A New Design For Production (DFP) Methodology with Two Case Studies

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Abstract

Concurrent engineering (CE) design demands the consideration of product life-cycle issues in the early product design stage. Among various life-cycle issues, this work concentrates on production and how to optimize a product design to minimize its production costs. This paper proposes the use of cost as the measure of the productivity and defines Design for Production (DFP) as methods that lead to a product design with minimum production costs while satisfying all the functional requirements. Based on this definition, this work proposes a DFP methodology. The novelty of this methodology lies on three aspects 1) the use of the Operation-Based Costing (OBC) method to measure productivity, 2) the identification of relations and boundaries between product design and production activities, and 3) the integration of product design, production cost estimation, and metamodeling-based optimization to search for the optimal product design. The proposed DFP methodology has been applied to the optimal design of two industry products, an industrial silencer and a linear air diffuser. The results from these studies demonstrate the effectiveness of the proposed method, whose assumptions and limitations are also elaborated.

Keywords: Design for Production, Concurrent Engineering, ARSM, Operation-based Costing

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Introduction

Product design heavily influences cost, quality, and time-to-market and thus profit to an enterprise. 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 stage [1, 2]. The concurrent engineering (CE) techniques can enhance the integration of teamwork management and computer technologies to increase the productivity of product design. However, current CE techniques are mainly management-oriented and qualitative in nature. More quantitative methods and technologies are desired to avoid "pitfalls" of qualitative CE techniques, such as the unnecessary simultaneity, information chaos, and incapability of searching the optimal design [3].

A simultaneous consideration of product life-cycle issues at the early design stage known as Design for Excellence (DFX) has achieved great success over the past two decades [4]. As one of the DFX methodologies, DFMA developed by Boothroyd and Dewhurst has been successfully commercialized into software tools [2]. Through the analysis of manufacturability and assemblability, they showed how the product design decisions could influence individual manufacturing operations, such as casting, injection molding, and CNC milling. Venkatachalam [5], Zannier and Pardasani [6] commented that most DFM methods were unable to provide redesign suggestions, and absent of integrated engineering effort to maximize functional and manufacturability objectives. In addition, the DFMA methodology only focuses on individual manufacturing operations, for example, design for injection molding. Ideally, to achieve the overall efficiency, a product design should be optimized considering all the related production issues, not only individual operations [7]. Thus a DFP strategy, which extends beyond the DFMA, should be more practical and useful for manufacturers.

DFP is a recently evolved product design methodology. However, its philosophy has been well documented since the 60's [8, 9]. The recent research in Refs. [10, 11] 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 DFM from DFP as studies of the feasibility of manufacturing the product from DFP, while DFP evaluates manufacturing capacity and measures the manufacturing time. They have also found that DFP required information about the product designs as well as details of the manufacturing as a whole. In general, they assumed that the reduced manufacturing cycle time would bring profit to a company. Such an assumption raises concerns. 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 researches on the DFP philosophy but under different titles are also seen in the literature [7, 12-15], to name a few.

In this work, we argue that cost should be used as the ultimate measure of productivity, based on which the definition of design for production (DFP) is given. Then a quantitative DFP methodology is developed to aid design engineers to examine all the related production issues in search of a minimum-cost product and production strategy.

Proposed Design For Production Methodology

Definition of DFP

The founders of industrial engineering emphasized the use of cost as a measure of productivity for production systems. Over a period of time, engineering professionals began to use physical measurement such as *units of production per unit time* and *units of production per unit machine hour*. It is partially because of the general accounting approach does not directly associate costs with production; instead many cost items are categorized as overhead costs. It is found often in industry that the physical measurement may point to an improvement in productivity, but in fact the production cost has increased. For an example, increasing the productivity measured by *units of production per unit machine hour* by installing high-capacity machines may cause losses in purchasing the machinery. Under a competitive business environment, the objective of increasing profit for commercial organizations can only be achieved by increasing sales and reducing the cost of production [16]. Cost is the common indicator into which all resources throughout the manufacturing system can be translated and measured. Thus cost should be the ultimate measure of productivity. By using cost as the measure of productivity, we define DFP as "systematic methods that lead to a product design with minimum production costs while satisfying all the functional requirements."

An Overview of the Proposed DFP Methodology

Specifically, four elements are being considered essential to the proposed DFP methodology:

1. The use of Operation Based Costing (OBC) method to measure productivity and quantify production costs.

2. Study of relations and boundaries between product design and production issues to generate DFP design guidelines.
3. Quantification of relations between product design variables and cost elements of the OBC model.
4. The use of metamodeling-based optimization methods for design optimization.

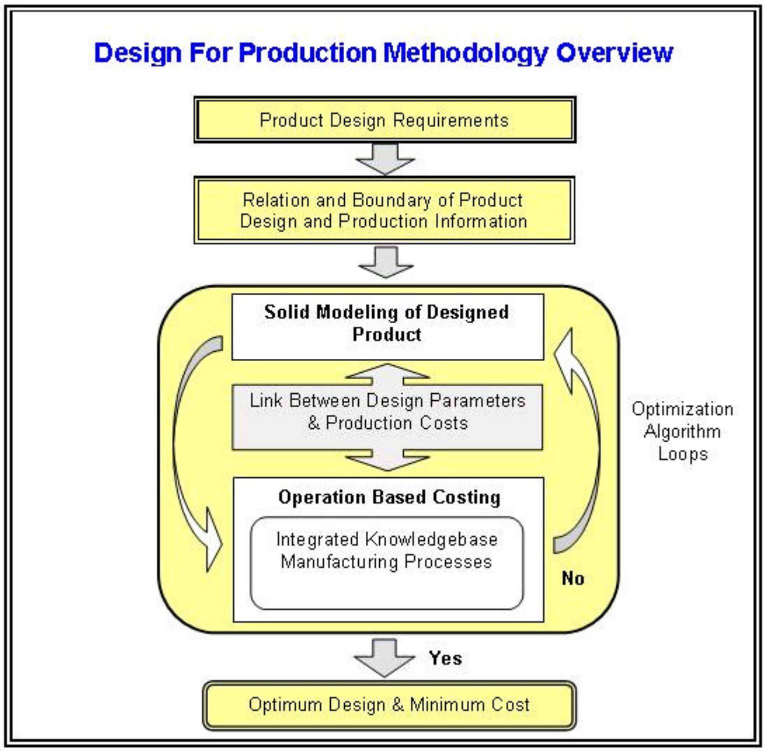


Figure 1 An overview of the proposed Design for Production (DFP) methodology.

The integration of these four elements forms the core of the proposed DFP methodology. As shown in Figure 1, the product design requirements are interpreted and initial conceptual product design and process plan can be created. Based on the theory of OBC [17, 18], the relationship between product design and production cost elements could be analyzed (to be discussed later). Parametric equations and / or knowledge-based models can be created to associate design variables and cost elements, base on which optimization can be applied in search of the product design that leads to the minimum production costs.

Assumptions

As production situations can be very complex, this study focuses on the basic and important production issues in developing the proposed DFP. Some assumptions of the production and design are made as listed below to define the scope of this study. The developed DFP methodology, however, is expected to be fundamental so that it can be extended to accommodate more complicated production situations.

- **A Single Product**: 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 product families or groups are treated.

- **Historical Manufacturing Information**: The cost and manufacturing information used are based on the historical data within a manufacturing company. This work assumes that the majority of the necessary input information required by the cost analysis and DFP is available, or can be obtained within the company.

- **Annual Cost Analysis**: The quantity of output in the OBC is based on the annual production and is fixed throughout the cost analysis, for example, 10,000 units/year. Average values are used for the interest rate, tied rate, and depreciation.

- **Fixed Handling and Scheduling**: The variation of a product design is assumed to have little effect on the handling and scheduling. This assumption is made on the observation that for a product of a certain function, the change in design parameters normally is not significant enough to affect the material handling strategy. For simplicity, the scheduling is assumed to be always acceptable and the change of product design would not cause any constraint on the manufacturing process. We do recognize that in many situations, the change of product design does affect the material handling and cause scheduling difficulties.

- **Standard Operation**: For simplicity, the frequency of machine breakdown, maintenance, and setup-time is considered the same as the average of previous years.
- **Process Planning**: For a given product design, it is assumed that a feasible process plan can be generated by an expert. The generation of process plan or computer aided process planning (CAPP) has been intensively studied such as in Ref. [19]. This work does not incorporate CAPP, but a CAPP system can greatly help the proposed DFP methodology in achieving design automation.

Following sections will discuss respectively the four components of the proposed DFP methodology.

Operation-based Costing (OBC) Method

Among many cost estimation methods (see Wong 2002 for a detailed review), the activity-based costing has attracted many engineering applications since its development in the 1980s' by Robert Kaplan and Robin Cooper [20]. 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. However, the activity-based costing method does not sufficiently address the structure of production system analysis and it is meant for management accounting.

A new cost estimation method, operation-based costing (OBC) method, is recently developed by Strong and his team [17, 18, 21]. This method has the advantage of tracing activities that consume resources in a production system without spending excessive effort by changing the overall corporate cost management system. For each operation in a manufacturing process, OBC breaks down the cost into eight major elements. The sum of all eight costs of each operation gives the total cost of the operation. These elements are as follows.

1. **Machinery** for the operation; including the cost of capital, installation and training, depreciation, maintenance and repair, energy and other consumption, salvage, tax, and so on.
2. **Fixture** to hold material or help shape the material undergoing an operation; the cost of the fixture is calculated similarly to the machinery.
3. **Operator** to operate the machine or work with other tools and materials undergoing an operation; including the cost of salary and other payments such as overtime and bonus, fringe benefits, and supports.
4. **Space** for a workstation to conduct an operation, and a small buffer space for inputs and outputs of the operation; including the cost of rental, utilities, cleaning, and so on.
5. **Contract** with outside parties for some operations or for support functions and services required in production. For example, the cost of transport is the most common contract cost.
6. **Incentive** to control quality and timely delivery of materials from suppliers; the cost can be in the form of an incentive or penalty.
7. **Material** to fabricate the products required by customers;

8. **Tied Cost**: the resources "Tied Up" in inventories in and around each operation; the cost includes the opportunity cost, insurance on inventory, and taxes on the inventory value.

The OBC model is programmed in Microsoft Excel as a combination of spreadsheet and macros. Users just need to manually input cost and manufacturing information and click on a specific macro button to calculate the results. Figure 2 illustrates the data flow between worksheets. More detailed examples on OBC are given in Refs. [17, 22].

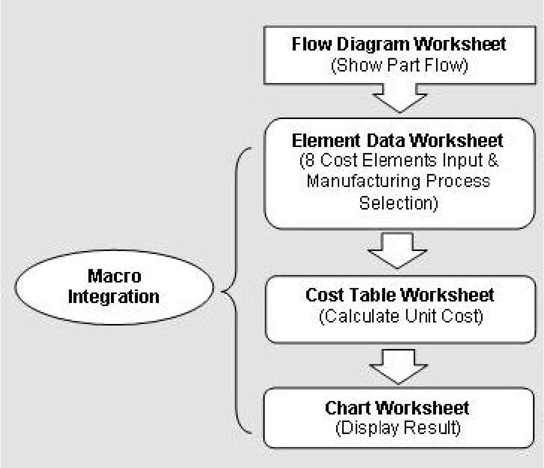


Figure 2 Data flow of OBC and its integration with a solid modeler.

For a given product, a detailed production process is constructed with all of the related operations including purchasing, manufacturing operations, and delivery. The cost of the entire production process is then the sum of all operation costs. Such an approach provides all of the detailed activity information, which is organized and structured around the production operations. Thus a production system can be simulated and modified to minimize the overall production cost. Tests with industrial examples revealed that the OBC is a robust and practical measurement of productivity. It also provides insights to an existing production system for potential improvement. The proposed DFP methodology demands an accurate and operation-oriented cost estimation of production systems. After comparing various cost estimation methods, the OBC method was chosen as the foundation for productivity measurement for the DFP.

Relations and Boundaries between Product Design and Production

It is widely understood that design decisions greatly impact the production system. But not all of the production issues are affected by design decisions. To develop a design for production methodology, a careful identification of relations and boundaries between product design and product will help engineers to focus on and quantify design-related production costs.

In this work, the relationships between production issues and product design are first categorized into direct, indirect, and negligible relationships [23, 24]. Similar categorization can be found in Refs. [7, 25-27]. In this work, direct relationships indicate that design variables directly affect production activities, and such relationships can usually be captured in a parametric equation. For example, the product overall dimension directly relates to the machine envelop (See the first row in Table 1).

Indirect relationships indicate the relationships between production activities and design variables are complex. Quantification of such relationships usually relies on the interaction with other factors. Thus indirect relationships are usually hard to describe via a parametric equation; instead knowledge-based, case-based reasoning or other similar methods may be used. For instance in Table 1, the relationship between product tolerance with the machine feed rate is complex and dependent on other factors such as product material, complexity of shape, the machine properties, and so on. Thus such a relationship is classified as indirect.

Negligible relationships are those weak interactions between design factors and production issues, and in most situations can be ignored for simplicity. For example, the life span of machinery is considered having a negligible relationship with any product design parameters. Such negligible relationships define the design-independent issues and thus help us concentrate only on the direct and indirect relationships, or design-dependent 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	
Fixture (Jigs, Fixtures, including tools such as dies, molds, and patterns)	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

Table 1 Categorization of product design and production relationships.

Table 1 forms a general qualitative guideline on developing the relationship of product design and production. It lists the relationships between four types of design variables, namely dimension, material, tolerance, and geometric shape, with the four main cost elements as stipulated by the OBC method. Those elements include machine, material, labor and fixture costs. In many situations, a weak relationship exists between design variables and the rest of the 8 cost elements, including space, tied, incentives, and contract costs. Other production issues, such as scheduling and safety, are considered invariant with the variation of design variables.

Identifying the relationships described above can provide designers with insight to understand the interactions between product design and production issues. It can further help the quantification of such relationships. However, the relations between product design and production issues are complex and vary with certain products and manufacturers. It is acknowledged assumptions made above might be violated and the categorization and content of Table 1 might change. Thus Table 1 should be reexamined and modified for a specific design task. It is hoped that the essence of the table is useful, i.e., the establishment of the relationships between four types of design variables and the eight cost elements for each operation.

Quantification of Relations Between Design Variables and Cost Elements

For a given product design, it is assumed that a standard process plan can be generated and thus OBC is applied to quantify the costs of each operation. For the purpose of optimization, one needs to quantify the relationships between design variables and cost elements, so that whenever a design is changed, its corresponding product costs can be estimated and thus the optimum searched. For direct relationships in Table 1, usually a parametric equation can be built. While for indirect relationships, more complicated and domain dependent knowledge base might be necessary. In the two case studies, those two methods are used to build relationships. More details are described in later sections.

Design Optimization

Most conventional optimization algorithms, however, are based on well-defined objective and constraint functions with explicit expressions [28]. The optimization process is not transparent to engineers and usually only one single solution is found, which often is not the best in real design practice. Some recent optimization methods treat the objective function as an unknown function, whose expression is unknown, however, functional outputs can be computed if inputs are given. Then by systematically generating a set of input-output pairs (points) using the *Design of Experiments* (DOE) methods, a "metamodel," often a polynomial function, is constructed by regression analysis such as the least square method. Based on the polynomial function, the optimization process can be carried out using conventional optimization methods. Such a method is called the metamodeling-based optimization. This approach can deal with optimization problems with discontinuous and continuous functions, and / or discrete and continuous design variables. It allows simultaneous computation of a number of different design points. The entire process is intuitive, visible, and controllable by engineers. Engineers can also gain knowledge about the relative importance of each design variable from the obtained polynomial function [29]. For the proposed DFP, the complex OBC process involves many equations, models, and sometimes, expert knowledge. It involves human interactions and thus a transparent and intuitive optimization process is desired. The problem lends itself well to the metamodeling-based optimization. In this study, a metamodeling-based optimization method, called the Adaptive Response Surface Method (ARSM), has been chosen. More details about ARSM can be found in Refs. [30, 31].

Procedure of DFP

To apply the proposed DFP method, following steps are to be followed:

Step 1: Identify design variables and other related design functions such as performances

Step 2: Analyze relations and boundaries between design and production; identify design-dependent production issues.

Step 3: Apply OBC to model the cost elements for the production of the product

Step 4: Quantify the relations between design variables and cost elements

Step 5: Call the optimization routine to search for the optimal product design (See Figure 5).

The proposed DFP methodology has been applied to two industry design cases, the design of industrial silencers and air diffusers. The design of silencers involves only dimensional design variables of parametric relations with production costs. The design of diffuser involves dimensional as well tolerance design variables. The relation between variables and costs is more complex. The above DFP procedure was followed to carry out the two product designs.

Design of Industrial Silencers

Industrial silencers [32] are used primarily on diesel engines in the marine, generator, construction vehicle, and military vehicle industries. Figure 3 depicts a commercial COWL silencer. The silencer is manufactured using metal plates and long pipes as the raw materials. The major operations involved are stamping, bending, cutting, and rolling.

As the spiral component is the key to a silencer, three spiral parameters, the outer diameter, spiral gap, and spiral depth are chosen as the design variables, shown in Figure 4. These three variables can determine the density of spirals as well as the overall spiral size and product size.

Such influences further translate to the material consumption and manufacturing costs, which are to be quantified using the OBC method. The design must produce an allowable gas flow rate and back pressure from the silencer, while satisfying its damping function. Also, the overall silencer sizes are constrained by the available space of the installation site. The design optimization model is formulated as follows.

$$\min_{w.r.t.\ \bar{x}} \qquad \text{cost}(\bar{x}) = \text{Total production cost} \qquad \bar{x} = od, depth, gap$$

$$\begin{aligned}&\text{subject to}\\ &\qquad \text{Spiral surface area} \geq \text{Graph Area Function}\\ &\qquad \text{Current exhaust velocity} \leq \text{Maximum velocity}\\ &\qquad \text{Overall size} \leq \text{Maximum Given space}\\ &\qquad x_i \in [x_{l,i},\ x_{u,i}], \quad i = 1,\ 2,\ 3\end{aligned}$$

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

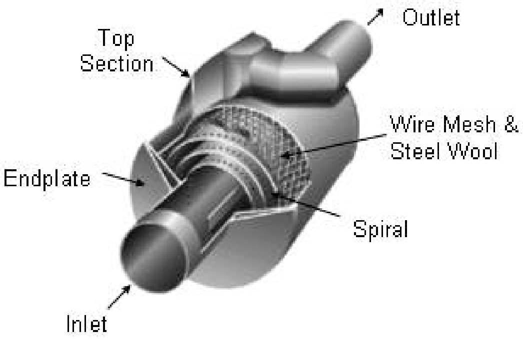


Figure 3 Diagram of an industrial silencer [25].

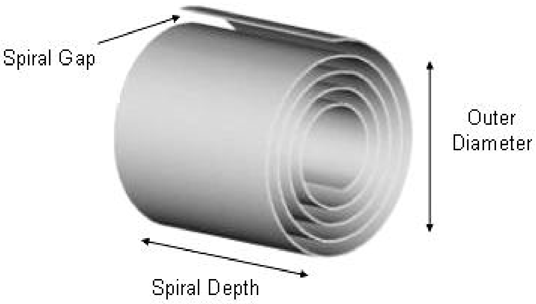


Figure 4 Chosen design variables for the silencer.

The OBC method is applied to model the design objective – the total production cost. The silencer geometric model is constructed in the Pro/Engineer environment. The Pro/Engineer programmatic tool, Pro/Toolkit, is used to extract and control the solid model construction and display. The ARSM program reads the dimensions and material parameters from the Pro/Engineer database, which are then sent to the OBC models. ARSM then carries out the optimization procedure by calling the OBC model in Excel to determine the minimum cost. The constraints are modeled and coded in the Pro/Toolkit program; they are simultaneously checked by the ARSM module to ensure that the design constraints are satisfied. This process is illustrated in Figure 5.

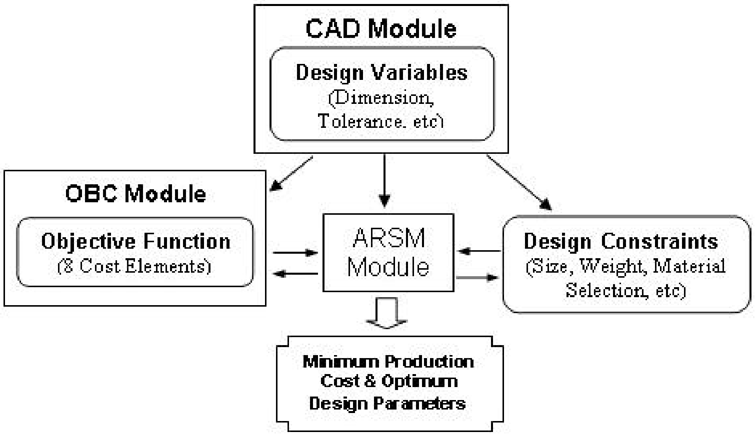
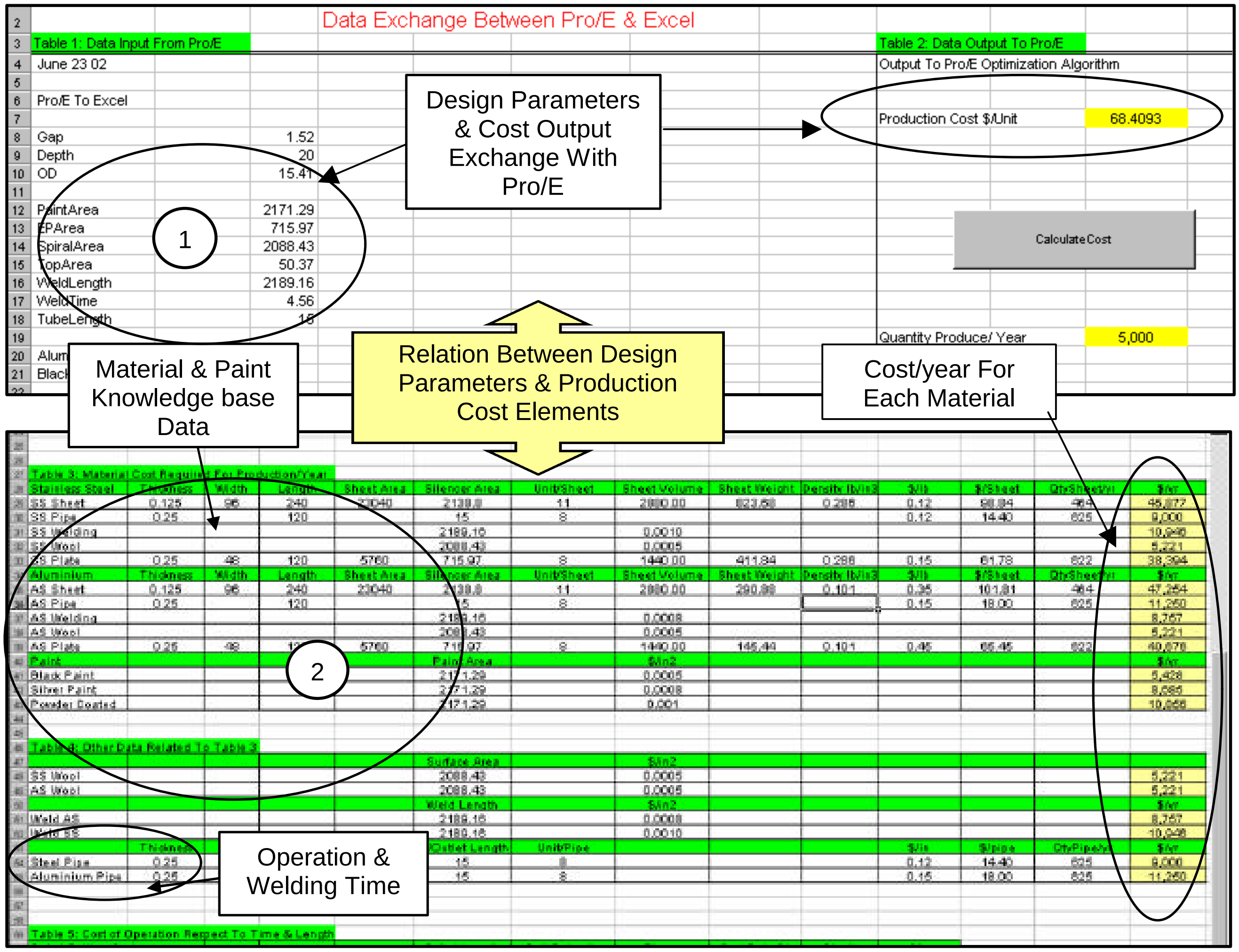


Figure 5 Interaction of ARSM with OBC and CAD models.

Figure 6 depicts an intermediate data exchange worksheet between the solid model (Pro/Engineer is used in this study.) and the OBC model. The number ① shows the information retrieved from the solid model. It consists of the tree design variables, silencer area, and welding time. The spiral dimensions are related to the production activities of raw material, paint material, and operation welding time. These values are linearly formulated within the ElementTable spreadsheet in the OBC model, as shown in area ② in the figure. Within the model, Excel macro carries out the cost calculations and gives the unit production cost. In area ②, the relationships of silencer components and material costs are formed through a series of parametric equations. These parametric equations calculate the amount of material used for each silencer component. In addition, the paint cost is obtained by multiplying the overall silencer area with unit material cost. The welding material cost is calculated based on the total length of welding. All these parametric equations are omitted here due to space limit. Details can be found in Ref. [24].



Data Exchange Between Pro/E & Excel

Table 1: Data Input From Pro/E

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Pro/E To Excel

Gap	1.52
Depth	20
OD	15.41
PaintArea	2171.29
EPArea	715.97
SpiralArea	2088.43
TopArea	50.37
WeldLength	2189.16
WeldTime	4.56
TubeLength	15

Table 2: Data Output To Pro/E

Output To Pro/E Optimization Algorithm

Production Cost $/Unit	68.4093
Quantity Produce/ Year	5,000

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	$/yr
SS Sheet	0.125	96	240	23040	2138.8	11	2880.00	823.68	0.288	0.12	98.84	464	45,877
SS Pipe	0.25		120		15	8				0.12	14.40	625	9,000
SS Welding					2189.16		0.0010						10,946
SS Wool					2088.43		0.0005						5,221
SS Plate	0.25	48	120	5760	715.97	8	1440.00	411.84	0.288	0.15	61.78	622	38,394
Aluminium	**Thickness**	**Width**	**Length**	**Sheet Area**	**Silencer Area**	**Unit/Sheet**	**Sheet Volume**	**Sheet Weight**	**Density lb/in3**	**$/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	40,678
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

Table 4: Other Data Related To Table 3

					Surface Area		**$/in2**						
SS Wool					2088.43		0.0005						5,221
AS Wool					2088.43		0.0005						5,221
					Weld Length		**$/in2**						**$/yr**
Weld AS					2189.16		0.0008						8,757
Weld SS					2189.16		0.0010						10,946
	Thickness				**Outlet Length**	**Unit/Pipe**				**$/in**	**$/pipe**	**QtyPipe/yr**	**$/yr**
Steel Pipe	0.25				15	8				0.12	14.40	625	9,000
Aluminium Pipe	0.25				15	8				0.15	18.00	625	11,250

Table 5: Cost of Operation Respect To Time & Length

Figure 6 Parametric relations between design variables and production cost elements.

Results

The DFP design strategies and the developed silencer design system have been tested by inputting different sets of user requirements. The user inputs are shown in the first six columns in Table 2, and the cost savings are shown under the ARSM columns. The cost of the obtained optimal design is compared with that of the design suggested by company catalog. It is shown that the application of DFP gives an average of more than 40% in cost reduction. The ARSM is also compared with a well-known local optimization method, the BFGS based Quasi-Newton method. The comparison shows that the ARSM can obtain better optimization results than BFGS.

Model	Inlet/Outlet Diameter	Flow Direction	Material	Paint	Max. Dimension	Performance Constraints	BFGS	ARSM
							% Cost Reduction	% Cost Reduction
PR	5	Standard	Aluminum	Black	20,20,20	OK	8.53	40.08
PR	8	Standard	Aluminum	Black	30,30,30	OK	29.57	55.98
PR	10	Standard	Aluminum	Black	40,40,40	OK	41.79	67.37
TL	5	Standard	Aluminum	Black	20,20,20	OK	8.62	40.20
TL	5	Reverse	Stainless	Black	20,20,20	OK	8.72	40.59
SR	5	Reverse	Stainless	Black	20,20,20	OK	10.42	42.45
SR	5	Reverse	Stainless	Silver	20,20,20	OK	10.38	42.62
SR	6	Reverse	Stainless	Powder	25,25,25	OK	22.22	52.02
Average Cost Reduction For BFGS & ARSM							17.53	47.66
Note: The cost calculation is on the basis of an annual 5,000 units of production.								

Table 2 Test results of the silencer design by using the DFP methodology.

Design of a Linear Air Diffuser

The second case study is performed on a linear air diffuser unit. The product line is referred to as the LBMH series. LBMH is an air distribution device, which is usually installed in floors, windowsills or high sidewalls. It can be designed for either supply or return air applications.

LBMH is constructed using heavy-duty aluminum material that consists of a rectangular border frame, mandrel core, and support bar to place the mandrel core on top of the frame (See Figure 7). 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.

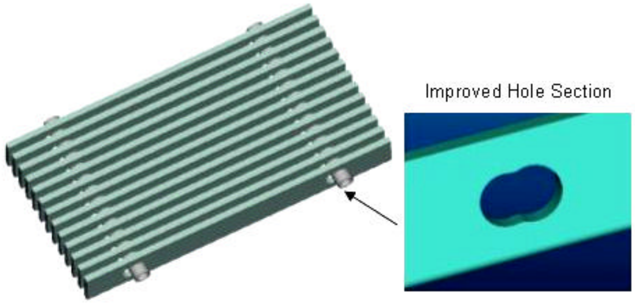

Figure 7 LBMH air diffusers. Figure 8 Improved design for the mandrel core.

The analysis of LBMH production revealed the mandrel core assembling process utilized 25% of the total production time. Due to manufacturing errors, it is time consuming to insert the tube through all of the tubes. It also results in high scrap ratio. In addition, the pushing rod is easily bent for wide mandrel cores, resulting in the pin becoming stuck within the tube. It normally takes long setup and operation time and causes high stress on operators. The improved design shown in Figure 8 applies a locking mechanism. Two overlapping holes with differences in radii are used in place of a single hole. The larger hole is for the tube to slide through and align with other mandrel bars. When the bars have been properly spaced, the tube can be knocked into the smaller radius hole using a hammer, assuming the design tolerance ±0.005-0.01 inch is satisfactory. Three design variables are chosen in this study, the length of core bar, *L*, the controlled room temperature, *t*, and the die tolerance to stamp the two overlapping holes, *TOL*.

Relationships between Design and Production

We assume that the length of core bar, *L*, drives other dimensions. The material cost can be estimated through parametric equations. The core assembly time is also modeled as a function of the number of tube and mandrel bars, and mandrel bar's length via parametric equations. The challenge in modeling is the tolerance-cost relationship as it relates to the manufacturing process.

By employing a knowledge-based approach, the tolerance design focuses on the selection of a proper manufacturing process in producing the punch die for the notch in the improved design. The knowledge-based data in the LBMH cost model provides a selection of three applicable processes: die casting, investment casting, and machining process. The cost-tolerance relationships for all processes are obtained from Ref. [34]. The following is an example of an equation for calculating the relative cost (RC) of the die casting process.

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

where Tol is the die hole tolerance. The knowledge base can help choosing the process that leads to the minimum die-manufacturing cost that thus the lowest production cost. Other information such as machine setup cost, die processing cost and die's life are also taken into consideration. Table 4 lists a detailed comparison for all three possible processes, based on the assumed demand for die use. In this case, the machining process is selected. All the relevant tolerance-cost data with machining are then included into the fixture cost element section of the OBC model. It is to be noted that for different size of diffusers, the number of mandrel holes will be different. Therefore, the demand "Qty/yr" will vary, which leads to different optimal choice of die-making processes. In this work, the selection of process is automatic via knowing reasoning.

Die Process	Tol. Range	Tolerance	Initial $	Setup $	$/Operation	Qty/Die	Qty/yr	$/Die
Die Casting	0.001 - 0.02	0.005	1000	200	300	50000	12000	2,762
Investment Casting	0.002 - 0.02	0.005	1000	175	250	42000	12000	3,179
Machining	0.002 - 0.02	0.005	1000	250	500	20000	12000	2,243

Table 3 Knowledge-based process selection.

Design Optimization

For a diffuser design, following design requirements are to be satisfied, the maximum noise criterion (NC) value, and the airflow rate (CFM) requirement according to the room volume. For simplicity, the final optimization model is as follows.

$$\min_{w.r.t.\ \vec{x}} \quad \cos t(\vec{x}) \qquad \vec{x} = L, Tol, t$$

$$\text{subject to}$$

$$\text{Current airflow rate} \geq \text{Required airflow rate}$$

$$\text{Current NC} \leq \text{Maximum NC}$$

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

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

Input Parameters					Test Output				
Room Temperature (°F)	Static Pressure (in H2O)	Length (in)	Width (in)	Tolerance (in)	Perform.	Initial Cost ($)	Final Cost ($)	% Reduct.	Die Processing Method
70	0.2	4	1.5	0.005	OK	33.94	33.60	1.00	Die Casting
70	0.2	12	2	0.005	OK	39.50	37.85	4.18	Machining
70	0.2	20	3	0.005	OK	53.78	47.26	12.12	Machining
70	0.2	40	6	0.005	OK	102.16	86.54	15.29	Machining
70	0.2	50	5	0.005	OK	107.44	96.27	10.40	Die Casting
70	0.2	96	6	0.005	OK	180.15	159.96	11.21	Machining
Average % Cost Reduction								9.03	
Note: The cost calculation is on the basis of an annual 1,500 units of production.									

Table 4 Test results of the air diffuser design by using the DFP methodology.

Results

A few different design requirements are input to test the DFP methodology. Table 4 lists the test results. The results show an average of 10% reduction in the 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. Therefore, smaller sized grilles have less potential for cost saving, mainly because the material cost that is directly related to size does not significantly affect the entire production cost. The LBMH program has shown the potential design improvement that can be achieved through the implementation of the DFP application.

Conclusions

In this work, the design for production (DFP) is defined as methods that lead to a product design with minimum production costs while satisfying all the functional requirements. A new DFP methodology is developed and presented with two industrial applications. The first contribution of the proposed DFP is the use of the OBC as the tool to quantify production costs. The OBC is not only by far the most appropriate costing method for productivity measurement, it also lends itself well for the DFP because quantification of design and production relationships become possible by associating design variables with individual cost elements. Secondly, the definition of relations and boundaries between product design and production helps design engineers focus only on design related production issues and also give freedom to production engineers make design independent decisions. Thirdly, the integration of meta-modeling based optimization methods with cost estimation and product design proves to be a promising approach due to many engineering advantages these methods bear. Finally, the procedure of the DFP is systematic and facilitates the design automation. A preliminary DFP software tool was developed for the silencer design to demonstrate its application in industry. The design projects of industrial silencer and linear air diffuser were used to test and demonstrate the effectiveness of the DFP methodology. The outcome presents potential savings in production cost and time.

The proposed methodology can also be extended to consider other product life-cycle or CE issues into the optimal product design. For example, the product’s environment costs can be evaluated from the disposal costs for scraps and pollutants generated at each operation and final product. Provided the environmental impacts could be quantified as costs, the environmental costs can then be added to the overall production costs for optimization. Other CE issues such as assembliability and serviceability would also be addressed in a similar fashion. These considerations, however, are beyond the scope of this work.

It is recognized that the proposed method is at its infant stage. The product/production relationship is conceptually defined but great difficulties are found to generalize the parametric expressions. More solid design guidelines still need to be explored to accommodate the complex relationship between product design and production costs. Also constructing a knowledge base is problem dependent. How to link design with other production issues such as supplier, handling and scheduling and production quantity should be further studied. In addition, the developed DFP methodology needs to be further assessed for more complex manufacturing systems and product designs.

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