DEVELOPMENT OF AN AUTOMATIC DESIGN AND OPTIMIZATION SYSTEM FOR INDUSTRIAL SILENCERS

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ABSTRACT

Current Computer Aided Design (CAD) software tools focus on rapid production of computer models, which usually takes place after the product design is completed. The product design process, which has more significant influence on product life-cycle costs, is not fully supported. This work documents the development of an automatic design and optimization system for industrial silencers. The developed system greatly reduces the production costs and shortens the silencer design time from one day to a few minutes. Moreover, the system proves the feasibility of developing an open-architecture CAD system supported by Design of Experiment (DOE) based optimization methods to integrate product life-cycle considerations into the design. It is expected that the developed system can help the development of similar systems for other products. Through the development of this system, some further research issues are identified.

KEYWORDS: design automation, design of experiments, design optimization, parametric design, silencer

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INTRODUCTION

Today's global market demands quicker, cheaper, and better product designs for manufacturing industries. The computer aided technologies help to reduce production time and costs. However, most current CAD tools function as a productivity aid to help speed up the modeling and drawing generation process. The product design, that generally influences 70-80% product life-cycle costs [1] has not been directly supported by current CAD tools.

In the framework of concurrent engineering, much research has been done recently in the area of design automation with integrated optimization tools with CAD systems. One contribution proposed by the research team from Brigham Young University [2] provides a methodology of integrating parametric design with a programmatic toolkit to optimize product design. The methodology was applied to the design of jet component using interactive CATIA environment together with the programmatic program, CATIA IUA language. The complicated free-form surfaces of the airfoil and impeller of turbine blade are designed using CATIA programmatic toolkit. Also they tried to develop a common graphical user interface (GUI) to ease the programming and communication between various CAD packages. Line and Steiner in their research [3] proposed a concept of automatic calculation of product architecture metrics using a solid modeling program, I-DEAS, as the modeling tool. A program that uses internal I-DEAS functions is created to find all of the joined parts. The strength of each joint is calculated for adjusting the parts connectivity and the average joint strength to obtain a satisfactory design. They define the architecture of product as the scheme in which functions are mapped to physical components. The result is a modular architecture (a one-to-one mapping of function to component) and an integral architecture (a many-to-one mapping of function to component).

Then, Line and Steiner's method of architecture calculation is coded and integrated with the CAD tool to perform the calculation of architecture metrics automatically. A similar concept on design automation was developed by Chan and Lewis [4], which involved integration of manufacturing and cost information into the engineering design process. Their research was proposed to create a Design for Manufacture (DFM) System called DFM-C System for Small to Medium Size enterprises (SMEs) to seek for manufacturing and economic benefits. The DFM-C system was designed to apply to the conceptual phase of design process and its structure was based on an expert system called CLIPS (C-Language Integrated Production System). There are three basic components in the DFM-C system: a knowledge base that contains designs and design-related knowledge, the Material Selection (MS), Manufacturing Process (MP), and Cost Estimation Module to select appropriate material and processes, and an inference engine. The program is written in C and is integrated with the CLIPS expert systems programs for filtering incompatible processes and optimizing selected processes. Bras and Kalyan-Seshu [5,6] integrated design for "X" tools with CAD systems (I-DEAS and Pro/E) to achieve optimal design ("X" stands for manufacturing, assembly, environment, etc.) Due to the un-availability of programming tools, the integration was semi-automatic. Forster and coauthors [7] proposed an automatic design method to construct tolerance chains of a mechanical assembly. Esche and coauthors [8] addressed the product and process design using knowledge-based module in hot forging processes. The authors used the combination of concurrent engineering and knowledge-based system to motivate the development of Automated Concurrent Engineering Software (ACES) for part design and manufacturing. The system combines deterministic and empirical knowledge of a variety of product aspects to provide decision-making power to the designer. The ACES is capable for material and machine selection, process design, die design, and early cost estimation. The user first specifies the basic design requirements. The part geometry is generated in an associated CAD system. Then, the relationship between customer requirements and the part model is established with constraints and is imposed automatically on the system. The system will alert the user of any design constraint violation during design and modification phase. Thus, overall design process is iterative with integrated design, manufacturability analysis, and cost analysis procedures. In a brief summary, it is generally believed by many researchers today that the commercial CAD systems should be advanced to a "design" tool considering product life-cycle aspects rather than being a mere modeling tool.

In the CAD industry, a recent technology called behavior modeling is an encouraging move from the CAD developers along the direction of supporting product design. Behavior modeling is offered by Parametric Technology Corp. in their Pro/Engineer package, in short, Pro/E. This function can link the geometric computation and finite element analysis of Pro/E with the modeling. However, the behavior modeling has to rely on its internal database. It does not allow users to optimize the product from perspectives such as cost, functional performances, manufacturability, and other life-cycle aspects. As today many researchers are trying to optimize a product considering manufacturing process, production, and other life-cycle issues, a more flexible and open structure is needed to support design optimization. In addition, when the behavior-modeling tool calls a finite element analysis (FEA) process in optimization to evaluate an objective function, the computation time and cost can be prohibitive. To reduce the computational cost, a local optimization method is usually used and thus the global design optimum cannot be obtained. Similar features can be found in other CAD tools, such as IDEAS, UNIGRAPHICS, CATIA and so on. A latest trend of development seems to enhance the integration capability of these tools with other popular engineering tools, e.g., the latest CATIA Version 5.0 integrates Microsoft Excel. However, such integration is done on a one-to-one basis and relies on the collaboration between different vendors to share proprietary information. It is desirable to have an open-architecture CAD system that can integrate various tools without getting the difficulty of proprietary information sharing, and can effectively and efficiently optimize a product from various product life-cycle considerations.

In this work, an automatic design and optimization system for industrial silencers is developed. Given the developed system, users define customized objective and constraint functions for design optimization. An efficient global optimization algorithm, the Adaptive Response Surface Method (ARSM) [9], is adopted as the optimization algorithm. Based on the concept of Design of Experiments (DOE), ARSM inherits many advantages of DOE-based optimization methods, such as supporting parallel computation, providing engineers with more insight to the problem, and greatly easing the integration of various CAD/CAE software tools [10]. The developed system supports simultaneous design and modeling of a product. If appropriately set up, the entire design and optimization process can be fully automated. Given this system, a customer can put his /her order through the Internet; and a few minutes later the customer can receive the completed and customized design. Such a design not only satisfies customers' performance and geometric requirements, it also brings the minimum manufacturing costs to the manufacturer. In addition to the development of a practical design system for industrial silencers, this system was also developed to demonstrate the possibility of developing an open-architecture design tool by integrating a CAD tool and a DOE-based optimization method, to realize the simultaneous design-modeling-optimization cycle, and to show the potential of integrating design automation, optimization, and web-based design to minimize the design cycle time.

AN OVERVIEW OF THE DEVELOPED SYSTEM

System Structure and Information Flow

Based on the modeling and interactive programming tools offered by most CAD tools today, the developed system provides an open architecture to allow customized design evaluation functions such as costs and performances be included in the formulation of an optimization problem. Optimization algorithms drive the geometric model change. When a model is changed, the associated model data such as dimension, volume, inertial of moments can be obtained instantly from the database of the CAD model. Such data can be used for cost and other design evaluation functions, which are either objective or constraint functions in an optimization model. By iteratively varying the product design and obtaining corresponding design evaluation feedback, the process can converge to the optimum, which yields the minimum-cost product or the best performing product, depending on how the optimization problem is formulated. Figure 1 illustrates the system structure and the information flow.

As shown in Figure 1, customers interact with the developed system by inputting the requirements and receiving the final optimal design. The system entails the automatic modeling module using Pro/E, the performance and cost evaluation module, and the optimization module. As the automatic modeling depends on specific CAD tool, the other two modules can work with any engineering software tools. For example, for product performance evaluation, one might apply FEA or Computational Fluid Dynamics (CFD) tools from various vendors. It will be explained later that these tools can be easily applied and linked with the performance and cost evaluation module, in search for the optimum. Therefore, for a specific product design, various commercial tools and customized models such as cost analysis models can be integrated into the framework of the system, in support of an open-architecture optimal design tool. All of three modules will be described in more detail in following sections.

(Insert Figure 1 about here.)

Optimization Algorithms

Figure 1 shows that two optimization algorithms are integrated in the system to search for the optimal design, the well-known Broyden-Fletcher-Goldfarb-Shanno (BFGS) method [11] and Adaptive Response Surface Method. (ARSM) [9,10]. The selection of either of these two methods is according to the computation complexity of objective and constraint functions, as well as the optimization requirements. The BFGS, as an efficient local optimization method, is applied when a local optimum is satisfactory and the evaluation of objective and constraint functions is quick and inexpensive, especially when a simple and explicit formula for these functions is available. If a global optimum is desired and computation-intensive function evaluations are involved, such as FEA or CFD simulations, the efficient global optimization algorithm ARSM can be applied. The optimization results by using the BFGS and ARSM will be compared later in the System Test Section.

(Insert Figure 2 about here.)

The adaptive response surface method (ARSM) is a new approximation-based optimization method that is intended for computation intensive design optimization problems [9,10]. It is rooted in the Response Surface Method, a systematic Design of Experiment (DOE) approach [12]. In ARSM, a function evaluation is treated as a computer "experiment." The constructed model from computer experiments is called a response surface model, or surrogate. ARSM employs the second order polynomial function as the response surface model and the Latin Hypercube Design (LHD) method for planning experimental designs / points [13]. LHD forms a stratified random sample set to estimate the output. As shown in Figure 2, the algorithm of ARSM takes the design variables, objective function, constraints, initial design space (range of design variables), and experimental points to fit a response surface model using the least square method. Based on the response surface model, a global optimization is carried out to find the design optimum. Then the original design space is systematically reduced. In the new space, additional points are added and a new surrogate is generated. This process iterates until the algorithm converges or a satisfactory design is obtained. ARSM was successfully tested against many well-known test problems as a global optimization method for computation-intensive design problems. For the purpose of time and cost saving, this method needs much fewer computation-intensive processes to reach the global optimum or close-to-global-optimum solution. More importantly, as computer experiments can be performed independently to the optimizer, ARSM does not demand a full integration of various software tools for optimization. For example in the silencer case, a detailed cost analysis was performed in Microsoft Excel. Only data files are transferred between the developed interactive CAD program and the Excel tool, rather than a full integration of Excel into the CAD program. The use of ARSM or other optimization algorithms rooted in the Design of Experiments (DOE) is an essential strategy to support the open architecture of a CAD tool. Conventional optimization algorithms are mostly sequential and they usually demand high interaction between the optimizer and objective / constraint function evaluation modules. In that case, evaluation modules and the optimizer are usually fully integrated, as seen in today's CAD packages. An optimizer based on the principle of DOE, not limited to the ARSM, takes only the output data from those "experiments," for example, the maximum Von-Mises stress from a FEA. The optimizer does not care about which machine and which FEA tool was used to perform the "experiment," as long as the FEA result is credible. Therefore, it provides the possibility to cluster a few tools for analysis and optimization without laboriously integrating those tools.

Web-based Optimal Design

The integration of optimization and a CAD tool is further built on a web-based design platform to reduce the design response time. That is to say, a customer of a manufacturer only needs to send product requirements via the Internet and the optimal design process can be triggered upon receiving the customer's request. The final optimal design is then reported back to the customer through the Internet.

INDUSTRIAL SILENCER DESIGN

Industrial silencers are used primarily on diesel engines in the marine, generator, construction vehicle, and military vehicle industries [14]. Due to the wide range of applications, the silencers must routinely be customized to meet the needs of customers. At present, nearly forty percent of silencer orders require customization. Such a high degree of customization makes the product design a demanding task. Presently before production of a customized silencer, a minimum of one day is required to create the manufacturing drawings and enter the relevant material resource planning (MRP) information into the computer system. Usually the customer must approve the initial drawings. The time for this process ranges from a couple of days to a week depending on the level and complexity of customization.

An industrial silencer usually consists of endplate, spiral, top piece, inlet and outlet sections as shown in Figure 3. Given the wide range of application of silencers, there are many different configurations. These configurations vary in the number, position, and direction of inlets and outlets. A two letter symbol is used to describe the configurations, such as PR, TL, and SR (as will be shown in the first column in Table 1).

(Insert Figure 3 about here.)

The inner spiral section of the silencer is the key feature of the silencer design. This feature enables the device with passive and reactive sound damping ability. Steel wool is inserted in the spiral to act as damping material. The inlet tube is attached to exhaust manifold that channels the exhaust gas to go through the spiral section and exit through the outlet tube. Figure 4 depicts the inner spiral section of a silencer.

The equation set defining the cross-section of the spiral is given as follows:

$$\begin{aligned} r &= \left(\left(Outer\ Radius - Inner\ Radius\right)\cdot t\right) + Inner\ Radius \\ q &= t \cdot 360 \cdot \left(\left(Outer\ Radius - Inner\ Radius\right) \div Spiral\ Gap\right) \\ z &= 0 \end{aligned} \tag{1}$$

where ‘t’ increases from 0 to 1.

(Insert Figure 4 about here.)

When ordering a silencer, a customer will usually specify the configuration, material, paint color, minimum inlet/outlet diameters, exhaust flow rate, maximum overall size, and maximum backpressure of the silencer. The silencer configuration is determined by the layout of the customers' system whose noise is to be dampened. The material choice depends on the environment that the silencer is going to work under. The finished color of the silencer should be specified to match the engine system. Inlet and outlet diameters are determined by the system pipelines. The exhaust flow rate is the flow rate from the system to the silencer. The maximum overall size is given because the silencer has to fit into the space available on site. The maximum backpressure is usually specified by customers to ensure a low backpressure of the silencer. As silencers are mostly used with engines, excessive exhaust backpressure can cause high exhaust gas temperatures and a reduction in engine horsepower. Customers will also give the criterion on the dampening effect. The customer inputs and requirements are collected through the Internet as shown in Figure 5. Given all these inputs and constraints, our task is to generate instantly the optimal design that leads to minimum manufacturing cost and satisfies all the customers' requirements.

(Insert Figure 5 about here.)

OPTIMIZATION MODEL

For an optimization model, three elements have to be specified. These elements are variables, objectives, and constraints. This section will discuss in detail each of the elements for the silencer design.

As the size of inlet/outlet has to be designed according to customers' system settings, they are not attractive design variables. The spiral coil is crucially important to the performance and the manufacturing cost of the silencer. In the design optimization, three geometric parameters are chosen as the optimization variables; they are Spiral Outer Diameter (OD), Spiral Depth (SD), and Spiral Gap (SG), as shown in Figure 4. Changing these three variables, the overall size, total damping area, backpressure, and cost of the silencer will be different.

The design objective is the total manufacturing cost. The cost analysis is performed using the Operation Based Costing (OBC) Method [16, 17]. OBC provides a manufacturing operation based cost model, in which for every operation, 8 cost elements including 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. The software of the OBC cost analysis model is programmed in Excel as a combination of spreadsheet and macros. The program consists of several Excel worksheets. Other worksheets can be added depending on the collected product data and manufacturing information, but for every product design, four major worksheets are generated as follow:

1) Flow Diagram Spreadsheet – a manufacturing process diagram describing the material and part flow between operations.
2) Element Data Spreadsheet – a detailed analysis of the 8 cost elements of each operation described in the Flow Diagram Spreadsheet.

3) Cost Table Spreadsheet – a table used to gather input from the Element Data Spreadsheet and to perform iterative cost calculation.

4) Output Spreadsheet – all costs calculated from the Cost Table Spreadsheet are output or displayed for the user to interpret the cost distribution and to identify the potential production and design improvements.

The OBC method is rooted in and deemed to be an extension to the well-known Activity Based Costing (ABC) method [18]. Compared to ABC, it focuses on the production system. It features a meticulous quantification of production costs associated with a given product design [16]. Thus it is more amenable to study the influence of design decisions to the production costs. For the silencers [19], the OBC method is applied. Relationship between the design variables and individual costs elements is built through parametric formula or knowledge reasoning. When a design variable is changed in the permitted range, the resultant production cost variation will be output from the OBC spreadsheets.

Figure 6 shows the cost calculation by using the OBC method for the silencer. The area 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, which shows only a part of the Element Data Spreadsheet. 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. From area ②, the relationships of silencer components and material costs are formed through a series of parametric equations. Similarly, other types of cost elements are computed in the Element Data Spreadsheet by either parametric equations or knowledge reasoning through Excel macros.

(Insert Figure 6 about here.)

Three major constraints are considered in the optimal design. The first is the overall size constraint of the silencer. The other two constraints are performance constraints. As it is understood that the sound damping effect is directly related to the total spiral surface area, we can control the total surface area to ensure that the performance is satisfactory. In an ideal case, one should fully define the spiral by including all the geometric details and, the property and positions of the damping material inserted in the spiral. Then a detailed CFD model should be built to accurately predict the damping performance of a design. This method, however, is very complicated and resource demanding. In this work, the performance criterion is taken from manufacturers' catalog, as those products have been fully tested. By studying the catalog, we found that for silencers with satisfactory performance, a relationship exists between the inlet / outlet diameter and the total surface area, as illustrated in Figure 7. In our design, because the inlet / outlet diameter is not a design variable, we can use the diameter to find the minimum damping surface area and use this area as a threshold. The optimal design then should have larger surface area than the threshold to ensure satisfactory performance. The curve in Figure 7 was obtained through regression analysis.

(Insert Figure 7 about here).

The third constraint is that the maximum silencer backpressure should be lower than that specified by the customer to ensure an overall low backpressure for engines. The relationship between the backpressure caused by the silencer and the exhaust gas velocity can be found in Figure 8. This figure is obtained by averaging similar curves across various silencer configurations. For silencers operating under 900º F, a correction coefficient is applied [15]. From customers' backpressure specification, one can find the maximum exhaust gas velocity from Figure 8. The optimal design thus should ensure the exhaust gas velocity less than the maximum allowable velocity.

(Insert Figure 8 about here.)

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

$$
\begin{aligned}
&\min_{w.r.t.\ \bar{x}} \quad \cos t(\bar{x}) \qquad \bar{x} = OD,\ SP,\ SG \\
&\text{subject to} \\
&\qquad \text{Spiral surface area} \geq \text{Required area} \\
&\qquad \text{Exhaust velocity} \leq \text{Maximum velocity} \\
&\qquad \text{Overall size} \leq \text{Given space} \\
&\qquad x_{\mathrm{i}} \in [x_{l,i},\ x_{u,\,i}], \quad i = 1,\ 2,\ 3
\end{aligned}
\tag{2}
$$

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

AUTOMATIC DESIGN GENERATION

In this work, Pro/E is chosen as our CAD system due to its full parametric and associative feature and its availability. Other similar packages can be used as well. Parameters can be defined in Pro/E to describe the characteristics of each feature, assembly, or part. Examples of model parameters are dimensions, volume and material cost. The parameters can be divided into two groups: user parameters and Pro/E parameters. User parameters are defined by the user while Pro/E parameters, such as dimensions, are automatically created during the modeling process. The user has full control over the values stored in each parameter. For example, you can change a dimensional parameter to modify the dimension of a modeled part. For Pro/E, being parametric means any modification of a parameter automatically drives the solid model to change accordingly. The parametric nature of Pro/E allows for 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” [20]. The parameters of a model can be used in equations referred to as relations. By properly defining these relations and organizing parent / child relationship, a few parameters can drive the change of all the related features, and thus the product design. The associativity 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 and simultaneously to any modification of the part. Associativity within Pro/E allows the user to make modifications to an assembly or part and have those modifications be reflected in the manufacturing drawings and other associated applications.

Since Pro/E is chosen as the CAD system, its programming tool, Pro/Toolkit, is then selected to interact with Pro/E. Pro/Toolkit has a library of C functions that are available to the user to customize product design and automate the design process. Pro/Toolkit is a programmatic tool similar to the open architecture feature of I-DEAS and macros programming in most other commercial CAD packages. This tool allows the creation of external and internal programs that interact with the Pro/E environment and model database. One can create menu and perform associated functions through Pro/Toolkit programming. More importantly, one can "talk" with the internal database to retrieve, modify, and save data to initiate model revisions.

This work uses Pro/Toolkit to automate the silencer design. Based on a pre-modeled generic silencer prototype, a Pro/Toolkit program reads the model data and drives the design change. When a new group of design variables is sent to the program, which interacts with the prototype model, a new silencer design can be generated instantly with various configurations and dimensions.

The dimensions, materials, costs, and configuration of each silencer component must be modified and recorded. For each silencer component a structure class has been created within the program. 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;
```

Structures like the one above have been created for each silencer component. This allows for objective-oriented programming for a clear data management.

Based on a generic silencer model, the parent-child relationships between features are carefully defined. Numerical relations between geometric dimensions are also heavily used within the Pro/Toolkit 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, the selected design variables are modified by the user input. The majority of modified parameters are calculated from a complex set of interdependent relations based on the user's modifications. Relations in the code are in the form of C functions. As the design variables take new values, the relation functions calculate other associated parameter values. New values of all variables are then passed to the Pro/E model database and, as a result, a new design can be generated immediately.

SYSTEM INTEGRATION

Given the interactive programming tool and the full parametric and associative capability of CAD tools, the optimization process can be well integrated with the modeling process. In the silencer case, once the customers' requirements are input to the program developed with Pro/Toolkit, the performance evaluation modules and the cost analysis module will interact with the initial product model to retrieve necessary information such as the total mass, area, material, and so on. This information is available in the Pro/E database whenever a model is generated. The optimizer reads the performance and cost values and then generates a new set of design variables according to its algorithm. This process iterates until an optimum is obtained. In the end, the final product is then the optimal design, with the cost and all the performance readings available. As the entire design and modeling process is fully automated, the designer can obtain the optimal design in no time.

As shown in Figure 1, the developed silencer design system can be roughly divided into three modules: automatic modeling module, performance and cost analysis module, and the optimization module. In specific, the automatic modeling module is programmed using

Pro/toolkit. Pro/Toolkit functions are linked to the database of Pro/Engineer. Thus all the Pro/Engineer parameters, variables and strings can be read and modified by this external program. The optimization module consists of two major parts. One is the program “cowl.c” and the other is the ARSM optimization tool, which is also written in C. The “cowl.c” program interacts with the cost analysis module and the ARSM optimization tool. Because in the silencer design case we use simple mathematical models for performance evaluation, these models can be easily and conveniently coded in the “cowl.c” file. However if a complicated CFD model is built for the acoustic analysis, this performance evaluation model should be separated from the “cowl.c” file. The cost analysis module is created using Microsoft Excel. Within this model, some macro functions are created to run the tasks of the production cost calculation. In order for the “cowl.c” program to automatically evoke the macros within the Excel, an executable 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. The “cowl.c” program can then call the executable file to run the Excel macros. Through the “cowl.c” program, all the parameters and values can be linked to Excel and Pro/Engineer. When running the developed system, the design parameters are then entered 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 is used to create a user defined menu system under the Pro/Engineer interface as well as to control the silencer assembly modeling, which is loaded to Pro/Engineer. When the ARSM is called, it sends the design parameters to update the “outexcel.dat” file and “RunExcelMacro.exe” is executed to open the corresponding spreadsheets and run the macros within the spreadsheets. 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. 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 search in the ARSM. After the procedure, “RunExcelMacro.exe” will then close the Excel file and return to the Pro/Engineer interface. The optimum values such as those of dimensions obtained from the ARSM algorithm are finally sent back to update the product model. The data log file records all the values during the execution of the ARSM. User can check the final cost value in the Excel file and obtain the optimal product design in Pro/Engineer. Figure 9 shows the modules in the optimal silencer design system and related data flow between modules.

To not completely make design engineers “blind”, the developed Pro/Toolkit program also provides interactive capability for the silencer design. A customized menu system has been developed as shown in Figure 10. From the menus, one can make modifications or start the optimization process manually.

(Insert Figure 10 about here.)

For the silencer design, the Pro/Toolkit program is further integrated with the web ordering function to form an automatic, rapid-responding, optimal design generation system. A customer can log onto the manufacturer’s web page and fill in a simple form as shown in Figure 5. The customers’ requirement data was then collected by a CGI program and sent to a data file, which was read by the Pro/Toolkit program. After an optimal design is generated, the product performance data and estimated price, along with the 3-D model, are output back to the customer through the Internet. The entire process takes only 50 seconds in a local intranet. It is expected to take about a few minutes in the World Wide Web. If the customer is satisfied with the design, all the product drawings are readily available for production. The data flow process of the system is illustrated by Figure 11.

(Insert Figure 11 about here).

The customer will get the final output, through the Internet, as shown in Figure 12. The product model was shown by COSMOS player so that the customer can translate, zoom in / out, and rotate the product. All the performance requirements are also outputted, along with the quoted price. It is to be noted that the quoted prices is based on the minimized manufacturing cost from the design optimization.

(Insert Figure 12 about here.)

SYSTEM TESTING

In this work, a group of different customers' inputs are given to test the integrated system. The results demonstrated that an average of 47.66% cost reduction has been achieved for all designs with satisfactory performances by using the ARSM, while only 17.53% by using the BFGS method. The cost savings are largely due to the fact that product designs are often very conservative while many constraints are present. The time it takes to run each design case is about one minute for either ARSM or BFGS. It confirms that the ARSM can search for the global optimum and the BFGS might converge with only a local optimum.

(Insert Table 1 about here.)

CONCLUSIONS AND FUTURE WORK

This work documents the development of an automatic design and optimization system for industrial silencers. By using the developed system, the user can

1. Shorten the custom design time from at least one day to a few minutes; the design and modeling process is fully automated without any human intervention.
2. Reduce the production costs by more than 40% percent through design optimization
3. Generate a product design satisfying all the functional and size requirements
4. Produce all the engineering drawings automatically, and
5. Attract and collect customer orders through the Internet

Though the developed automatic design system is dedicated for silencers, the developed system is believed to be able to benefit other manufacturers. It addresses the need for an open-architecture CAD tools to support the optimal design considering customized product life-cycle issues. By developing the silencer design system, it proves following concepts:

1. Designs of Experiments (DOE) based optimization strategies are promising candidates to be integrated with current CAD tools to support open-architecture design optimization. Existing optimization capabilities built in CAD tools are internal, non-transparent, mostly local methods, and strongly interrelated with application modules such as FEA. In this work, a DOE-based optimization method, ARSM, was chosen to integrate a detailed customized cost analysis process with other performance evaluation models. Such a method can conveniently integrate various tools and efficiently search for the global optimum.

2. By utilizing parametric modeling, interactive programming, and an open-architecture optimization strategy, a product can be automatically and simultaneously designed, modeled, and optimized.
3. Web-based design can be enhanced with the automation and optimization capability. Current web-based design platforms are more focused on the communication and other computer science related issues. This work demonstrates the possibility of integrating automation, optimization, and Internet to push the limit of reducing the design cycle time.

During the implementation, tremendous difficulties have occurred due to the poor documentation and limited resources of the Pro/Toolkit tool. It is also found that the coding process is time consuming and the developed code is product and CAD software dependent. A generally applicable tool to assist coding would be very helpful. It is also to be noted that the developed system is based on the assumption that a common product platform is available for silencers. How to automate the conceptual design generation remains a challenging research issue.

ACKNOWLEDGEMENT

Supports from the Phillips and Temro Industries and Natural Science and Engineering Research Council (NSERC) of Canada are gratefully appreciated.

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Table 1 Testing Results of the Integrated System (Based on the assumption of annual 5,000 units of production).

Model	Inlet/Outlet Diameter	Flow Direction	Material	Paint	Max. Dimension	Performance	BFGS % Change	ARSM % Change
PR	5	Standard	Aluminum	Black	20,20,20	3000,30,500	8.53	40.08
PR	8	Standard	Aluminum	Black	30,30,30	3000,30,500	29.57	55.98
PR	10	Standard	Aluminum	Black	40,40,40	3000,30,500	41.79	67.37
TL	5	Standard	Aluminum	Black	20,20,20	3000,30,500	8.62	40.20
TL	5	Reverse	Stainless	Black	20,20,20	3000,30,500	8.72	40.59
SR	5	Reverse	Stainless	Black	20,20,20	3000,30,500	10.42	42.45
SR	5	Reverse	Stainless	Silver	20,20,20	3000,40,800	10.38	42.62
SR	6	Reverse	Stainless	Powder	25,25,25	4000,40,800	22.22	52.02
Average Value For BFGS & ARSM							17.53	47.66

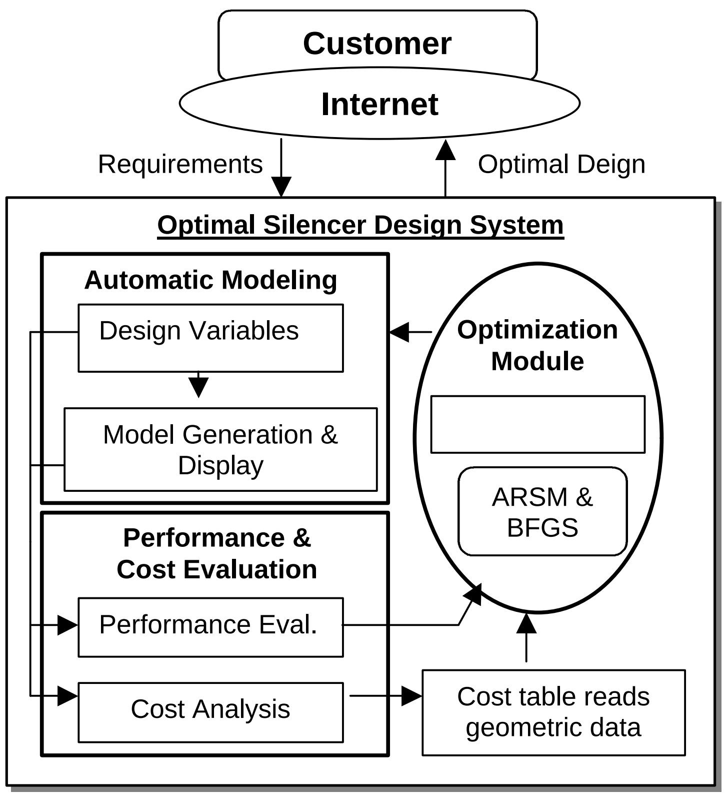

Figure 1 Structure and information flow for the optimal silencer design system.

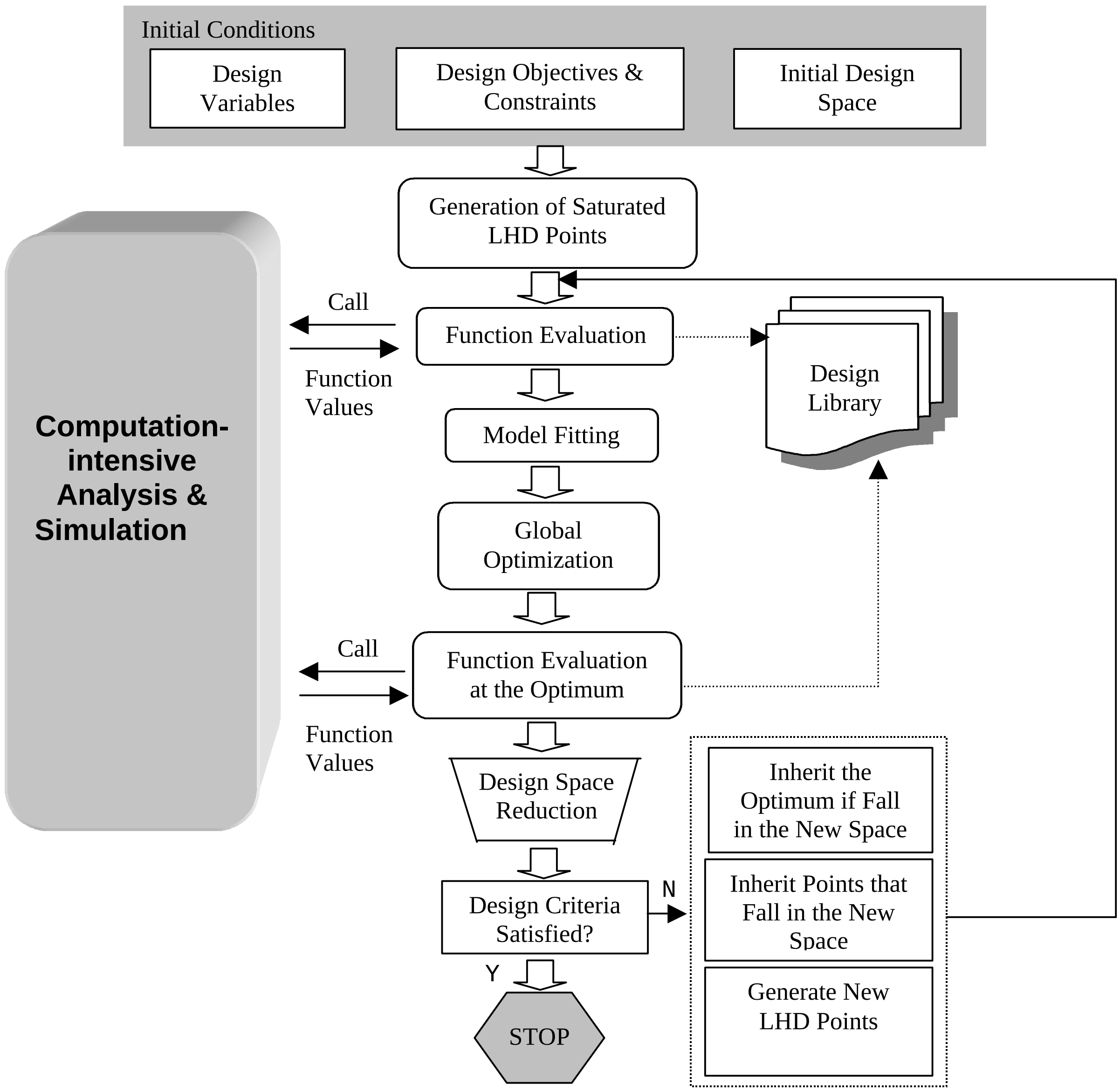

Figure 2 The flowchart of the ARSM.

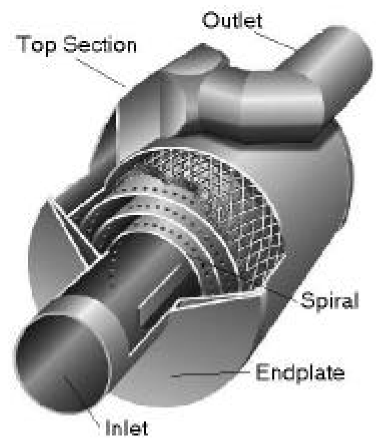

Figure 3 Basic configuration of an industrial silencer [15].

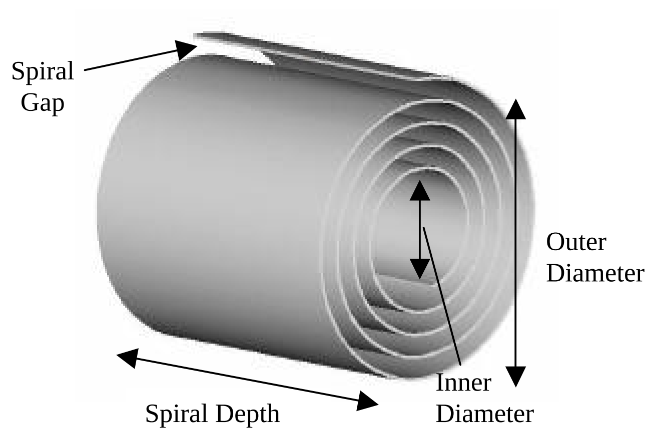

Figure 4 Geometric parameters of the spiral.

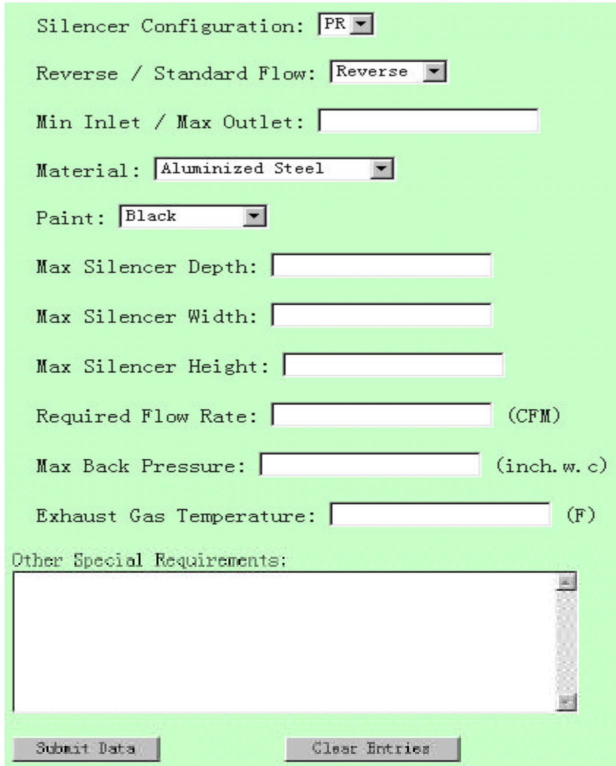

Figure 5 The web page takes customers' order.

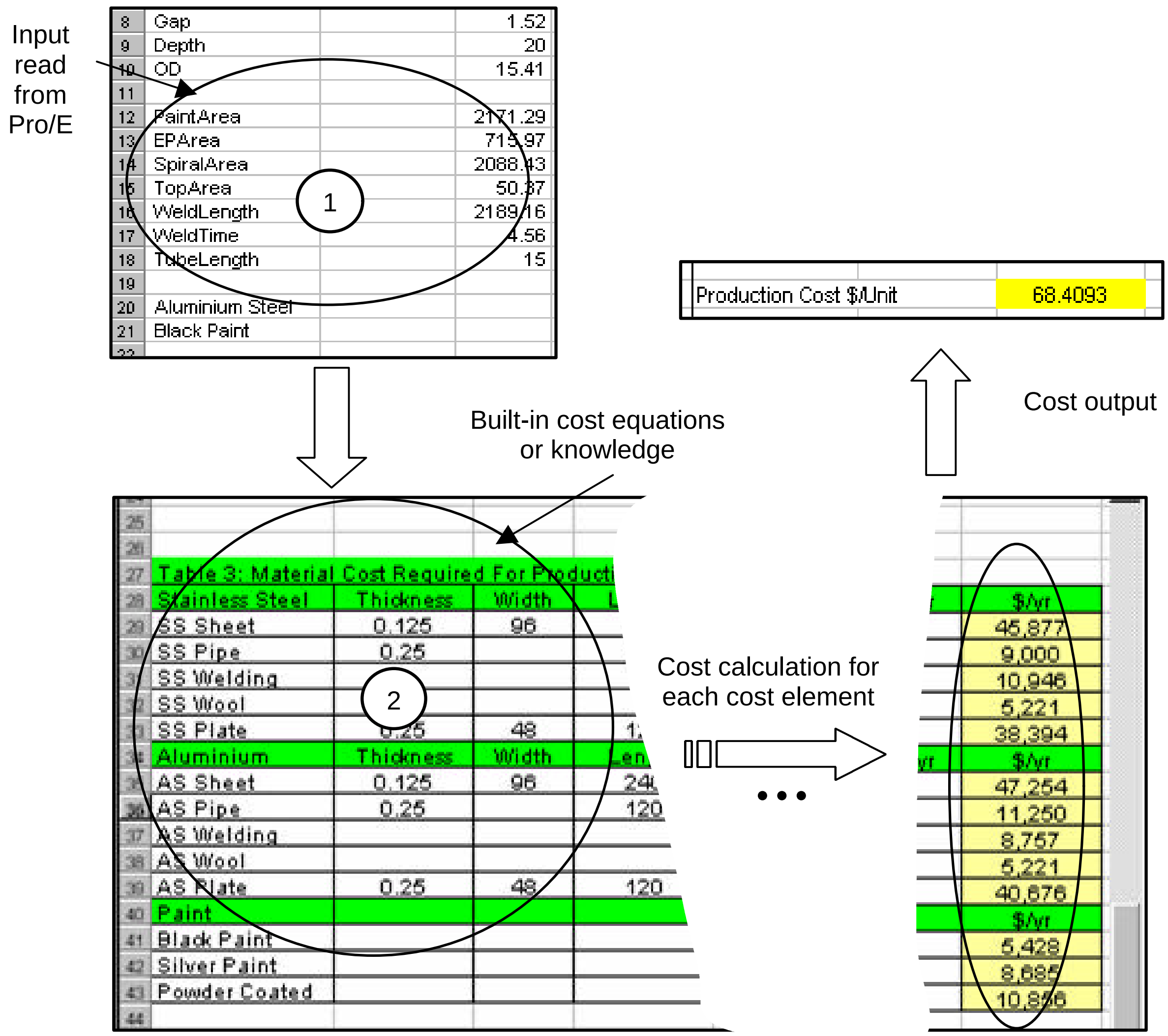

Figure 6 Cost calculation using the OBC method.

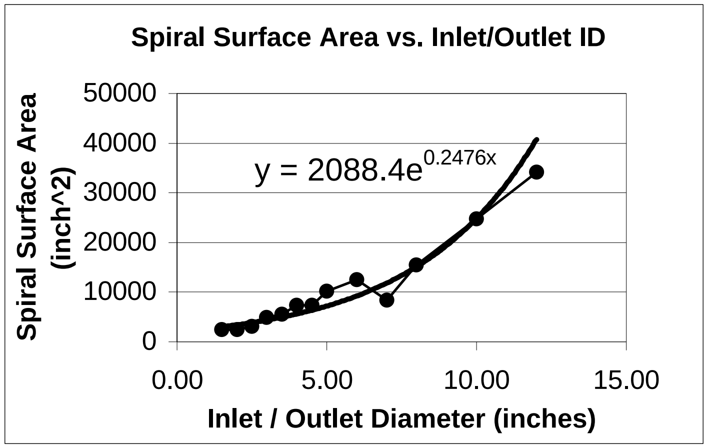

Figure 7 Relation between inlet / outlet diameter and the damping surface area from existing designs.

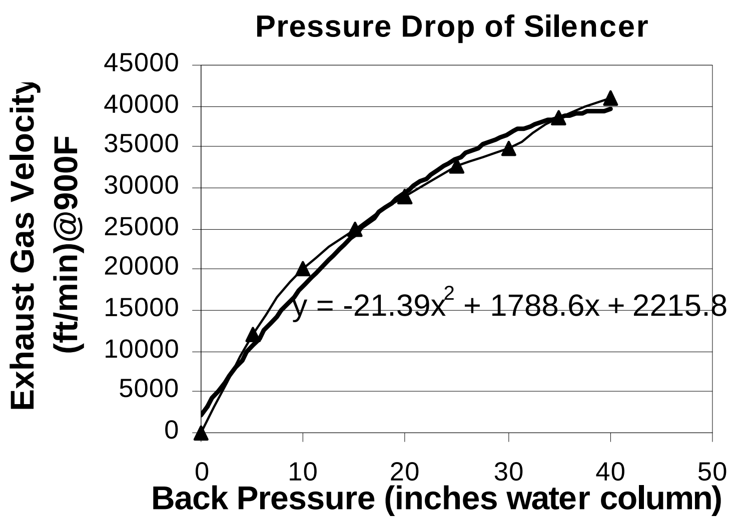

Figure 8 Modeled Relation between Back Pressure and Gas Velocity.

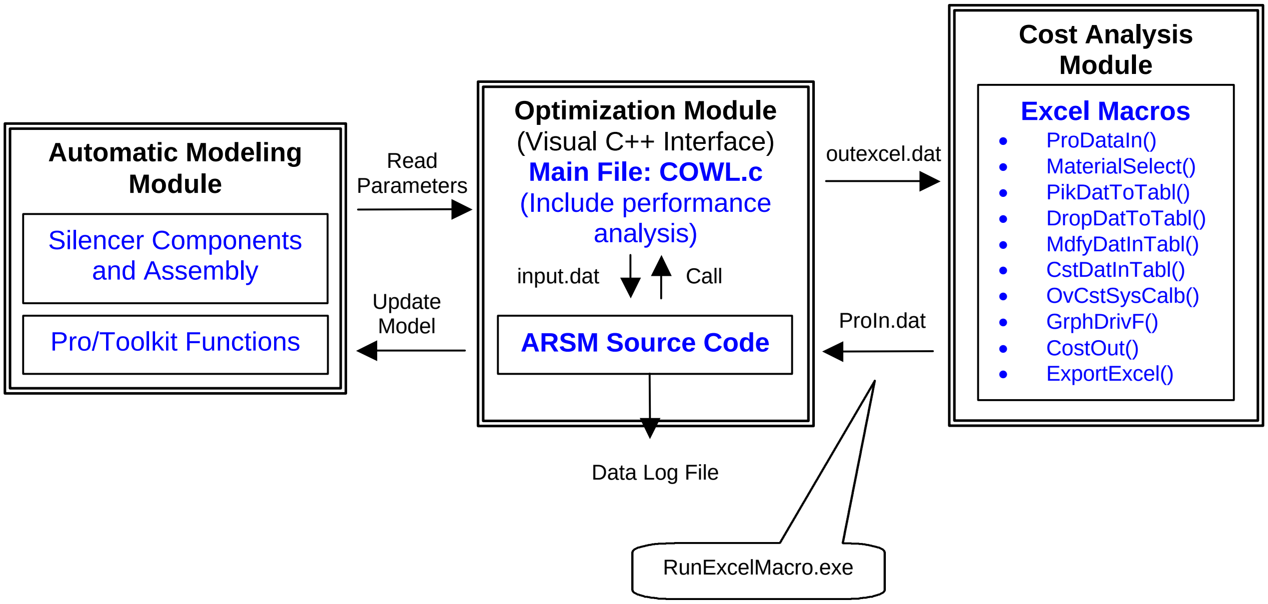

Figure 9 Interactions between system modules.

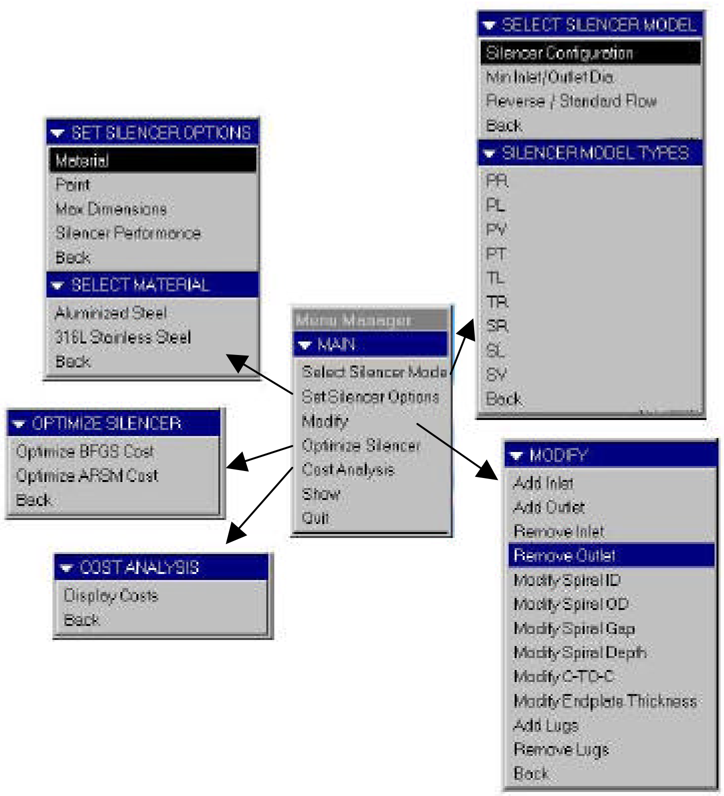

Figure 10 Menu structure of the program developed with Pro/Toolkit.

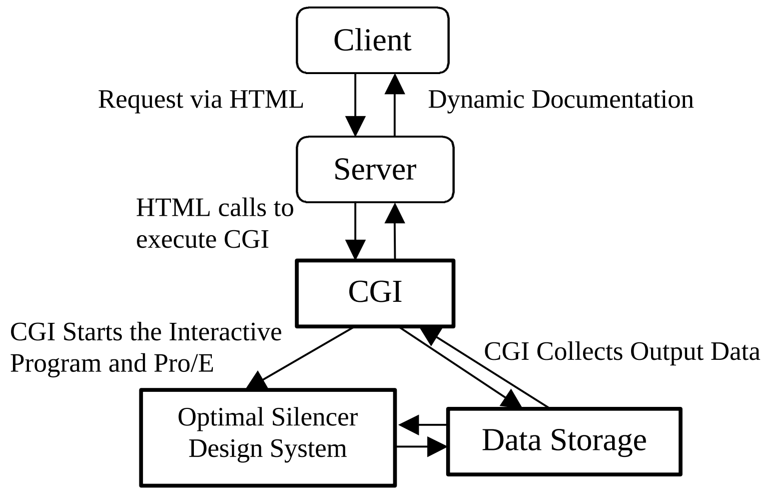

Figure 11 Information flow between the web application and the silencer design system.

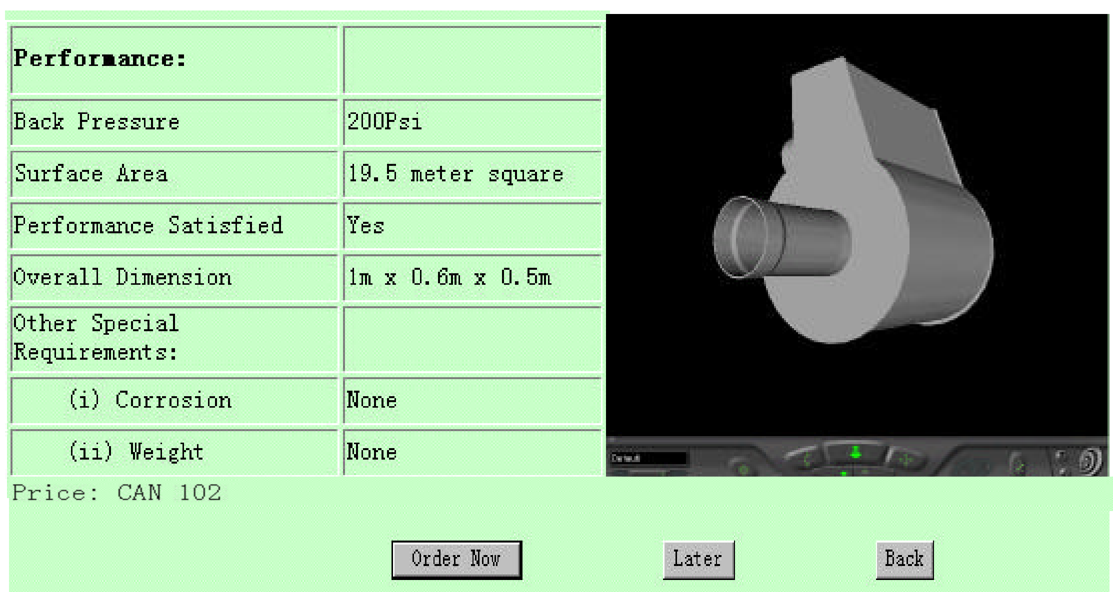

Figure 12 Design output seen by customers on the Internet.