00												
PurPaint	14	cannes of liquid and powder	4	PaintMatAv	1.00			pPaintMat	1.00												
PurWool	15	wool material	5	WoolAv	1.00			pWool	1.00												
PurPlate	16	coil form,kg	6	RollPlateAv	1.00			pRollPlate	1.00												
Cutting	21	inlet, outlet length	7	CutPipe	1.00			SPipeAv	1.00							SPipeScrap	0.005				
Swaging	22	expand inlet pipe diameter	8	InOutTube	1.00			CutPipe	1.00												
DeburrTube	23	smoothing the edges	9	InOutTubeR	1.00			InOutTube	1.00												
PunchPlate	24	cut from coil to strip	10	CutTopR	1.00	CutSpiralR	1.00	RollSteelAv	1.00							RollSteelScrap	0.005				
ShearCut	25	punch into endplate shape	11	CutPlate	1.00			RollPlateAv	1.00							RollPlateScrap	0.005				
DeburrPlate	26	smoothing plate edges	12	EndPlateR	1.00			CutPlate	1.00												
PressBend	27	v shape bend	13	TopPlateR	1.00			CutTopR	1.00												
RollBend	28	roll into spiral shape	14	BendSpiral	1.00			CutSpiralR	1.00												
InsertWool	29	steel wool insert betwwen spiral	15	SpiralPlateR	1.00			BendSpiral	1.00	WoolAv	1.00										
Welding1	31	weld inlet, outlet to plates	16	WeldTopR	1.00			WeldMatAv	1.00	InOutTubeR	1.00	TopPlateR	1.00								
Welding2	32	weld endplate, top to spiral	17	SidePlateR	1.00			WeldMatAv	1.00	InOutTubeR	1.00	EndPlateR	1.00								
TigWelding	33	assembly all sections together	18	RawCowl	1.00			SidePlateR	1.00	WeldTopR	1.00	WeldMatAv	1.00	SpiralPlateR	1.00						
Painting	34	powder or liquid paint	19	PaintCowl	1.00			RawCowl	1.00	PaintMatAv	1.00										
Packing	41	put silencer into boxes	20	CowlFinish	1.00			PaintCowl	1.00												
Shipping	42	ship to customer	21	DlvrCowl	0.99	LateDlvrCowl	0.01	CowlFinish	1.00									BadCowl	0.01	ObseleteCowl	0.008

Table 3: Operation

sq m

Oprn	Oprn #	nOper	fctr	nMach	fctr	nSpac	Fctr	nFixx	Fctr	qCtrt	Fctr	Qref	qCtrt	Fctr	Qref	qIncv	Fctr	Qref	qIncv	Fctr	Qref	oTiCt	Oprn	nOper	Oper Time (min)	(in hrs)	fctr	Multiplier
PurSteel	11	ReceiveOp	0.05			ReceiveSpc	5.00															0.10	PurSteel	ReceiveOp	1.0	0.017	0.05	1.2
PurPipe	12	ReceiveOp	0.05			ReceiveSpc	5.00															0.10	PurPipe	ReceiveOp	1.0	0.017	0.05	
PurWeld	13	ReceiveOp	0.05			ReceiveSpc	5.00																PurWeld	ReceiveOp	1.0	0.017	0.05	
PurPaint	14	ReceiveOp	0.05			ReceiveSpc	5.00																PurPaint	ReceiveOp	1.0	0.017	0.05	
PurWool	15	ReceiveOp	0.05			ReceiveSpc	5.00																PurWool	ReceiveOp	1.0	0.017	0.05	
PurPlate	16	ReceiveOp	0.05			ReceiveSpc	5.00															0.10	PurPlate	ReceiveOp	1.0	0.017	0.05	
Cutting	21	CutOp	0.02	CircularSaw	1.00	SawSpc	5.00																Cutting	CutOp	0.5	0.008	0.02	
Swaging	22	SwagOp	0.02	RotarySwaging	1.00	FormSpc	8.00	SwagFix	1.00														Swaging	SwagOp	0.5	0.008	0.02	
DeburrTube	23	DeburOp	0.02	HandGrinder	1.00	DeburSpc	5.00																DeburrTube	DeburOp	0.4	0.007	0.02	
PunchPlate	24	ShearOp1	0.02	ShearPunch1	1.00	ShearSpc	8.00																PunchPlate	ShearOp1	0.5	0.008	0.02	
ShearCut	25	ShearOp2	0.03	ShearPunch2	1.00	ShearSpc	8.00																ShearCut	ShearOp2	0.6	0.010	0.03	
DeburrPlate	26	DeburOp	0.07	HandGrinder	1.00	DeburSpc	5.00																DeburrPlate	DeburOp	1.5	0.025	0.07	
PressBend	27	PressOp	0.10	PressBrake	1.00	FormSpc	8.00																PressBend	PressOp	2.0	0.033	0.10	
RollBend	28	RollOp	0.14	RollBending	1.00	FormSpc	8.00																RollBend	RollOp	3.0	0.050	0.14	
InsertWool	29	WoolOp	0.02			FormSpc	8.00																InsertWool	WoolOp	0.5	0.008	0.02	
Welding1	31	Welder1	0.02	MigWeld	1.00	WeldSpc	5.00	MigFix	1.00														Welding1	Welder1	0.4	0.007	0.02	
Welding2	32	Welder2	0.02	MigWeld	1.00	WeldSpc	5.00	MigFix	1.00														Welding2	Welder2	0.4	0.007	0.02	
TigWelding	33	Tigwelder	0.02	TigWeld	1.00	WeldSpc	5.00	TigFix	1.00														TigWelding	Tigwelder	0.5	0.008	0.02	
Painting	34	Painter	0.10	PaintModule	1.00	PaintSpc	5.00																Painting	Painter	2.0	0.033	0.10	
Packing	41	PackOp	0.07			PackSpc	5.00																Packing	PackOp	1.5	0.025	0.07	
Shipping	42	ShipOp	0.10			StoreSpc	10.00			DlvTruck	0.99		BadReturn	0.01		LateFee	0.02		BadFee	0.02			0.10	Shipping	ShipOp	2.0	0.033	0.10	

Table 4: Cst: Matl/ Yr+ /Unit

For 1.0 For 1.5 discount

Type	Name	Desc	base $/yr	add $/unit	units	units/yr	$ for qty 1.0	$ for qty 1.5	$/unit/yr	$/unit/yr
Matl+	pRollSheet	in2, area of sheet require for spiral	0	9.45	prt	5,000	47,254	70,881	9.45	0.00
Matl+	pSPipe	in, pipe required for inlet/outlet	0	2.25	prt	5,000	11,250	16,875	2.25	0.00
Matl+	pWeldMat	in, weld material depend on length of welding	0	1.75	prt	5,000	8,757	13,135	1.75	0.00
Matl+	pWool	kg, wool insert within spiral	0	1.04	prt	5,000	5,221	7,832	1.04	0.00
Matl+	pRollPlate	in, material use for punch	0	8.14	prt	5,000	40,676	61,014	8.14	0.00
Matl+	pPaintMat	in, paint material needed to paint one unit	0	1.09	prt	5,000	5,428	8,142	1.09	0.00
Matl-	SPipeScrap	Unt, scrap from cutting	0	0.10	prt					
Matl-	RollSteelScrap	Unt, scrap from shear punch	0	0.15	prt					
Matl-	RollPlateScrap	Unt, scrap from shear punch	0	0.20	prt					
Matl-	BadCowl	Unt, bad product return from customer	0	0.25	prt					
Matl-	ObseleteCowl	Unt, product obselete in storage	0	0.18	prt					

Table 5: Cst: Oper/ sh yr   (1 shift year = 2,080 hrs, 40hrs/weeks * 52 weeks)

Type	Name	Desc	Qctrl	$/shift yr	salary $/yr	other pay $/yr	fringe1 $/yr	support $/yr	support hrs/yr	nominal hrs/yr	overtime hrs/yr	fringe2 hrs/yr	shift hrs/yr	Weld Time $
Oper	ReceiveOp		0	21,543	15,000	1,200	1,000	200	100	2,080	50	350	1,680	
Oper	CutOp		0	21,914	15,000	1,500	1,000	200	100	2,080	50	350	1,680	
Oper	SwagOp		0	21,295	15,000	1,000	1,000	200	100	2,080	50	350	1,680	
Oper	DeburOp		0	21,048	15,000	800	1,000	200	100	2,080	50	350	1,680	
Oper	ShearOp1		0	20,676	15,000	500	1,000	200	100	2,080	50	350	1,680	
Oper	ShearOp2		0	21,048	15,000	800	1,000	200	100	2,080	50	350	1,680	
Oper	PressOp		0	29,962	22,000	1,000	1,000	200	100	2,080	50	350	1,680	
Oper	RollOp		0	27,733	20,000	1,200	1,000	200	100	2,080	50	350	1,680	
Oper	WoolOp		0	21,914	15,000	1,500	1,000	200	100	2,080	50	350	1,680	
Oper	Welder1		0	21,667	15,000	1,300	1,000	200	100	2,080	50	350	1,680	
Oper	Welder2		0	21,295	15,000	1,000	1,000	200	100	2,080	50	350	1,680	
Oper	Tigwelder		0	25,169	18,000	1,000	1,000	200	100	2,080	50	350	1,680	159.6
Oper	Painter		0	20,676	15,000	500	1,000	200	100	2,080	50	350	1,680	
Oper	PackOp		0	21,048	15,000	800	1,000	200	100	2,080	50	350	1,680	
Oper	ShipOp		0	25,010	18,000	1,000	1,000	200	100	2,080	50	350	1,680	

Table 6: Cst: Mach, Fxx /yr

| | | | | | | | | | install incl in Pur Cst | | | | | | | (inc. time spent) | Added major | | | Calc, (/Yr) | | | Roll Cost Length |
| | | | | | approx | Cap | Cap | Cap | Wear | Cap | Cap | Cap | Wear | Othr | | | | | | not used | used | | |
Type	Name	Desc	Qctrl	$/yr	$/unit	unit	units/yr	Pur Cst	Install Cst	Sell val, N	Sell val, W	Qty yr use	Qty yr	dep int %	M&R	srvc cst	Maj/yr	MajRe/Prt	Tax	cap,int	cap,int	diff	$/yr
Mach	CircularSaw	cutting steel	0	395	0.08	prt	6,000	1,000	100	0	0	8	5	8	500	200			13	182	182	0	
Mach	RotarySwaging	for swaging operation	0	394	0.03	prt	6,000	2,000	200	0	500	10	8	8	200	50			36	308	278	-30	
Mach	HandGrinder	smoothing	0	379	0.10	prt	8,000	1,000	0	0	0	5	5	8	800	120			19	240	240	0	
Mach	ShearPunch1	punch operation	0	466	0.03	prt	6,000	2,500	150	0	300	10	8	8	200	50			45	371	353	-18	
Mach	ShearPunch2	punch operation	0	616	0.16	prt	6,000	2,500	150	0	300	10	8	8	1,000	200			45	371	353	-18	
Mach	HandGrinder	smoothing	0	180	0.04	prt	5,000	500	0	0	0	5	5	8	200	50			10	120	120	0	
Mach	PressBrake	for press bend	0	753	0.12	prt	8,000	5,000	500	0	500	20	15	8	1,000	150			108	495	490	-5	
Mach	RollBending	spinning	0	1,430	0.02	prt	8,000	2,000	200	0	1,000	15	15	8	200	100			51	235	208	-27	1044.215
Mach	MigWeld	welding	0	153	0.08	prt	6,000	300	0	0	0	8	5	8	500	100			4	50	50	0	
Mach	MigWeld	welding	0	103	0.16	prt	5,000	300	0	0	0	8	5	8	800	50			4	50	50	0	
Mach	TigWeld	welding	0	169	0.10	prt	6,000	500	0	0	0	8	5	8	600	80			7	83	83	0	
Mach	PaintModule	painting	0	662	0.06	prt	8,000	5,000	1,000	0	1,500	20	10	8	500	50			72	540	525	-15	
Fixx	SwagFix		0	391	0.02	prt	6,000	1,000	0	0	0	3	3	8	100	0			18	373	373	0	
Fixx	MigFix		0	78	0.02	prt	6,000	200	0	0	0	3	3	8	100	0			4	75	75	0	
Fixx	MigFix		0	78	0.02	prt	6,000	200	0	0	0	3	3	8	100	0			4	75	75	0	
Fixx	TigFix		0	117	0.02	prt	6,000	300	0	0	0	3	3	8	100	0			5	112	112	0	

Table 7: Cst: Spac /yr

Type	Name	Desc	Qctrl	$/yr	$/sq m/yr	sq m
Spac	ReceiveSpc		0	5	4.7	1
Spac	SawSpc		0	5	4.7	1
Spac	DeburSpc		0	5	4.7	1
Spac	ShearSpc		0	5	4.7	1
Spac	FormSpc		0	5	4.7	1
Spac	WeldSpc		0	5	4.7	1
Spac	PaintSpc		0	5	4.7	1
Spac	PackSpc		0	5	4.7	1
Spac	StoreSpc		0	5	4.7	1

Table 8: Cst: Ctrt, Incv /yr

Type	Name	Desc	Qctrl (always =0)	base $/yr	$/unit	unit	approx units/yr
Ctrt	DlvTruck	truck delivery on contract	0	100	0.004		5,000
Ctrt	BadReturn	returns product by retailer	0		0.02		200
Incv	LateFee	reduced price if prdct late	0		2.5		800
Incv	BadFee	reduced price to customer of bad product	0		5		200

Table 9: Cst: TiCt

Type	Name	Desc	Int %
TiCt		fctr yr prdctn stored, yrly int %	8

COWL Production Cost Chart Output

Cost Distribution By Cost Type

Legend:
- Shipping
- Packing
- Painting
- TigWelding
- Welding2
- Welding1
- InsertWool
- RollBend
- PressBend
- DeburrPlate
- ShearCut
- PunchPlate
- DeburrTube
- Swaging
- Cutting
- PurPlate
- PurWool
- PurPaint
- PurWeld
- PurPipe
- PurSteel

X-axis (Cost Type): Matl+, Matl, In/Out, Oper, MSFC, M&R, Other

Y-axis (Cost Distribution): -5.0 to 45.0
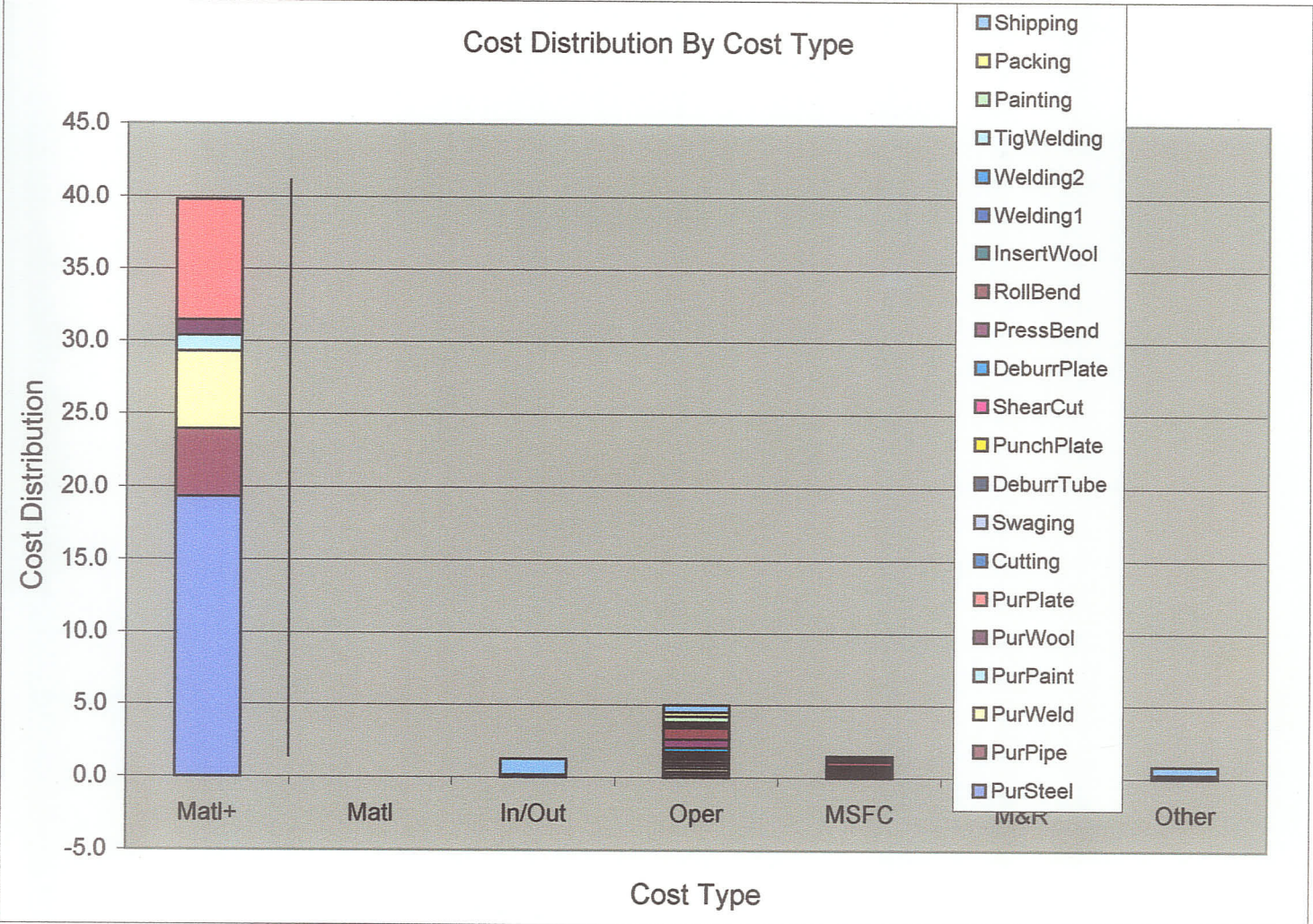
Appendix C
LBMH Air Diffuser Project

LBMH Models

Narrow Spacing

1/4" (6) Spacing, 1/8" (3) Bars

0° Deflection	**LBMH 15A**
15° Deflection	**LBMH 16A**

Wide Spacing

1/2" (13) Spacing, 1/8" (3) Bars

0° Deflection	**LBMH 15B**
15° Deflection	**LBMH 16B**

1/2" (13) Spacing, 3/16" (5) Bars

0° Deflection	**LBMH 25B**
15° Deflection	**LBMH 26B**
30° Deflection	**LBMH 27B**

Pencil Proof Spacing

7/16" (11) Spacing, 3/16" (5) Bars

0° Deflection	**LBMH 25C**
15° Deflection	**LBMH 26C**
30° Deflection	**LBMH 27C**

PRICE LBMH Series premium quality linear bar grilles feature precision heavy duty aluminum mandrel tube construction for clean, crisp styling, efficient air distribution, and exceptional strength characteristics. LBMH linear bar grilles are recommended for floor and sill applications in high traffic areas.

Core Styles

Narrow Bar Spacing
Core 15A 0° Deflection
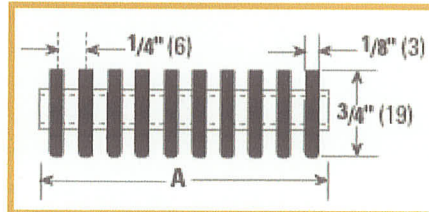
Core 16A 15° Deflection
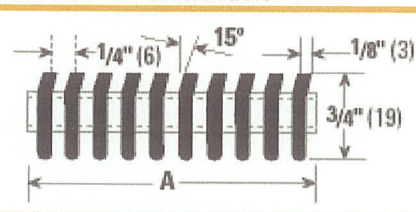
Wide Bar Spacing
Core 15B 0° Deflection
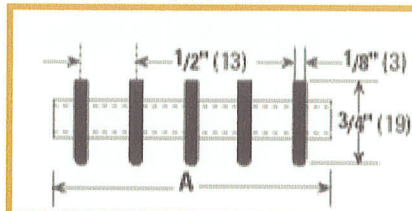
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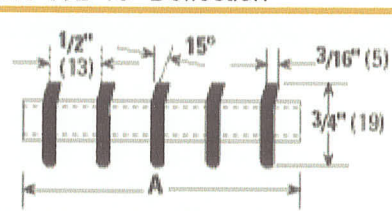
Core 25B 0° Deflection
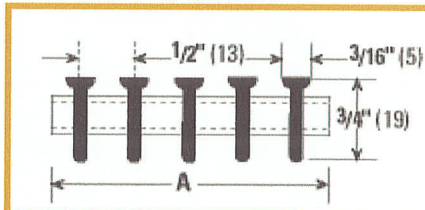
Core 26B 15° Deflection
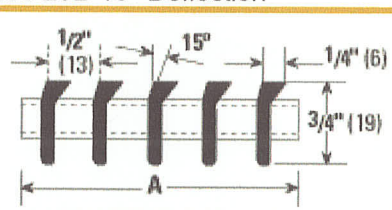
Core 27B 30° Deflection
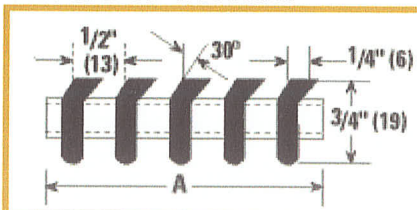
Pencil Proof Bar Spacing
Core 25C 0° Deflection
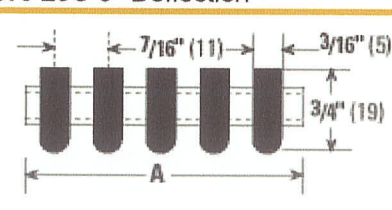
Core 26C 15° Deflection
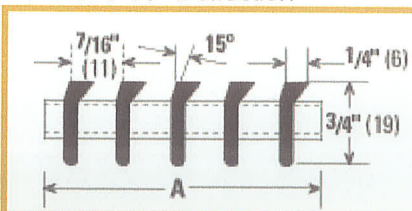
Core 27C 30° Deflection
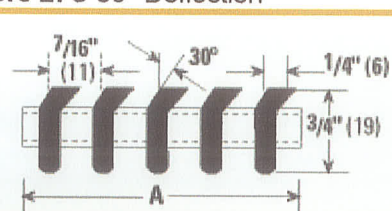
LBMH Design Constraints Graph

Flow Rate vs Grille Width

$$y = 0.3639x^2 + 12.341x - 8.9601$$

Y-axis: Flow Rate (CFM/ft), 0 to 90
X-axis: Width (in), 0 to 7

Flow Rate Correction Factor

Legend:
- 1.5 in
- 2 in
- 2.5 in
- 3 in
- 3.5 in
- 4 in
- 5 in
- 6 in
- Log. (1.5 in)
- Log. (2 in)
- Log. (2.5 in)
- Log. (3 in)
- Log. (3.5 in)
- Log. (4 in)
- Log. (5 in)
- Log. (6 in)

$$y = 8.4484Ln(x) + 55.067$$
$$y = 6.352Ln(x) + 42.84$$
$$y = 4.8035Ln(x) + 32.675$$
$$y = 4.392Ln(x) + 28.738$$
$$y = 3.3257Ln(x) + 22.357$$
$$y = 2.4671Ln(x) + 16.837$$
$$y = 1.9295Ln(x) + 12.58$$
$$y = 1.3074Ln(x) + 8.1067$$

Y-axis: Flow Rate (CFM/ft), 0 to 50
X-axis: Static Pressure (in H20), 0 to 0.3

NC vs Static Pressure

y = 4.566Ln(x) + 11.654

NC

Static Pressure

NC vs GrilleWidth

y = 13.922x^{0.3234}

NC

Width (in)

NC vs Grille Length

$y = 4.6011 \text{Ln}(x) - 17.595$

NC

Length (in)

LBMH OBC Model
(Cost Element Table Worksheet)

Table 1: Quantity Out

YrlyOut	Qnty
DlvrLBMH	1,500

Table 2: Part Relations

Oprn	Oprn#	Out Dim	OprnRw#	Out	fctr	Out	fctr	In+	fctr	In	fctr	In	fctr	Matl- (Sc)	fctr (Scrap)	Matl- (Dg)	fctr (Damage)	Matl- (Od)	fctr (Obselete)
PurFrame	11	12' long frame stack	1	FrameBarAv	1.00			pFrameBar	1.00										
PurTube	12	12' long pipe stack	2	TubeAv	1.00			pTube	1.00										
PurCore	13	10' long core bar	3	CoreBarAv	1.00			pCoreBar	1.00										
PurSupportBar	14	bar bought in different sizes	4	SupportBarAv	1.00			pSupportBar	1.00										
PurWeld	15	weld rod material	5	WeldMatAv	1.00			pWeldMat	1.00										
PurClip	16	clip for frame and core	6	ClipAv	1.00			pClip	1.00										
SawCut1	21	frame cut with length	7	FrameCut	1.00			FrameBarAv	1.00					FrameScrap	0.02				
FrameHole	22	punch hole at side of frame	8	HFrameR	1.00			FrameCut	1.00										
SawCut2	23	tube & core cut to size	9	CoreCut	1.00	TubeR	1.00	TubeAv	1.00	CoreBarAv	1.00			Tube&CoreScrap	0.02				
CoreHole	24	punch hole on core bar	10	HCoreR	1.00			CoreCut	1.00										
Welding1	25	weld frame corner to corner	11	HalfFrame	1.00			HFrameR	1.00	WeldMatAv	1.00								
Welding2	26	weld frame insert support bar	12	FullFrame	1.00			HalfFrame	1.00	SupportBarAv	1.00								
TigWelding	27	weld tight support bar	13	FrameR	1.00			FullFrame	1.00										
CoreAssembly	31	insert tube to core hole	14	CoreR	1.00			HCoreR	1.00	TubeR	1.00					CoreDmg	0.03		
Assembly	32	clip frame and mandrel core	15	LBMHR	1.00			CoreR	1.00	FrameR	1.00	ClipAv	1.00						
Packing	41	put LBMH into boxes	16	LBMH	1.00			LBMHR	1.00										
Shipping	42	ship LBMH to customer	17	DlvrLBMH	0.99	LateLBMH	0.01	LBMH	1.00							BadLBMH	0.03	ObseleteLBMH	0.03

The damage part during assembly process is reduced to 0.5% for improved design

Table 3: Operation

sq m

Oprn	Oprn #	nOper	fctr	nMach	fctr	nSpac	Fctr	nFixx	Fctr	Qref	qCtrt	Fctr	Qref	qCtrt	Fctr	Qref	qIncv	Fctr	Qref	qIncv	Fctr	Qref	oTiCt	Name	1 Oper Time (min)	Time (hrs)	Utilize
PurFrame	11	ReceiveOp	0.320			ReceiveSpc	5.00																	0.10	PurFrame	3.69	0.0615	0.320
PurTube	12	ReceiveOp	0.127			ReceiveSpc	5.00																	0.10	PurTube	1.46	0.0244	0.127
PurCore	13	ReceiveOp	0.531			ReceiveSpc	5.00																	0.10	PurCore	6.12	0.1020	0.531
PurSupportBar	14	ReceiveOp	0.122			ReceiveSpc	5.00																		PurSupportBar	1.41	0.0235	0.122
PurWeld	15	ReceiveOp	0.173			ReceiveSpc	5.00																		PurWeld	2.00	0.0333	0.173
PurClip	16	ReceiveOp	0.065			ReceiveSpc	5.00																		PurClip	0.75	0.0125	0.065
SawCut1	21	CutOp	0.058	CircularSaw	1.00	SawSpc	5.00																	SawCut1	2.00	0.0333	0.058
FrameHole	22	HoleOp	0.072	PunchFrame	1.00	PunchSpc	8.00																	FrameHole	2.50	0.0417	0.072
SawCut2	23	CutOp	0.216	BandSaw	1.00	SawSpc	5.00																	SawCut2	7.50	0.1250	0.216
CoreHole	24	HoleOp	0.072	PunchCore	1.00	PunchSpc	8.00	HoleDie	1.00																CoreHole	2.50	0.0417	0.072
Welding1	25	Welder1	0.014	MigWeld	1.00	WeldSpc	5.00	MigFix	1.00																Welding1	1.00	0.0167	0.014
Welding2	26	Welder2	0.101	MigWeld	1.00	WeldSpc	5.00	MigFix	1.00																Welding2	7.00	0.1167	0.101
TigWelding	27	Tigwelder	0.072	TigWeld	1.00	WeldSpc	5.00	TigFix	1.00																TigWelding	5.00	0.0833	0.072
CoreAssembly	31	CoreOp	0.454	Extrude	1.00	AssemblySpc	10.00	Clamp	1.00																CoreAssembly	31.50	0.5250	0.454
Assembly	32	AssemblyOp	0.202			AssemblySpc	10.00	ClipHolder	1.00																Assembly	14.00	0.2333	0.202
Packing	41	PackOp	0.072			PackSpc	5.00																		Packing	5.00	0.0833	0.072
Shipping	42	ShipOp	0.072			StoreSpc	10.00			DlvTruck	0.99	BadReturn	0.01		LateFee	0.02		BadFee	0.02					0.10	Shipping	5.00	0.0833	0.072

Operation time is reduced by half in the improved design

Table 4: Cst: Matl/ Yr+ /Unit

									For 1.0	For 1.5 discount
Type	Name	Desc	base $/yr	add $/unit	units	units/yr	$ for qty 1.0	$ for qty 1.5	$/unit/yr	$/unit/yr
Matl+	pFrameBar	12' long frame stack	2,188	2.92	ft	3,000	10,939	15,314	3.65	0.24
Matl+	pTube	12' long pipe stack	415	0.22	ft	7,500	2,077	2,908	0.28	0.02
Matl+	pCoreBar	10' long core bar	3,981	0.53	ft	30,000	19,904	27,865	0.66	0.04
Matl+	pSupportBar	bar bought in different sizes	305	0.16	kg	7,500	1,526	2,137	0.20	0.01
Matl+	pWeldMat	weld rod material	1,500	4.00	kg	1,500	7,500	10,500	5.00	0.33
Matl+	pClip	clip for frame and core	300	0.08	kg	15,000	1,500	2,100	0.10	0.01
Matl-	FrameScrap	scrap from cutting	0	0.05	kg					
Matl-	Tube&CoreScrap	scrap from cutting	0	0.05	kg					
Matl-	CoreDmg	Damage part	0	0.50	Qnty					
Matl-	BadLBMH	damaged from delivering	0	0.10	Qnty					
Matl-	ObseleteLBMH	damaged from long shelf time	0	0.10	Qnty					

Table 5: Cst: Oper/ sh yr

(1 shift year = 2,080 hrs, 40hrs/weeks * 52 weeks)

Type	Name	Desc	Qctrl	$/shift yr	salary $/yr	other pay $/yr	fringe1 $/yr	support $/yr	support hrs/yr	nominal hrs/yr	overtime hrs/yr	fringe2 hrs/yr	shift hrs/yr
Oper	ReceiveOp		0	27,238	20,000	500	1,000	500	100	2,080	50	350	1,680
Oper	CutOp		0	28,476	21,000	500	1,000	500	100	2,080	50	350	1,680
Oper	HoleOp		0	29,714	22,000	500	1,000	500	100	2,080	50	350	1,680
Oper	Welder1		0	27,238	20,000	500	1,000	500	100	2,080	50	350	1,680
Oper	Welder2		0	27,238	20,000	500	1,000	500	100	2,080	50	350	1,680
Oper	Tigwelder		0	27,238	20,000	500	1,000	500	100	2,080	50	350	1,680
Oper	CoreOp		0	33,429	25,000	500	1,000	500	100	2,080	50	350	1,680
Oper	AssemblyOp		0	30,333	22,500	500	1,000	500	100	2,080	50	350	1,680
Oper	PackOp		0	27,238	20,000	500	1,000	500	100	2,080	50	350	1,680
Oper	ShipOp		0	27,238	20,000	500	1,000	500	100	2,080	50	350	1,680

Cost of machine and fixture in existing manufacturing process (Rows highlighted with pink color)

Table 6: Cst: Mach, Fxx /yr

							install incl in Pur Cst							(inc. time spent)		Added major		Calc, (/Yr)		
						approx	Cap	Cap	Cap	Wear	Cap	Cap	Cap	Wear	Othr			not used	used	
Type	Name	Desc	Qctrl	$/yr	$/unit	unit	units/yr	Pur Cst	Install Cst	Sell val, N	Sell val, W	Qty yr use	Qty yr dep	int %	M&R	srvc cst	Die Cost	Tax	cap,int	cap,int	diff
Mach	CircularSaw	cutting frame	0	704	0.35	prt	1,500	2,000	500	200	0	5	5	8	500	100		36	568	600	32
Mach	PunchFrame	punch hole on frame	0	1,048	0.71	prt	1,500	3,000	1,000	400	0	5	5	8	1,000	100		52	896	960	64
Mach	BandSaw	cutting tube and core	0	704	0.35	prt	1,500	2,000	500	200	0	5	5	8	500	100		36	568	600	32
Mach	PunchCore	punch hole on tube and core	0	1,464	0.37	prt	1,500	5,000	500	300	0	5	5	8	500	100		92	1,272	1,320	48
Mach	MigWeld	weld corner of two frame	0	592	0.14	prt	1,500	1,500	500	100	0	5	5	8	200	100		28	464	480	16
Mach	MigWeld	weld four corner and insert support bar	0	592	0.14	prt	1,500	1,500	500	100	0	5	5	8	200	100		28	464	480	16
Mach	Extrude	force expand small pin through tube	0	1,593	0.69	prt	1,500	5,000	1,000	250	0	5	5	8	1,000	100		93	1,400	1,440	40
Mach	TigWeld	secure support bar on frame	0	721	0.14	prt	1,500	2,000	500	100	0	5	5	8	200	100		37	584	600	16
Fixx	HoleDie	die used for punch bar hole	0	875	0.33	prt	1,500	2,000	300	0	0	5	3	8	500	300		23	552	552	0
Fixx	MigFix	weld corner of two frame	0	226	0.07	prt	1,500	500	0	0	0	5	3	8	100	100		6	120	120	0
Fixx	MigFix	weld four corner and insert support bar	0	226	0.07	prt	1,500	500	0	0	0	5	3	8	100	100		6	120	120	0
Fixx	TigFix	secure support bar on frame	0	301	0.07	prt	1,500	800	0	0	0	5	3	8	100	100		9	192	192	0
Fixx	Clamp	for mandrel core assembly	0	150	0.20	prt	1,500	500	100	0	0	5	3	8	300	0		6	144	144	0
Fixx	ClipHolder	insert clip	0	50	0.07	prt	1,500	200	0	0	0	5	3	8	100	0		2	48	48	0

Cost of machine and fixture in the improved design (Rows highlighted with pink color)

Table 6: Cst: Mach, Fxx /yr

Type	Name	Desc	Qctrl	$/yr	$/unit	unit	approx units/yr	Cap Pur Cst	Cap Install Cst	Cap Sell val, N	Wear Sell val, W	Cap Qty yr use	Cap Qty yr dep	Cap int %	Wear M&R	Othr srvc cst	Added major Die Cost	Tax	Calc (/Yr) not used cap,int	used cap,int	diff
Mach	CircularSaw	cutting frame	0	704	0.35	prt	1,500	2,000	500	200	0	5	5	8	500	100		36	568	600	32
Mach	PunchFrame	punch hole on frame	0	1,048	0.71	prt	1,500	3,000	1,000	400	0	5	5	8	1,000	100		52	896	960	64
Mach	BandSaw	cutting tube and core	0	704	0.35	prt	1,500	2,000	500	200	0	5	5	8	500	100		36	568	600	32
Mach	PunchCore	punch hole on tube and core	0	1,464	0.37	prt	1,500	5,000	500	300	0	5	5	8	500	100		92	1,272	1,320	48
Mach	MigWeld	weld corner of two frame	0	592	0.14	prt	1,500	1,500	500	100	0	5	5	8	200	100		28	464	480	16
Mach	MigWeld	weld four corner and insert support bar	0	592	0.14	prt	1,500	1,500	500	100	0	5	5	8	200	100		28	464	480	16
Mach	TigWeld	secure support bar on frame	0	721	0.14	prt	1,500	2,000	500	100	0	5	5	8	200	100		37	584	600	16
Fixx	HoleDie	die used for punch bar hole	0	1,062	0.33	prt	1,500	2,743	300	0	0	5	3	8	500	300	2,743	32	730	730	0
Fixx	MigFix	weld corner of two frame	0	226	0.07	prt	1,500	500	0	0	0	5	3	8	100	100		6	120	120	0
Fixx	MigFix	weld four corner and insert support bar	0	226	0.07	prt	1,500	500	0	0	0	5	3	8	100	100		6	120	120	0
Fixx	TigFix	secure support bar on frame	0	301	0.07	prt	1,500	800	0	0	0	5	3	8	100	100		9	192	192	0
Fixx	Clamp	for mandrel core assembly	0	150	0.20	prt	1,500	500	100	0	0	5	3	8	300	0		6	144	144	0
Fixx	ClipHolder	insert clip	0	50	0.07	prt	1,500	200	0	0	0	5	3	8	100	0		2	48	48	0

Table 7: Cst: Spac /yr

Type	Name	Desc	Qctrl	$/yr	$/sq ft/yr	sq ft
Spac	ReceiveSpc	receive storage area	0	4	3.7	1
Spac	SawSpc	cutting area	0	4	3.7	1
Spac	PunchSpc	punch area	0	4	3.7	1
Spac	AssemblySpc	assembly area	0	4	3.7	1
Spac	WeldSpc	welding area	0	4	3.7	1
Spac	PackSpc	packing area	0	4	3.7	1
Spac	StoreSpc	storage area	0	4	3.7	1

Table 8: Cst: Ctrt, Incv /yr

Type	Name	Desc	Qctrl (always =0)	base $/yr	$/unit	unit	approx units/yr
Ctrt	DlvTruck	truck delivery on contract	0	500	0.004		1,500
Ctrt	BadReturn	returns effort by retailer	0		0.05		10
Incv	LateFee	reduced price if product late	0		5		20
Incv	BadFee	reduced price to customer of bad product	0		5		10

Table 9: Cst: TiCt

Type	Name	Desc	Int %
TiCt	purchase & storage	fctr year production stored, yearly interest %	8

Appendix D

Design Automation

Pro/Toolkit Function Guide

The following Pro/Toolkit functions will be discussed to show how they may be used in a C program. The functions describe in this section are adopted from Appendix D of Charles' thesis (Friesen, 2001). In addition, the variables passed and received from each function will be explained. The variable declaration is given in the application section for each function. While the following functions are briefly explained in the Pro/Toolkit user guide, the information presented there does not allow immediate usage of the functions. The following information is based upon my experience and the comments found in the Pro/Toolkit source code and header files for each of the functions below.

D.1 Mandatory Functions

int user_initialize()

"User_initialize()" is the function within the users code that is executed first by Pro/Engineer. Each Pro/Toolkit program must contain this function otherwise the program will not run. Also, the function returns the value 0 to Pro/Engineer signifying successful initialization of the user program. Within this function the solid models should be initialized and the main user menus should be created.

void user_terminate()

"User_terminate()" is the function within the users code that is executed at the completion of the program. This is a void function and its contents may remain empty.

Although the function is a void and it may have no purpose it must exist for the Pro/Toolkit user program to function correctly.

ProStringToWstring() and ProWstringToString()

Within Pro/Engineer character strings are stored as "wide" strings. The functions ProStringToWstring() and ProWstringtoString() convert Pro/Engineer wide strings to C language character strings. For the following Pro/Toolkit function any string passed to the function must be in the wide string format. The conversion functions allow for user input into C language character strings and for Pro/Engineer strings to be displayed through C language coding.

Application:

Convert wide string to character string:

ProWstringToString(wchar_t widestring, char* string);

Convert character string to wide string:

ProStringToWstring(char* string, wchar_t widestring);

ProMdlRetrieve()

In order to display and interact with a model it must be retrieved from the disk. This is done using ProMdlRetrieve(). The wide string containing the model name, "modelname", and the model type, "modeltype" are passed to Pro/Engineer. The output of the function is the model handle, "modelhandle". This handle is used to communicate with the part.

Application:

ProMdlRetrieve(wchar_t modelname, modeltype, ProMdl &modelhandle);

Where modeltype is either "PRO_PART" or "PRO_ASSEMBLY".

ProMdlNameGet()

To use some of the following function the Pro/Engineer assigned model name must be obtained. ProMdlNameGet "gets" the model name from the model. This is accomplished by passing the model handle, "modelhandle", to Pro/Engineer. The function outputs the Pro/Engineer model name, "promodelname".

Application:

ProMdlNameGet(ProMdl modelhandle, ProName promodelname);

ProMdlTypeGet()

The Pro/Engineer model type, "promodeltype" must also be found to use many of the following functions. The Pro/Engineer model type may be found by passing the model handle, "modelhandle", to Pro/Engineer. The function returns the Pro/Engineer model type in "promodeltype".

Application:

ProMdlTypeGet(ProMdl modelhandle, ProMdlType &promdltype);

ProMdlToModelitem()

To find the model item designation the ProMdlToModelitem function must be executed. This is done by passing the model handle, "modelhandle", to Pro/Engineer. The function returns the model item as "modelitem".

Application:

ProMdlToModelItem(ProMdl modelhandle, ProModelItem &modelitem);

ProMdlDisplay()

To display the model in Pro/Engineer the function ProMdlDisplay should be used. Another function named ProSolidDisplay could be used, however, ProMdlDisplay is more versatile and is capable of displaying a wider range of Pro/Engineer model types. Application:

ProMdlDisplay(ProMdl modelhandle);

ProSolidRegenerate()

ProSolidRegenerate can be used to regenerate the model. In the Cowl Program this function is used after each silencer design modification to ensure that the parent / child relationships are valid. Application:

ProSolidRegenerate(ProMdl modelhandle, PRO_B_FALSE);

Where "PRO_B_FALSE" is a boolean value that instructs the function not to enter resolve mode if a parent child relationship fails.

ProFeatureSuppress() and ProFeatureResume()

Features and parts may be suppressed and resumed within Pro/Engineer using the ProFeatureSuppress and ProFeatureResume Functions. To suppress or resume a part or feature the model handle of the part or the part that contains the feature must be passed to Pro/Engineer. This is the first variable passed. The second variable is the internal id number of the part or feature. This number can be found from the model tree within the Pro/Engineer environment. If the second variable is an array of internal id's to be suppressed the third variable represents the total number of internal id's. The third

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variable sets the options for suppressing or resuming a feature or part. The total number of suppressing or resuming options is passed in the fourth variable. Please see the ProFeature header file (ProFeature.h) for more information on the resuming and suppressing options.

Application:

These function are shown as suppressing and resuming only one feature

ProFeatureSuppress(ProMdl modelhandle, int &id, 1, ProFeatureDeleteOptions &deloptions, 1);

ProFeatureResume(ProMdl modelhandle, int &id, 1, ProFeatureResumeOptions &resoptions, 1);

ProParameterInit()

To modify a parameter within an assembly, part or feature the parameters must first be initialized. This is done using the ProParameterInit function. To initialize a parameter the model item of the model to which the parameter belongs must be passed to Pro/Engineer along with the name of the parameter. This is done in "modelitem" and "parametername", respectively. The function then outputs the parameter class as "parameter".

Application:

ProParameterInit (ProModelItem &modelitem, ProName parametername, ProParameter &parameter);

ProParameterValueGet()

To "get" a parameter value the parameter class, "parameter", must be passed to Pro/Engineer. Pro/Engineer will then return the parameter value structure, "parametervalue".

Application:

ProParameterValueGet (ProParameter &parameter, ProParamvalue &parametervalue);

ProParameterValueSet()

To "set" a parameter value the parameter value structure, "parametervalue", must be modified and passed to Pro/Engineer along with the parameter class, "parameter". Application:

ProParameterValueSet (ProParameter &parameter, ProParamvalue &parametervalue);

D.2 Menu Functions

The menu functions are adequately explained within the Pro/Toolkit user guide and will not be discussed here. The required functions to create a menu are listed here:

1. ProMenuFileRegister()

2. ProMenubuttonActionSet()

3. ProMenuCreate()

4. ProMenuProcess()

Examining or copying the code used in the Cowl Program can aid in the menu code generation. Each menu requires a menu file. The menu file shows lists the text of a menu as it appears in the Pro/E environment. Each menu entry require three lines, the first line is the menu name has it appears in the code. The second and third text entries are not required; see the Pro/Toolkit user guide for information on them. One important tip, ensure that at then end of the menu file that more than three lines exist, even if they

are blank. If not enough carriage returns exist for the last menu entry the menu item will fail. This led to many problems in the Cowl Program.

D.3 Message Functions

ProMessageDisplay()

The ProMessageDisplay function allows the Pro/Toolkit programmer to display information within the Pro/Engineer environment. This is accomplished by referencing a message file. The message file, which is created by the user, contains a set of possible messages that the user could display. Wildcards, %, within the message file allow for the display of strings (%s), integers (%d), and doubles (%f). The Cowl Program message file was created generically so that many messages could be created with a small message file. The advantage of this method is that the message file could be created and forgotten since most of the message was coded into the Cowl Program.

The name of the message file is a wide string, "messagefile". The message to be sent is selected by the message name, "messagename". Finally any wildcards within the message file must be given their "additional information". If the wildcard, %d, is present, the additional information would be an integer value.

Application:

ProMessageDisplay(wchar_t messagefile, "messagename", additional information);

ProMessageDoubleRead()

The ProMessageDoubleRead function allows for user input of a double value. This function also limits the entered value with an array, "range", that determines the

maximum and minimum value the user can enter. The function outputs the user value into "uservalue".

Application:

ProMessageDoubleRead(double range[],double &uservalue);

ProMessageClear()

ProMessageClear scrolls the current message display area up one line.

Application:

ProMessageClear();

D.4 User Functions

Many user functions have been created within the Cowl Program. The most important functions will be briefly discussed.

UserSetupCat()

After the program is first begun the user is required to select a catalogue silencer. This is accomplished by selecting a silencer configuration, inlet/outlet size, and flow direction. The function, UserSetupCat, determines the appropriate values for each parameter within the silencer assembly. When the parameters have been set the function UserSetParameters is called upon.

UserSetParameters()

This function communicates the parameter values within the user program to Pro/Engineer. After the parameters are set the silencer assembly can be regenerated to obtain the catalogue silencer.

UserSetupModifiedParams()

With the catalogue silencer present the user can modify various parameters within the silencer. After each modification the UserSetupModifiedParams function is executed. Following this the silencer assembly is regenerated. The UserSetupModifiedParams function uses relation equation to maintain the silencer design characteristics while modifying variable parameters to reflect the users silencers modifications.

UserResumeUsed()

Once the modified parameters have been set the silencer must be assembled carefully in order to maintain the parent / child relationships. This function, UserResumeUsed, resumes the features and parts that are necessary for the silencer configuration after modification have been made.

D.5 Function Flow Chart

Legend:

| MENU FUNCTION | CHANGE MODEL FUNCTION | RETURN VALUE FUNCTION |
| USER INPUT FUNCTION | FILE UPDATED | CHANGE PARAMETER FUNCTION |

user_intialize

UserInitModel
UserInitPart
MenuSelectSilencerModel

UserSelectConfig → UserChoosePR
UserEnterDia → UserChoosePL
UserSelectFlow → UserChoosePV
→ UserChoosePT

MenuSetSilencerOptions
UserSelectMaterialAS
UserSelectMaterialSS
UserSelectMaterial
UserSelectPaint
UserEnterDimensions
UserEnterPerformance

UserChooseTL
UserChooseTR
UserChooseSR
UserChooseSL
UserChooseSV

UserChooseStandard
UserChooseReverse

UserSelectPaintBlack
UserSelectPaintSilver
UserSelectPaintPC

UserAddFrontMain
UserAddRearMain
UserAddFrontOption
UserAddRearOption
UserAddHole1
UserAddHole2
UserAddHole3
UserAddHole4

UserRemFrontMain
UserRemRearMain
UserRemFrontOption
UserRemRearOption
UserRemHole1
UserRemHole2
UserRemHole3
UserRemHole4

MenuModify
UserAddInlet
UserAddOutlet
UserRemoveInlet
UserRemoveOutlet
UserModSpiralID
UserModSpiralOD
UserModSpiralGap
UserModSpiralDepth
UserModCTC
UserModEPThk
UseAddLugs
UserRemoveLugs

ShowSilencer
UserSetupModifiedParams

MenuOptimizeSilencer
Optimize BFGS Cost → dfpmin
Optimize ARSM Cost → ARSM

GetMinDia
GetOptionHoleOffset
GetHeightFromCenter
GetTopOffset

ARSMOptimize

PERF
logJune2802.dat
CowlFeb2002.xls
ProIn.dat
outexcel.dat
input.dat

MenuShowSilencer
MenuQuit
UserSetupCat
UserSuppressAll
UserRegenModel
UserDisplayModel
UserSetParameters
UserResumeUsed

ARSMDisplayCosts
COST

GetCatSpiralDepth
GetCatTopMainDist
GetOptionHoleOffset
GetCatOptDist
GetTopDist
GetHeightFromCenter
GetCatEPDia
GetTopOffset
GetSpiralGap
GetTopHole34CenterDist

UserResumeThing
UserSuppressThing

UserSuppressThing
UserSetParameter

EPCOST
TOPCOST
WELDCOST
SPIRALCOST
LETCOST
LABOURCOST
PAINTCOST
PERF
COST

MenuCostAnalysis → BFGSDisplayCosts

user_terminate

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Appendix E

CD Contents

Directory Filename	Descriptions
Readme CD	User readme file for CD instructions
Arsm Source Code	C source code for ARSM algorithm
Bfgs Source Code	C source code for BFGS algorithm implemented in COWL program
COWL Project	Industrial Silencer Project
• CAD Model	Pro/Engineer part & assembly files
• Cost Model	OBC Excel file
• COWL Program	COWL.exe file
• Source File	Source code for industrial silencer project
LBMH Project	Air Diffuser Project
• CAD Model	Pro/Engineer part & assembly files
• Cost Model	OBC Excel file
• LBMH Program	LBMH.exe file
• Source File	Source code for air diffuser project
• Video Clip	Video documentation of LBMH manufacturing processes (avi format)
ProE Userguide	User guide for Pro/Engineer 2000i & Pro/Toolkit
VB Macro	Visual Basic source code for "RunExcelMacro.exe"
Video Demo	Demo avi video clips for COWL program, LBMH program and COWL web-based program