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Abstract. During recent years the increasing power of computers and communications has led to the use of more advanced analysis approaches within the mechanical engineering design process, or design process for short. Predictive Design Analysis (PDA), see [1], is an approach in which the final behavior of a product is predicted by combining information from different analysis techniques. This paper presents an application of PDA consisting of Design of Experiment (DOE) and Finite Element Analysis (FEA). The application is built as a World Wide Web (WWW) Client/Server application. The Client side User-interface interacts with the time-consuming FEA analysis performed on the server. This application serves as a powerful tool to the Designer or Analysts at all levels of abstraction in the design process, when examining the influence of different design variables on the product design.

1 INTRODUCTION

In the early age of industrial manufacturing, product quality was often poor. Most products needed to be adjusted individually in order to work properly. Since then the manufacturing techniques and skills have become more and more sophisticated, which has resulted in more reliable products. To increase the reliability even more, new methods have been introduced in the product development process in recent years. Statistical methods, i.e. DOE, have been used to evaluate experiments and numerical analyses. DOE are techniques to plan analyses, i.e. FEA, in order to decrease the number of analyses performed while maintaining a reasonable accuracy level. FEA is commonly used as a tool to verify whether or not a product design can withstand the loading and environment it is subjected to. The development of computers and communications has introduced new interesting possibilities in product development. Design teams can be geographically separated but still work close together on certain projects. Projects focusing on the possibilities and problems of new approaches of the design process are increasing [2-3].

2 OBJECTIVE

The objective set out for the work presented in this paper has been to provide the combination of design analysis methods and statistical methods with a user-friendly graphical interface. The implementation is developed as a Client/Server application,

where all time-consuming analysis and statistical evaluations are performed on the server. The client side is built up as a regular WWW browser application. The results calculated in the implementation could work as one of the decision rules to be used in the design process. Throughout the work, DOE is used to represent the statistical methods and FEA is used to represent design analysis.

3 HISTORY OF COMPUTING AND COMMUNICATION

The history of computing can be traced back over three thousand years, to Babylon and the clay tablets. But the real beginnings of computers as we know them today, however, lay with the "Difference Engine" in 1820 by the English mathematics professor, Charles Babbage. During the 1900 century the development was mainly pointed towards mechanical devices for office automation. By the Second World War the real development of computers began, with e.g. ENIAC, (Electronic Numerical Integrator Analyzor and Computer). It was used for preparation of firing tables for the Allied forces artillery. After the development of the integrated circuits in the seventies, the size of computers started to decrease and has done so ever since. Ultra-large scale integration (ULSI) increased the number of components on one chip into the millions. The numbers of personal computers in use more than doubled from 2 million in 1981 to 5.5 million in 1982. Ten years later, 65 million PCs were being used. Using either direct wiring, called a Local Area Network (LAN), or telephone lines, these networks could reach enormous proportions. The network is the key technology, linking PCs, workstations, and servers of various specialized kinds for printing and file storage. A buzzword of the early nineties has been Client/Server computing. Another approach to the network of workstations that is increasingly powerful but often under-utilized for much of the time is that of Cluster Computing, in which all the processing power on the network is viewed as a shared resource that can be applied to any computationally intensive task.

Along with the development of computers, the communication among computers has been enhanced. Under the leadership of the United States Department of Defense's Advanced Research Project Agency (DARPA), the architecture of a small network (ARPANET) was established to promote the sharing of super-computers amongst researchers in the United States. The first network of computers was established between Stanford Research Institute, UCLA, UC Santa Barbara, and the University of Utah. The second important development was the WWW containing the HyperText Markup Language (HTML), which was released in 1991 by CERN. In 1993 Mosaic was the first truly graphical, easy to use interface for the WWW that allowed the display of colors, pictures, graphics, even sound and videos. Sun Microsystems has in the mid-nineties released an Internet programming language called Java, which radically alters the way applications and information can be retrieved, displayed, and used over the Internet. Netscape developed Javascript, an extension to Java that enhanced the client side interactively even more. Other techniques released by the Microsoft Corporation in the late nineties are the Jscript and the Visual Basic VBscript, which interact, with WWW pages through the interface of ActiveX components. An extension to the original HTML is the

Dynamic HTML (DHTML), which builds upon existing HTML standards to expand the possibilities of WWW page design, presentation, and interaction.

4 WWW BASICS

Often confused with the Internet, the WWW is actually the sub-set of computers around the world that are connected with hypertext and WWW applications. A Web page's address on the Internet is called "URL", which stands for Uniform Resource Locator. HTML, which enables linking from page to page, set the WWW apart from other networked computer files. The pages are accessed by a WWW browser that interprets the files and displays them graphically. A "plug-in" is an application set up within the browser, usually shareware that adds functionality to the Web browser. Another type of function that can either be embedded in the browser or on a server are imagemaps. Imagemaps allow users to click on a particular spot in an image to retrieve another HTML document or to run a specified script.

The coding that supports links to a variety of information is known as "hypertext". A WWW page designed using frames is divided into separate areas, which act independently of each other. An individual frame can be stationary or it can be a container for loading other pages. DHTML is somewhat of an umbrella term encompassing several ways in which Web developers can breathe life into pages that have traditionally been static portraits of information. Basically two different techniques, Common Gateway Interfaces (CGI) or some client side scripting language can achieve the interactivity of a WWW page. CGI can be used for a variety of purposes, the most common being the handling of FORM requests for HTTP (Hyper Text Transfer Protocol). Forms allow for user defined information to be passed along from a Web browser to a CGI program for processing. The program then returns the appropriate documents either by generating a document on the fly or by loading an existing document through the WWW via HTTP. CGI can be written in a vast variety of programming languages that produce an executable file, e.g. C, C++, Java or Perl. The client side interactivity is achieved with DHTML. This means that page modifications should appear immediately following a trigger, such as a user selection. By and large, DHTML describes the abstract concept of breaking up a page into manipulable elements, and exposing those elements to a scripting language, e.g. Java Script or VBscript, which can perform the manipulations. JavaScript is a compact, object-based scripting language that is embedded directly in an HTML page. Vbscripts, on the other hand, are scripts that are placed on the server. To produce the interactivity, VBscripts use the connection to ActiveX controls. ActiveX components are then embedded in the HTML page. These statements can all recognize and respond to user events such as mouse clicks, form input, and page navigation.

5 THE PREDICTIVE DESIGN ANALYSIS APPROACH

The vast number of design procedure models have an overall similarity in that they all focus on the fulfillment of a need for the product that initiated the development activity, see e.g. [4]. The starting point of the majority of these models is the conceptual design phase. Traditionally, the synthesis in the conceptual design phase

is based on qualitatively oriented criteria. By using the PDA approach the designer will be able to evaluate some of these criteria using a quantitative approach, thus improving the probability of the subsequent decision making procedure. The result of PDA can then be evaluated further along with the remainder of the qualitative criteria by some known evaluation technique [5]. The process of developing the final design involves several iterations of synthesis, analysis, evaluation and decision making, where the totals cost of, and time consumed in, the project increase as the number of iteration increases. The PDA approach is very powerful in the way that it extracts the few vital variables from the many trivial ones and thus is able to extend the use of design analysis also to the early stages of the design phases.

The sensitivity to environmental factors, interactions between design variables and environmental variables and uncertainty in design dimension can all be evaluated with PDA. The most significant advantage of applying this approach is the shift from verification to predictive analysis in the design process.

6 STATISTICALLY DESIGNED EXPERIMENTS

A general approach to design of experiment (DOE) is to perform factorial experiments, which means a systematic arrangement of the experiment. This approach considers not only the basic parameter problem as do the one factor at a time experiments; it also takes interactions among the studied parameters into consideration. When the number of parameters increases, the time and money spent on performing the large numbers of experiments would be unreasonably high. The fractional factorial arrays assume that the result consists somehow of redundancy and is performed by carefully choosing a piece (fraction) of the total experiment. Statistical layouts are used to organize the parameters in such fractional factorial analysis to ensure a reasonable accuracy level. Using just a fraction of a full design will introduce aliases effects to the response. A response that confounds main effects with two-factor interactions, but does not confound any main effects, is said to have resolution III. Design resolution IV confounds two-factor interactions with other two-factor interactions and main effects with three-factor interactions. The most suitable use of fractional factorial designs is for locating important variables. Early in the experimentation series interactions are more likely to be unimportant where one is often far away from the optimum values. At later stages of the experiments when the important factors are known, highly fractionated designs should not be used. In the statistical experiment society, two main approaches to performing statistical experiments have evolved.

Taguchi introduced the first approach that can handle design variables with two, three or more levels, and even mixed levels can be used. Taguchi has constructed different types of orthogonal arrays that limit the experiments performed, which are fractional factorial arrays based on independent variables. All of these orthogonal arrays assume that the design variables are independent, which can be difficult to verify in advance. The main effects are calculated through standard statistical formulae and plots of main effects can be produced. The second main approach is what is referred to as the methods of western statisticians. These approaches also use fractional factorial arrays. The chosen arrays are slightly different from those

presented by Taguchi in that they are not so complex and they are not based on independent variables. This means that interaction effects can be studied directly along with the main effects. A systematic way to calculate the response average, main effects and interaction effects is the Yates algorithm, which takes the response as input and calculates the effects. These effects can then be viewed and interpreted mainly through some types of graphs called normal plots and cube plots. There exist many examples on the use of DOE to organize a number of FEA, see e.g. [6].

7   CLIENT-SERVER IMPLEMENTATION

The implemented application is a further development of the PDA approach. The work is built up as a Client/Server application that makes use of the advantages of the internet/intranet. The time-consuming FEA are performed on the server while the pre and post processing are performed on the client machine. The first decision the designer or analyst has to make is to choose the appropriate statistical design layout. These layouts are standard DOE layouts that can be found in statistics literature see e.g. [7]. Figure 1 shows the result of choosing a 2_{IV}^{4-1} layout, which is of resolution III and handles 4 variables in 8 analyses. To the right in Figure 1 the alternations of the design variables in the 8 analyses are shown along with the estimation of the statistical effects.

Figure 1. Input data setup for the FE analyses

The second step in the pre-processing phase is to fill out the FEA setup form shown in Figure 1. Firstly the location of the FEA input file on the client machine has to be specified. The appropriate name and values to the design variables also need to be assigned in this step. The name should correspond to those used in the FEA input file and the values are the levels to be evaluated statistically by the application. The third step is to choose the appropriate responses that are to be calculated in the analyses. The needed commands for producing the responses are appended to the

input file, when the submit button is pressed, to make the file complete. The last thing to define before sending the analysis request to the server is to fill out the correct username and project name. Each analysis project performed under a username has to have its own unique project name. Clicking on the submit button sends the data to the server and the CGI program starts the FEA with the input and output settings from the form data. After all the FEA are done the CGI program starts the statistical evaluation and presentation of the chosen responses.

The program sends a message back to the user when the analyses and evaluations are done, and the post-processing HTML page can be loaded. This page is built up from basically two frames. In the left, shown in the middle picture in Figure 2, a Java applet is loaded that contains all the user projects. The right frame is used to view selections made in the applet. The applet has a tree structure similar to the structure of file manager that engineering designers meet in their everyday work.

Every project contains a listing of the analysis data, see left top picture in Figure 2, defined in the pre-processing phase. A new project with different input data can easily be established. There are possibilities to choose another level for the current design variables or to test new design variables. If new design variables are chosen, the input file has to be rewritten and uploaded to the server. There is also a possibility to test the current design variable configuration on a different design product; hence a new input file has to be uploaded to the server. Submitting the new form data to the CGI application user will extend the Java applet tree with a new project. Further, the applet contains a subfolder named *result* containing another subfolder for each of the chosen response functions. The result folder includes a subfolder, named *runs*, with the FEA results and graphical presentations of the statistical evaluations. The FEA results are visualized through Virtual Reality Modeling Language (VRML) files for each analysis performed, which can be seen in the left bottom picture in Figure 2. The VRML is a file format for describing interactive 3D objects and worlds that can be dynamically modified through a variety of mechanisms. The user has such possibilities as to rotate, zoom, translate and seek certain model locations of the model with the built-in mechanism in the browser's plugin for handling VRML files.

The statistical calculation is also available for further evaluation. These HTML pages are built up from two vertical frames, in which the right one is divided into two horizontal frames. The different statistical result charts are shown in the left of these frames. The upper right frame displays the name conversions between the defined design variables and the letters shown in the result charts, along with buttons for further statistical evaluation. Depending on the method chosen for statistical analysis layout, different types of graphical representations will be available. If the Taguchi analysis layout is chosen, the result charts will be as shown in the right-hand pictures in Figure 2. The main effects shown in the top chart are the responses of each design variable that is created on the fly by the application. The mean value and the standard deviation of the response are also shown along with the result of each FEA. By clicking the Interaction plot button a form is created based on the current design variables. Choosing the relevant design variables, in the form creates the interaction plots between different design variables as shown in the bottom right picture of Figure 2.
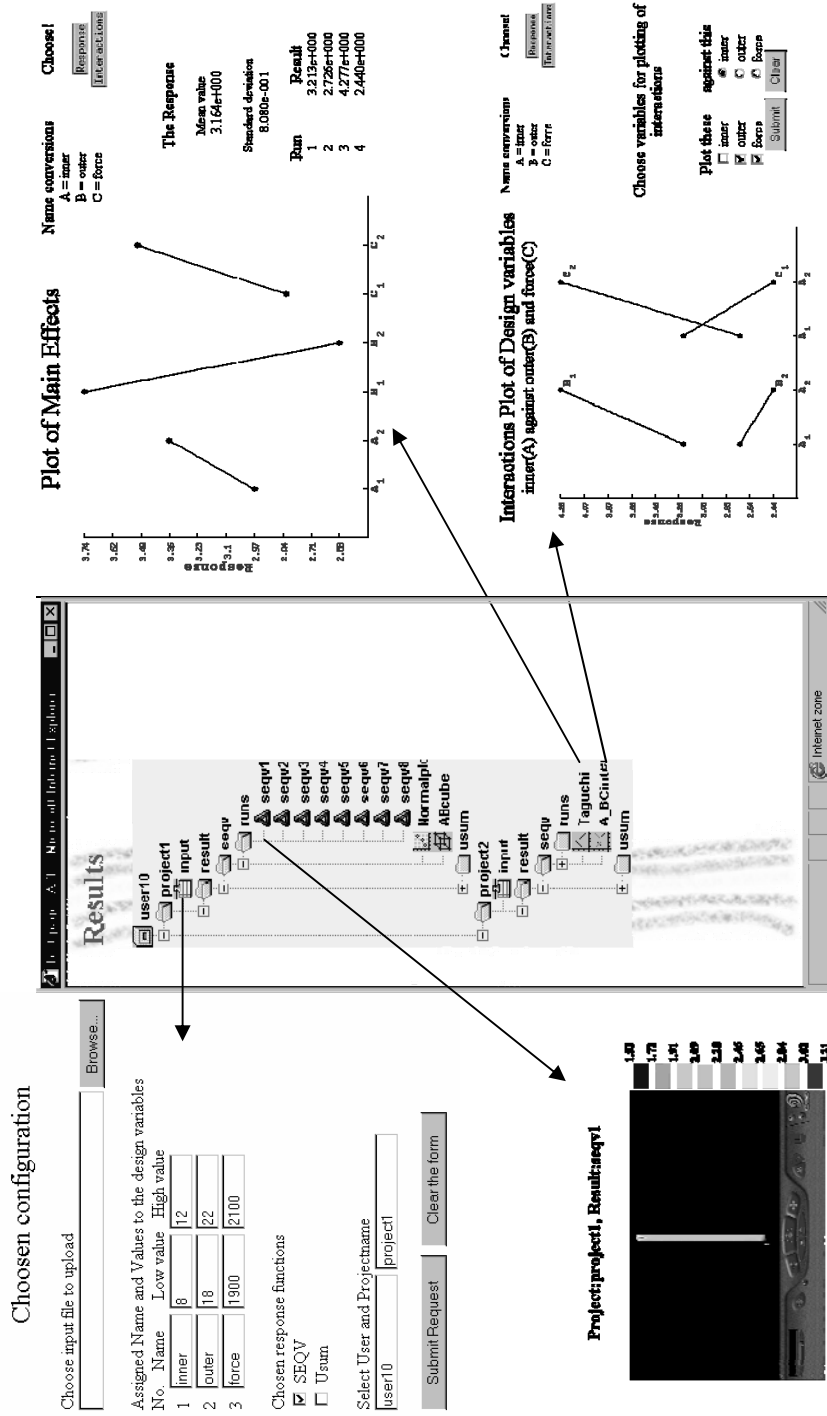
Figure 2. Post-processing interface: The left pictures display chosen FEA data and the corresponding VRML picture of the response. The middle picture shows the Java applet organising the result. The right charts display the resulting statistical evaluation.

8 AN EXAMPLE

The example chosen to exemplify the application is a component in a transportation device. The beam is a critical component in the device since the operator of the device is located close to the component. The beam has to behave in a controlled manner in case any structural load is applied. To ensure the behavior, different types of load cases are tested on the beam. The loadcase shown in this example is a direct side impact (crash) in the axial direction of the beam. The criterion is that the final design of the component must be able to withstand a load of 30 kN. The design layout of the component and visualisation of the design variables is illustrated in Figure 3.
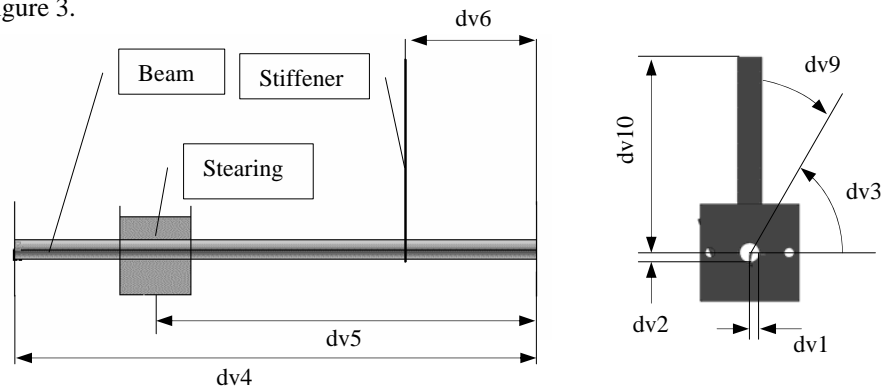

Figure 3.   Visualisation of the chosen design variables.

To sort out the important design variables, a design layout for ten variables in sixteen runs is chosen. The chosen layout, 2^{10-6}_{III}, is of resolution III and handles 10 variables in 16 analyses. One of the generators is J=AB, which means that the effects from J and interaction effect from AB cannot be separated in the statistical evaluation. Further, the analysis layout and the estimation of effects along with the aliases can be seen in Figure 1b. The variables selected and their assigned values are shown in the table below.

Table 1 Design variable definitions for the performed analyses.

Design variable	Description	Low Value	High value	16 Runs	8 Runs
1	Radius 1 of beam section (m)	20e-3	22e-3	A	A
2	Radius 2 of beam section (m)	20e-3	22e-3	B	B
3	Angle of beam section (°)	0	45	C	
4	Length of beam (m)	1.1	1.15	D	
5	Location of stearing (m)	0.6	0.62	E	
6	Location of stiffener (m)	0.275	0.28	F	C
7	Thickness of beam section (m)	2e-3	2.5e-3	G	D
8	Thickness of the stiffener (m)	2e-3	2.5e-3	H	
9	Angle of stiffener (°)	0	15	I	
10	Length of stiffener (m)	0.3	0.35	J	

All available options for Crash analyses (Crash response), see Figure 1, are selected. The graphical result presentation includes such things as stress and total displacement plots at the time of maximum contact force; see Figure 4.
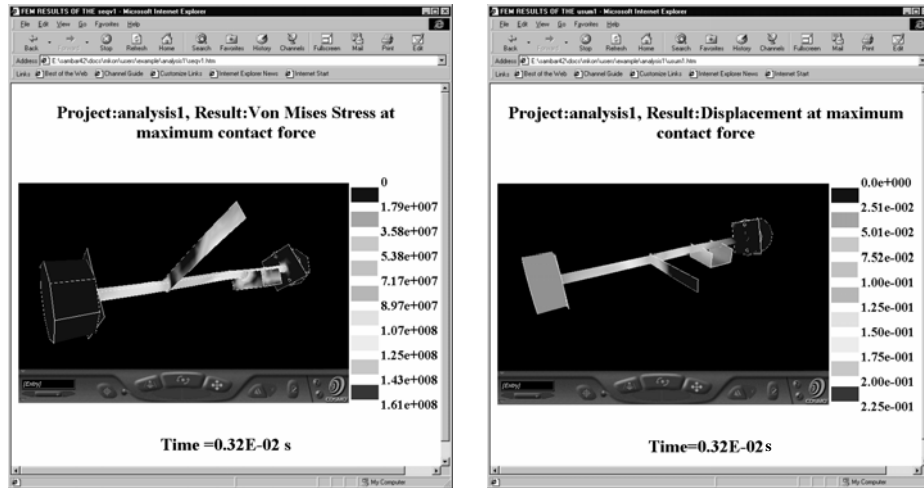
Figure 4.   VRML plots at the maximum contact force

For each analysis a history plot of the contact force is produced; see Figure 5. As can be seen from the two graphs, the behavior of the component is quite dependent on the design variable settings. Furthermore the maximum force also differs for the two graphs shown. These behaviors, along with the component mass, are evaluated statistically.
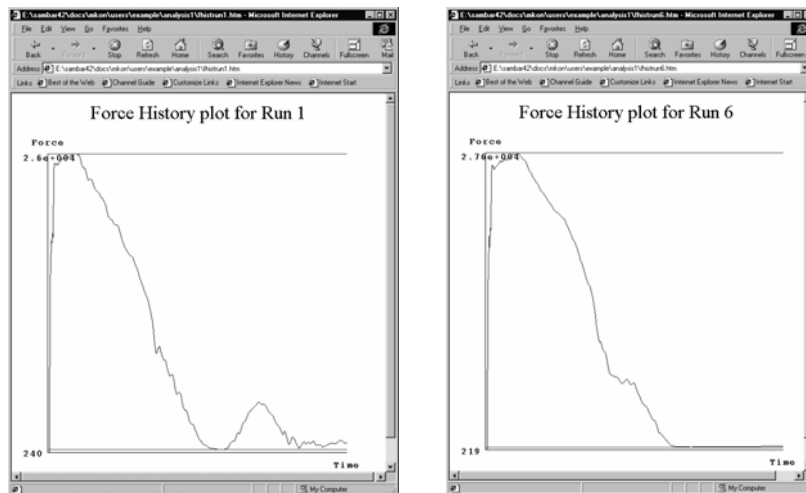

Figure 5.   Force history diagrams for analyses 1 and 6.

The normal plot in Figure 6 indicates that the important factors are the effects G+BI+FJ, A+FI+BJ, B+GI+AJ. In Figure 6 the mean value and standard deviation are shown along with the individual responses from each analysis. The mean value is above the criterion of 30 kN, but not all the analyses are above this value.

The Response

	Mean value	Standard deviation
	3.104e+004	3.824e+003

Normal probability plot of
Max contact force

Run	Result
1	2.604e+004
2	3.489e+004
3	2.761e+004
4	3.651e+004
5	3.249e+004
6	2.765e+004
7	3.434e+004
8	2.889e+004
9	3.298e+004
10	2.743e+004
11	3.421e+004
12	2.922e+004
13	2.626e+004
14	3.419e+004
15	2.722e+004
16	3.663e+004

Figure 6. Normal plot of the maximum contact and responses from each analysis.

A normal plot similar to the one shown above for the components' total mass indicates that the effects A+FI+BJ, B+GI+AJ, G+BI+FJ and H+CI+DJ have influences. To be able to get even more information, eight new analyses are performed with the variables A, B, F and G. The layout 2_{IV}^{4-1}, which is of resolution IV, is chosen to manage the 4 design variables in 8 analyses. The new set of variables is given new letters (A, B, C, and D) according to the *column 8* runs in Table 1. The layout is of resolution IV, which means that all main effects can be estimated without any aliases. The remaining variables are held at their lower values.

By studying the results of the maximum contact force in the second set of analyses, see figure 7, it can be seen that the important effects found in the first set of analyses still have substantial influence. The new analysis once again results in a mean value of 31 kN with a standard deviation of 3.8 kN. To highlight the actual response of each of the variables, a cube plot is constructed, see figure 7. As can be seen from the cube plot, the criterion value of 30 kN is only fulfilled when the beam thickness (D) is at its high level independent of the combinations of the radiuses.

Normal probability plot of Max contact force

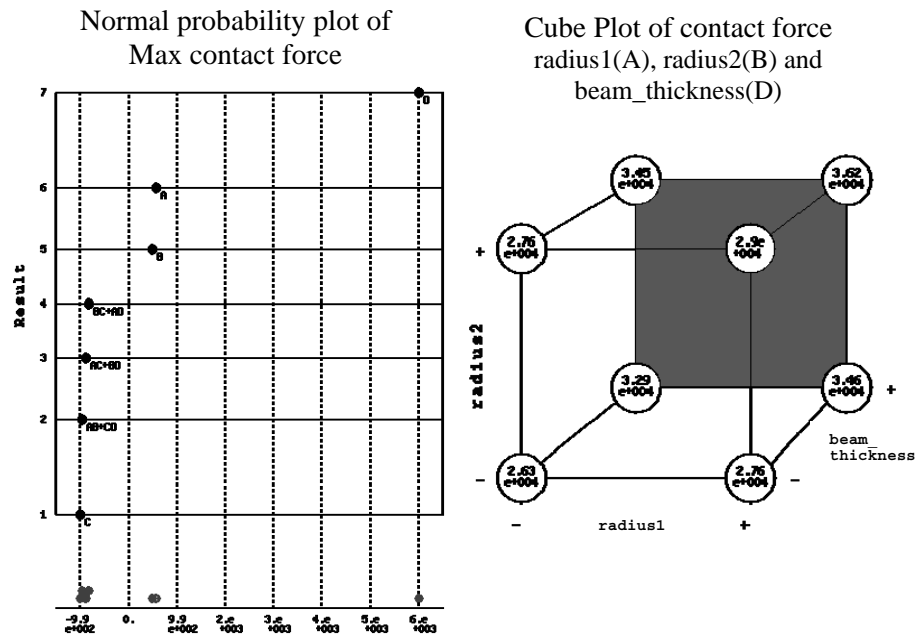## Cube Plot of contact force radius1(A), radius2(B) and beam_thickness(D)

Figure 7. Normal plot of the maximum contact force and a cube plot of the design variables A, B and D.

This also indicates that the shape of the beam has negligible influence and a simple circular section can be used. The total mass of the component is of course also dependent on the above studied variables. The cube plot in Figure 8 also shows that the small circular beam has the lowest weight, which is desirable in the transportation device.

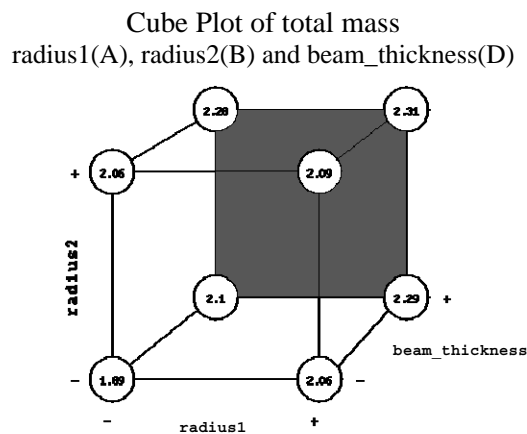## Cube Plot of total mass radius1(A), radius2(B) and beam_thickness(D)

Figure 8. Cube plot of the component mass from the last set of analyses.

The example studied illustrates how PDA decreases the number of design variables, from ten to four, that an engineering designer has to take into consideration when designing the component. In the remaining variables, only one variable setting would be important to fulfill the demand on the component. The other variables can be useful in trying to fulfill certain wishes, e.g. low mass, on the component.

9 CONCLUSION

The combination of DOE and PDA gives the designer a powerful analysis tool for evaluating the product, along with other engineering tools, at all phases of the design process. Based on the results the designer is able to sort out the important variables for further evaluation along with other criteria on the product. The optimum design variable configuration can be established by weighting the different evaluated responses in a decision table. The deployment of Internet or intranet makes it possible to use the application presented here by design teams that are geographically separated. Designers from different teams can view and further evaluate the result for their specific area of interest. Another great advantage of using a Client/Server application on the WWW is that the hardware configurations of the clients and servers are independent.

To make the application more interactive and more dynamic the language of XML (Extensible Markup Language) will be interesting to investigate. XML provides a formal syntax for describing the relationships between the entities, elements and attributes that make up an XML document, which can be used to recognize the component parts of each document.

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