

# CONCURRENT ENGINEERING: Research and Applications

## Internet-based Framework to Support Integration of Customer in the Design of Customizable Products

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**Abstract:** A necessary element to design and produce customer-centric products is the integration of customers in the design process. Challenges faced during customer integration into the design process include generating models of the customized product, performing analysis of these to determine feasibility, and optimizing to increase the performance. These tasks have to be performed relatively quickly, if not in real time, to provide feedback to the customer. The focus of this article is to present a framework that utilizes CAD, finite element analysis (FEA), and optimization to integrate the customer into the design process via the Internet for delivering user customized products. The design analysis, evaluation, and optimization need to be automated and enhanced to enable operation over the Internet. A product family CAD/FEA template has been developed to perform analysis, along with a general formulation to optimize the customized product. The CAD/FEA template generalizes the geometry building and analysis of each configuration developed using a product platform approach. The proposed setup is demonstrated through the use of a bicycle frame family. In this study, the focus is on the application of optimization and FEA to facilitate the design of customer-centric products.

**Key Words:** mass customization, customer-centric product development.

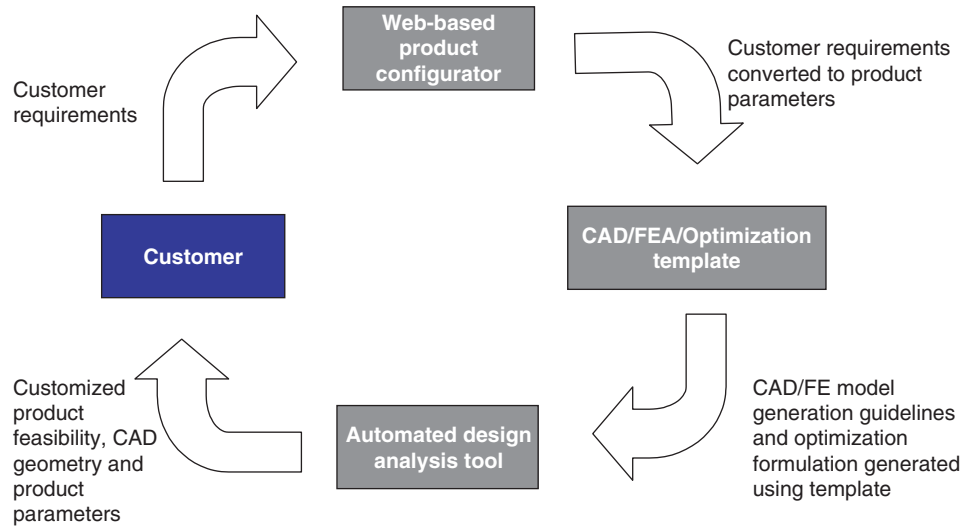
### 1. Introduction

Due to the competitive nature and saturation of homogeneous markets, companies are trying to satisfy an increasingly heterogeneous market to provide value addition and thus move into a niche market segment by providing customized products. This trend led to the concept of mass customization (MC). Pine [1] defined MC as ‘*a new way of viewing business competition, one that makes the identification of the wants and needs of the customer paramount without sacrificing efficiency, effectiveness and low costs*’. In order to offer mass customizable products, integration of the customer into the design process is essential to ensure that products can be tailored to his/her preferences and needs. Duray and Milligan [2] showed that the point of initial customer involvement affects the degree of customization. The value chain is described as a series of four processes – design, fabrication, assembly, and distribution. Thoben [3] classified the customized products based on the different intersection of customer orders with the entire production process, also called the Customer Order Decoupling Point (CODP) [4]. These

four categories are: (1) make-to-stock (MTS), (2) assemble-to-order (ATO), (3) make-to-order (MTO), and (4) engineered-to-order (ETO). MC requires support from the requirements provided by the customer in order to design and produce customized products, which requires high flexibility for modification of configuration, scaling, and attributes. In order to transform the customer requirements into the final product, a new set of tools needs to be developed, which can integrate the customer into the design process. These tools must be capable of collecting the customer requirements, transform them into product parameters and options, and then check the engineering and economic feasibility of the customer-specified products. Moreover, the customized product needs to be optimized for performance and cost.

Figure 1 shows the necessary elements in the customization procedure. The customer requirements are captured using product configurators [5] that allow the user to select from a set of predetermined options. Also the customer may be able to specify dimensions (like length, height, etc.) and/or performance parameters (weight, power, etc.) of the intending product. The configurators capture the customer requirements and convert it into product module selections and parameter values which are interpreted using the mass customization CAD/finite element analysis (FEA)/Optimization (MC-CAD/FEA/Opt) template. A Web-based product

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Figures 1, 3–5 and 7 appear in color online: <http://cer.sagepub.com>



**Figure 1.** The elements of MC framework.

configurator is presented, which is capable of being operated over the Internet. The Internet can be used to communicate and integrate the user in a real time and dynamic environment. Web-based systems have been used to generate product architecture information, obtain a product platform [6] and virtual design for MC [7].

In the case of mass-produced products, the products are designed and optimized to the exact product parameters, as specifications of the resulting products are known beforehand. In the case of mass customization, there are many possible configurations. The concept of ETO products for MC, which involve allowing the customer to specify his/her requirements, can be a very challenging task. Questions that need to be answered before producing the customized products include: Is the configuration specified by the user feasible? Is the customer-specified configuration optimum? Consider a product where key dimensions can have large structural implications; allowing a person with no knowledge in engineering to choose the specifications can create unstable structures. The user-specified configuration has to be analyzed and checked for feasibility. The product configurators can reduce the number of infeasible configurations by limiting the range of customer inputs for different parameters. But each user-specified design needs to be optimized subject to design and manufacturing constraints. Having a design analyst to analyze every consumer-specified configuration is not an efficient solution to the problem. The Internet provides the opportunity to communicate and integrate the user in a real-time basis, but commercially used design evaluation and optimization tools are resource intensive in operating. In addition, the user may not be skilled in operating engineering software. In order to address these issues, the design analysis, evaluation, and optimization need to be

automated and enhanced to enable operation over the Internet to achieve customization of products on real time. The CAD/FEA/Optimization template generates the necessary information required to perform the analysis of each user configuration. The (MC-CAD/FEA/Opt) template generalizes the analysis information for all possible configurations. The template uses the customer selection parameters from the product configurators, and generates the finite element (FE) and optimization models and final CAD geometry using FE and optimization tools. The engineering analysis and optimization tools are automated by using the Automatically Programmable Interface (API) capability. Saxon and Beaulieu [8] developed a Web-based engineering system as an in-house design tool at ArvinMeritor Light Vehicle Systems, Simulation and Analysis (LVS, S&A) department to perform automated analysis of stabilizer bars. Siddique and students [9,10] presented an agent-based framework to automatically generate 3D models of customer-specified designs and perform FEA [11] to determine the feasibility of a customized product. The limitation of the system is that, it only determines the feasibility of the product and does not address issues related to performance.

A well-built product family architecture forms the core for mass customizable products. Customization can be achieved through either modularity [12–16] or scaling [17]. Modularity involves breaking down the design into modules, with the common modules to all family members making up the product platform. Product variety is provided by adding optional modules requested by the customer to the platform. Scaling involves allowing customers to modify certain dimensions or parameters to customize the product to suit their needs. A combination of both modularity and scaling can be utilized to specify a product family with a considerable amount of variety.

The framework presented in this article supports both modular product family architecture and scaling. The MC involves using a platform to support customization of products.

The benefits of using a platform to better satisfy the customers have been highlighted by researchers and acknowledged by industries. Most of the Web-based approaches allow the users to select only from catalogues or options to generate configurations. In this study the focus is on MC, specifically integration of the customer in the design process to provide ETO products. This article presents a framework that utilizes a Web-based user interface to capture customer requirements and generate products customized to exact user specifications and optimize for maximum performance. First, user selections and specifications regarding the customization of the product are collected using a Web-based interface. These parameters and selections are then used to automatically build the CAD model of the customized product. The geometry is then meshed; material properties and boundary conditions are applied to the model. The analysis is then performed, results evaluated, and the analysis file passed to the optimizer. The customer-specified parameters are treated as constraints in the optimization formulation. If the optimization procedure does not yield a feasible design, the user is asked to select the dimensions that can be altered (Figure 2). Optimization is then performed using the selected dimensions as design variables allowing it to vary within a small range of its initial value. In the case of a feasible design, CAD model of the configuration, geometric dimensions, and specifications of the customized design are shown to the customer as feedback. The guidelines for automating the geometry generation, analysis, and optimization are captured in the (MC-CAD/FEA/Opt) template presented in Section 2.1. Since the products in MC utilize a common platform concept, general rules can be specified for the analysis of all family members. The capability of the system to generate customized

products from customer requirements is demonstrated through the utilization of a case study on the customization of bike frames (Section 3). The frames are custom-designed to suit the physique of the rider. The customer-specified design is automatically checked for structural feasibility and optimized in real time. The results from the feasibility study and optimization are passed back to the user as feedback. Section 2 presents a general framework to support Internet-based MC.

## 2. General Framework to Support Internet-based Mass Customization

The general framework to support the Internet-based design of ETO products, involving the use of CAD, FEA, and optimization, is shown in Figure 3. The main components of the system are: (1) Web-based user interface to gather user preferences, (2) CAD software and API, (3) CAD database, (4) common database, (5) FEA software and API, (6) FE database, and (7) design optimization module. The user interface is a Web page for the customer to specify parameters and selections related to the customized product. These user-specified parameters are categorized as structural, geometric, or a combination of both. For example, material preferences are categorized as structural, while dimensional parameters are a combination of both. The geometric parameters are transmitted to the CAD system with the use of a CAD/FEA template. The API for the CAD systems receives these parameters, invokes the CAD software, and builds the solid model of the customized product. The component files are then automatically exported as IGES files into a common folder accessible to the FE software to perform FEA, and optimization on the models to select modules/components for the final product and also determine the parameters of components. To generate CAD models from user selections and to

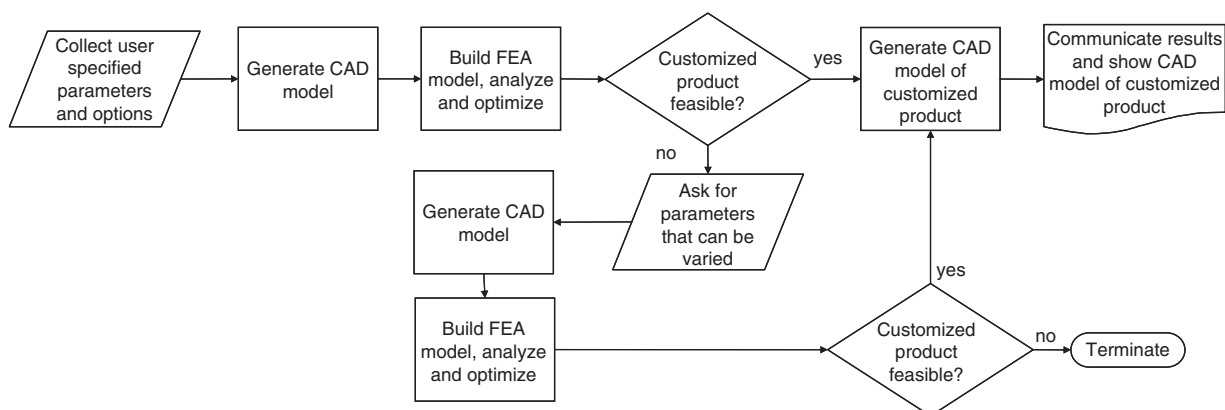


Figure 2. Flow of activities in the MC framework.

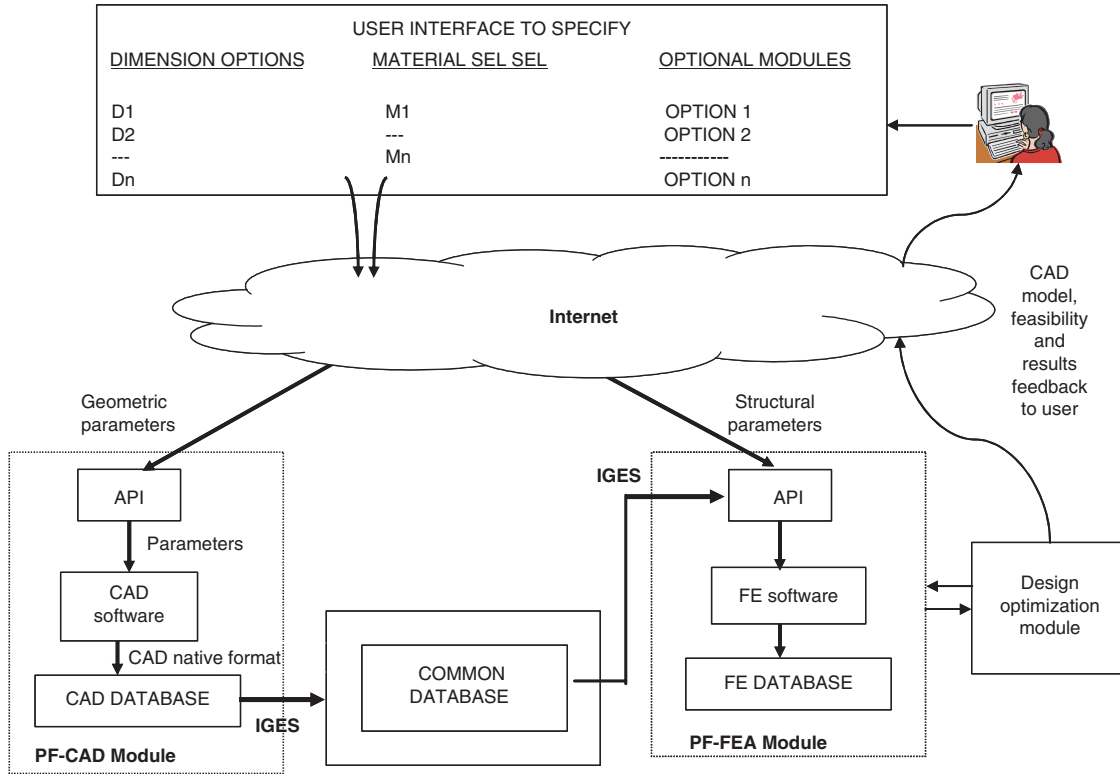


Figure 3. System architecture for Internet-based framework for customer-centric design and optimization.

perform FEA and optimization on these models, a set of well-defined guidelines and instructions are needed, which tell the software in a structured manner how to perform these tasks in different cases. The template-based representations that provide the foundation for the system are presented next. The general customized-product optimization formulation is presented in Section 2.2.

### 2.1 Combined Mass Customization CAD, FEA, and Optimization Template

The MC-CAD/FEA/Opt template is a set of well-defined and structured guidelines and instructions that generalizes the geometric construction and analysis information for all product varieties (Table 1). The template uses a top-down approach to define the product varieties using the platform as the core. The different varieties  $P_i$  can be generated by the addition of the product platform (PF) with optional modules (PO). For the purpose of generating the CAD and FEA model, information that needs to be included into the template are: assembly, geometry, material, mesh, and loading. Certain assembly and loading information is contained in the product family level, whereas some are contained in the module ( $ppm_i$  and  $pom_s$ ) and component ( $C_{pp}$  and  $C_{po}$ ) level respectively. The elements of  $P_i$  include – PP, PO, *AssemCon*, and *LoadCond*. It means a product variety

should embrace the PP, utilize product options (PO) to provide the varieties, and assembly constraints (*AssemCon*) to specify spatial relationships among them. The loading conditions (*LoadCond*) and boundary conditions (*BoundaryCond*) are also specified to complete the structural model for FE analysis. In the template, it is assumed that the PP is not a null or empty set. To provide varieties, the PO set cannot be empty either. The PO is a set of modules arranged in options that provide the same functions. As for PP and PO, they could be a single component or a module. Inside the product platform or product options, there are components and component-related characteristics, which include geometric, hierarchical, and parametric information. At the component level they also hold the information for the building of the FE model. This information includes material properties, element type, element sizes, boundary conditions, loads, and loading types associated with each component.

### 2.2 Optimization Formulation

A two-step process is utilized to optimize the customized product. The first step is to determine the optimized mass-customized product, with the user-specified configuration and parameters held as constants. If the user specifications do not lead to a feasible product, then additional input is gathered from the user and the second step is performed with the

**Table 1. Structure of CAD/FEA/Opt template to support mass customization.**

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**PF = {PP, PO, AssemCon, LoadCond}**

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PP = {ppm<sub>1</sub>, ppm<sub>2</sub>, ..., ppm<sub>j</sub>}

PO = {(po<sub>1</sub><sup>1</sup>, po<sub>2</sub><sup>1</sup>, ..., po<sub>a</sub><sup>1</sup>), (po<sub>1</sub><sup>2</sup>, po<sub>2</sub><sup>2</sup>, ..., po<sub>b</sub><sup>2</sup>), ..., (po<sub>1</sub><sup>x</sup>, po<sub>2</sub><sup>x</sup>, ..., po<sub>z</sub><sup>x</sup>)}

$$P_i \left\{ \begin{array}{l} (PP, po, AssemCon, LoadCond) | po = (pom_1, pom_2, \dots, pom_x) \\ pom_1 \in po_1^1, po_2^1, \dots, po_a^1 \\ pom_2 \in po_1^2, po_2^2, \dots, po_b^2 \\ \dots \dots \dots \\ pom_x \in po_1^x, po_2^x, \dots, po_z^x \end{array} \right\}$$

$$ppm_j = \left\{ \begin{array}{l} (C_{ppj}, AssemCon_{ppj}, \\ LoadCond, \\ BoundaryCond \end{array} \right) \left| \begin{array}{l} C_{ppj} = (ppc_1, ppc_2, \dots, ppc_k \in C_{pp}) \\ AssemCon_{po_x} = \left( \begin{array}{l} ppc_p, ppc_q \in C_{ppj} \\ x = 1, 2, \dots \quad y = 1, 2, \dots \end{array} \right) \end{array} \right. \left. \begin{array}{l} ppc_p, ppc_q \in C_{ppj} \\ ppc_p, ppc_q \in C_{ppj} \end{array} \right\}$$

ppc = (Geometry, material, element type, element size, LoadCond, BoundaryCond)

$$c \left\{ \begin{array}{l} (C_{po_x}, AssemCon_{po_x}, \\ Material, \\ Element size, \\ LoadCond, \\ Element type, \\ BoundaryCond \end{array} \right) \left| \begin{array}{l} C_{po_x} (poc_1, poc_2, \dots, poc_k \in C_{po}) \\ AssemCon_{po_x} = \left( \begin{array}{l} poc_r, poc_s \in C_{po_x} \\ r = 1, 2, \dots \quad s = 1, 2, \dots \end{array} \right) \end{array} \right. \left. \begin{array}{l} poc_r, poc_s \in C_{po_x} \\ poc_r, poc_s \in C_{po_x} \end{array} \right\}$$

poc = (Geometry, material, element type, element size, LoadCond, BoundaryCond)

BoundaryCond = set of boundary conditions for the component. Each boundary condition contains location, DOF, and magnitude.

LoadCond = set of loading conditions associated with the component. Each loading condition contains location, type, and magnitude

$$AssemCon = \left\{ \begin{array}{l} m_w AssemCon_1^{m_w}, \dots, m_x AssemCon_z^{m_x} \\ m_v, m_w, m_x, m_y \in PP \cup PO \end{array} \right\}$$

<sup>x</sup>AssemCon<sub>i</sub><sup>y</sup> = {Assem<sub>M</sub>, Assem<sub>R</sub>}

PP ≠ O, and PO ≠ O

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where, PF is product family; P<sub>i</sub>, customized product variety; PP, product platform; ppm<sub>j</sub>, product platform modules; PO, product options; pom<sub>s</sub>, product option modules; C<sub>pp</sub>, product platform component set; C<sub>po</sub>, product option component set; and <sup>x</sup>AssemCon<sup>y</sup>, assembly constraint between element x and element y.

customization parameters more relaxed. The general optimization formulation for Step 1 is:

$$\begin{aligned} \text{Minimize:} & \sum_{i=1}^m \Phi_i(X) \\ \text{Subject to:} & g_j(X) \leq k \\ & x_r = f(P) \\ & a_u \leq x_u \leq b_u \end{aligned}$$

where  $\sum_{i=1}^m \Phi_i(X)$  is the aggregate objective function; X<sub>r</sub>, set of design variables related to the user specifications x<sub>r</sub> ∈ X<sub>r</sub>; X<sub>u</sub>, set of design variables not related to the user specifications x<sub>u</sub> ∈ X<sub>u</sub>; X<sub>r</sub> ∪ X<sub>u</sub> = X; g<sub>j</sub> (constraints related to product performance like stress, deflection, etc.),

j varies from 1 to m; P, the user specifications for customization; and f, user specifications with X<sub>r</sub>.

In the first step, the customization problem is treated as a multi-criteria optimization problem. There are two types of design variables: (1) X<sub>r</sub>, dependent on the user inputs and (2) X<sub>u</sub>, not dependent on the user inputs. The dependence of X<sub>r</sub> on the user inputs is treated as a constraint in the problem formulation. The solution of the problem tries to find the values of X<sub>u</sub> that will optimize the customized product.

If the first step does not yield a feasible solution, the user is prompted to select the customization parameters that are flexible. The design variables set now comprises (1) X<sub>r</sub>, the user input but has a specific value, (2) X<sub>r</sub><sup>var</sup>, the user inputs, but are allowed to vary within the range



(in this case  $\pm 10\%$  of initial value), and (3)  $X_u$ , which is not related to user input. The general formulation is:

$$\begin{aligned} \text{Minimize: } & \sum_{i=1}^m \Phi_i(X) \\ \text{Subject to: } & g_j(X) \leq k \\ & x'_r = f(P) \\ & a_u \leq x_u \leq b_u \\ & 0.9 \times f(P) \leq x_r^{\text{var}} \leq 1.1 \times f(P) \end{aligned}$$

where  $X_r = X'_r \cup X_r^{\text{var}}$  and the rest of the variables are the same as presented in the Step 1 formulation.

The solution to the Step 2 formulation results in values of  $X_r^{\text{var}}$  and  $X_u$  for the given objective functions.

### 3. Case Study – Customizable Bike Frames

There is a simple, inarguable truth about cycling: your performance, endurance, and comfort on a bicycle are direct functions of how well that bicycle fits your proportions (<http://www.cannondale.com/bikes/custbike/c2.html>). Due to the success of the customizable frames in increasing the efficiency of the cyclist, companies like Cannondale started offering customizable frames in the market for the general customers. The process of customization starts with specifying the key dimensions by the customer to fit his/her physique. The process of customizing starts with the customer specifying the dimensions of the frame. A virtual model of the frame is generated by using CAD software; the tubes are cut and welded to precisely match the custom geometry, treated, painted, finished, and shipped. To guarantee the structural rigidity of customized designs, the designers, for example, in Cannondale use the CAD and FEA tools. The FEA of possible models will be performed beforehand anticipating all the possible configurations. Then the possible range of dimensions to be chosen by the customer will be worked out. Therefore while specifying the dimensions the customers can choose only from a predefined set of choices. This raises certain key questions: How customizable are the designs? How to provide more freedom to the customer in the customization process while maintaining the structural rigidity of the product? Can optimization techniques be performed on the user-specified configurations to improve the design, thus improving the efficiency of the customized product? Bicycle frames can be customized in many different ways, which is not the focus of this study. Rather, a specific-frame customization process is specified to demonstrate the Internet-based MC framework for better integration of the customer in the design of customized product.

The implemented setup for the framework utilizes CAD, FEA, and optimization for the customization of bike frames (Figure 3). Three types of frames available for customization are: men's, feminine, and tandem. The user interface, which is Web-based, is built using ASP technology that takes the following user inputs:

- The weight of the rider
- Desired arm reach (seat to handle)
- Total length of the frame
- Total height of the frame
- Floor to seat height
- Wheel radius
- Clearance

These user-specified parameters are then passed to the CAD and FE software from the Web page, which is used for FEA and optimization of the user configuration in real time. If the user specifications lead to an infeasible configuration then the user is prompted to select the dimensions that are flexible and can be varied to generate a feasible configuration during the second iteration. The second iteration is carried out with the user-specified flexible dimensions as the design variables so that a feasible configuration can be derived. The feasible customized product with the dimensions and geometry is shown to the user as feedback. Section 3.1 explains the MC information setup in detail.

#### 3.1 Implementation of the General Setup using ANSYS and ASP

The information server setup consists of two servers running on Microsoft Windows 2000 operating system. Server I houses the installation of the Internet Information Systems (IIS), with the user interface Web page and associated files located at the root folder of the IIS (Figure 4). Server II holds the installation of ANSYS. The user's selections and parameters are collected by ASP and then transmitted to the CAD/FEA template and the general optimization formulation. Server II then invokes Pro/E and ANSYS to perform analysis on the customized frame. The ANSYS output results, in the form of a text file, are then interpreted by ASP and communicated back to the user through the Web page.

#### 3.2 Web-based User Interface

The Web-based user interface of the MC system is shown in Figure 5. Customization of frames, from a user's point of view, is a four-step process. The first step involves selecting the type of model for customization from: men's, feminine, or tandem. In the second step, the user is prompted to enter the information

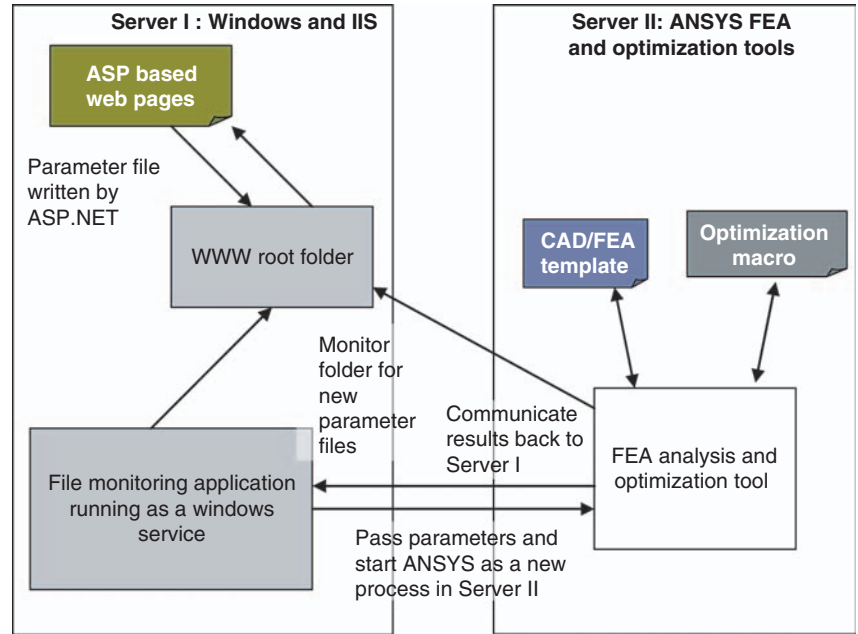


Figure 4. Information setup and implementation of the system.

related to the user and frame, which include weight of the rider, arm reach of rider, etc. The customization information is then submitted to CAD and FEA software with the use of ASP to determine the feasibility of the customized model. If the user specifications do not lead to a feasible configuration, after optimization, in Step 3, the user is prompted to select the dimensions specified in Step 2, which can be varied. A new optimization study is then performed with the selected parameters as the design variables by allowing them to vary within a range of +10% of its initial value. In the case of a feasible design, the dimensions of the resulting model and the geometry are shown to the user as a feedback. Optional analysis information is also included in the HTML result file generated by ANSYS. Currently the system only allows two iterations; if the second optimization leads to an infeasible configuration, the system communicates the result and then prompts the user to change the geometry and exits out of the loop.

### 3.3 Role of ASP

The ASP acts as an agent between customer and engineering analysis software. The information collected through the Web user interface needs to be passed to ANSYS to perform the analysis. The macro, which automates the analysis and optimization, resides in the working directory of ANSYS. The macro file takes both configuration and scaling parameters as input to generate the model of the customized bicycle frame. After performing the analysis, ANSYS outputs a text file containing the results of the analysis, JPEG picture files of the configuration, and 3D VRML model of the

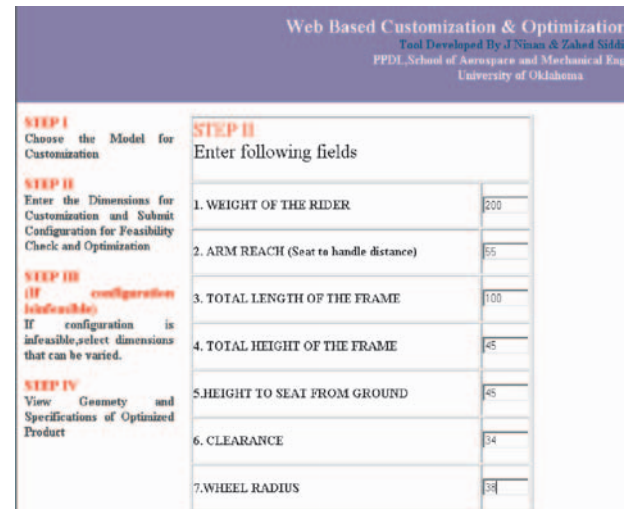


Figure 5. Web-based user interface for customization showing Steps 1 and 2.

configuration. The ASP searches for new files to appear, and opens and passes the information to the user. In those instances where the second iteration is needed for customization, ASP is used to modify the part of the macro file which specifies the design variables to include those parameters check marked by the user.

### 3.4 Mass Customization CAD/FEA/Opt Template for Bicycle Product Family

The CAD/FEA template (Table 2) is used to represent the frames for men's, feminine, and tandem models. Different components are added to the platform to

generate the frame of these three models. The frame platform for all the three models consists of components ST, CST, and CSB (Table 2). LTL, LTM, LTT, LTTF, HTTL, HTTM, HTTT, HSTF, HTL, HTM, HTT, STF, and DTT form the optional components for the family. *AssemRel* relates the geometry and spatial relations among the various components. The *LoadConds* and *BoundConds* describe the loading and end conditions for the FE formulation. Finite element and material information for each component are also contained in the template.

### 3.5 CAD/FEA/Optimization Macros

Macros are used to automate the commonly performed tasks in ANSYS using APDL scripting language. Since the product family is designed using the platform approach, the macro can be programmed to automate the whole process of analysis utilizing the MC-CAD/FEA/Opt template. With the use of looping, decision making, and other programming features embedded in APDL, the macro is used to generate the geometry and perform analysis of the user-specified configuration.

The geometry of each model is defined by the following parameters shown in Figure 6:

1. Seat tube angle (A in degrees)
2. Head tube angle (B in degrees)
3. Horizontal top tube length (D in cm)
4. Seat tube length (E in cm)
5. Fork rake (K)
6. Trail (I)
7. Front center (L)

The values of these parameters for standard models were obtained from [www.cannondale.com](http://www.cannondale.com). The user-specified parameters are related to these variables by using simple equations, thus enabling building the user-specified geometry. The objective of optimization is to minimize the volume subject to equivalent stress not exceeding  $\leq 82.7 \times 10^6$  Pa. The geometry and FEA model of the frame with initial user input is first generated. The weight of the person is the load applied in the FE model. The weight load is applied to represent the seated load. A displacement load is also applied at the bottom. The loads and constraints for men's and feminine members are similar. The macro contains information regarding the type of elements to be used and the relation between different geometric entities, the material properties and the application of loads and constraints for different product family members. Aluminum T-6 is assumed as

**Table 2. CAD/FEA Template for family of bicycle frames.**

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*PF* = {Men's, Feminine, Tandem}  
*PF* = {PP, PO, AssemRel, LoadCondA}  
*PP* = {ST, CST, CSB}  
*PO* = {LTL, LTM, LTT, LTTF, HTTL, HTTM, HTTT, HSTF, HTL, HTM, HTT, STF, DTT}  
*PFM*<sub>1</sub> = Men's = {PP, LTM, HTTM, HTM, AssemRel, LoadCond<sub>1</sub>, LoadCond<sub>3</sub>}  
*PFM*<sub>2</sub> = Feminine = {PP, LTL, HTTL, HTL, AssemRel, LoadCond<sub>1</sub>, LoadCond<sub>4</sub>}  
*PFM*<sub>3</sub> = Tandem = {PP, LTT, LTTF, HTTT, HSTF, HTT, STF, DTT, AssemRel, LoadCond<sub>1</sub>, LoadCond<sub>2</sub>, LoadCond<sub>3</sub>, LoadCond<sub>4</sub>, LoadCond<sub>5</sub>, LoadCond<sub>6</sub>}  
*LoadCond* = {LoadCond<sub>C</sub> + LoadCond<sub>A</sub>}  
*LoadCond*<sub>C</sub> = {LoadCond<sub>1</sub> + LoadCond<sub>2</sub>} Loads applied at the component level.  
*LoadCond*<sub>A</sub> = {LoadCond<sub>3</sub> + LoadCond<sub>4</sub> + LoadCond<sub>5</sub> + LoadCond<sub>6</sub>} Loads applied at the assembly level.  
*AssemRel* = Define the geometric relation between each of the components, for example, where each part is joined to each other.  
*BoundCond*<sub>1</sub> = {Point of intersection of CST & CSB, all DOF, 0}  
*BoundCond*<sub>2</sub> = {Lower End of HT, all DOF, 0}  
*LoadCond*<sub>1</sub> = {Top of ST, net Y-direction, Point Load, weight of the rider}  
*LoadCond*<sub>2</sub> = {Top of STF, net Y-direction, Point Load, weight of the rider}  
*LoadCond*<sub>3</sub> = {Point of intersection of LTM and ST, neg Y-direction, displacement, 0.1 in.}  
*LoadCond*<sub>4</sub> = {Point of intersection of LTL and ST, neg Y-direction, displacement, 0.1 in.}  
*LoadCond*<sub>5</sub> = {Point of intersection of LTT, ST, DTT, neg Y-direction, displacement, 0.1 in.}  
*LoadCond*<sub>6</sub> = {Point of intersection of LTT, ST, LTTF, neg Y-direction, displacement, 0.1 in.}  
*Element Type* = {Beam}  
*Material* = {Aluminum T6}  
*Element Size* = {6}

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\*The same material, element type and element size assumed for all components.

**Product Platform Components (PF):**

Seat Tube ST, Chain Stay Top CST, Chain Stay Bottom CSB.

**Product Optional Components (PO):**

Lower Tube Ladies LTL, Lower Tube Men's LTM, Lower Tube Tandem LTT, Lower Tube Tandem Front LTTF, Horizontal Top Tube Ladies HTTL, Horizontal Top Tube Men's HTTM, Horizontal Top Tube Tandem HTTT, Horizontal Top Tandem Front HSTF, Head Tube Ladies HTL, Head Tube Men's HTM, Head Tube Tandem HTTT, Seat Tube Front STF, Diagonal Tube Tandem DTT.



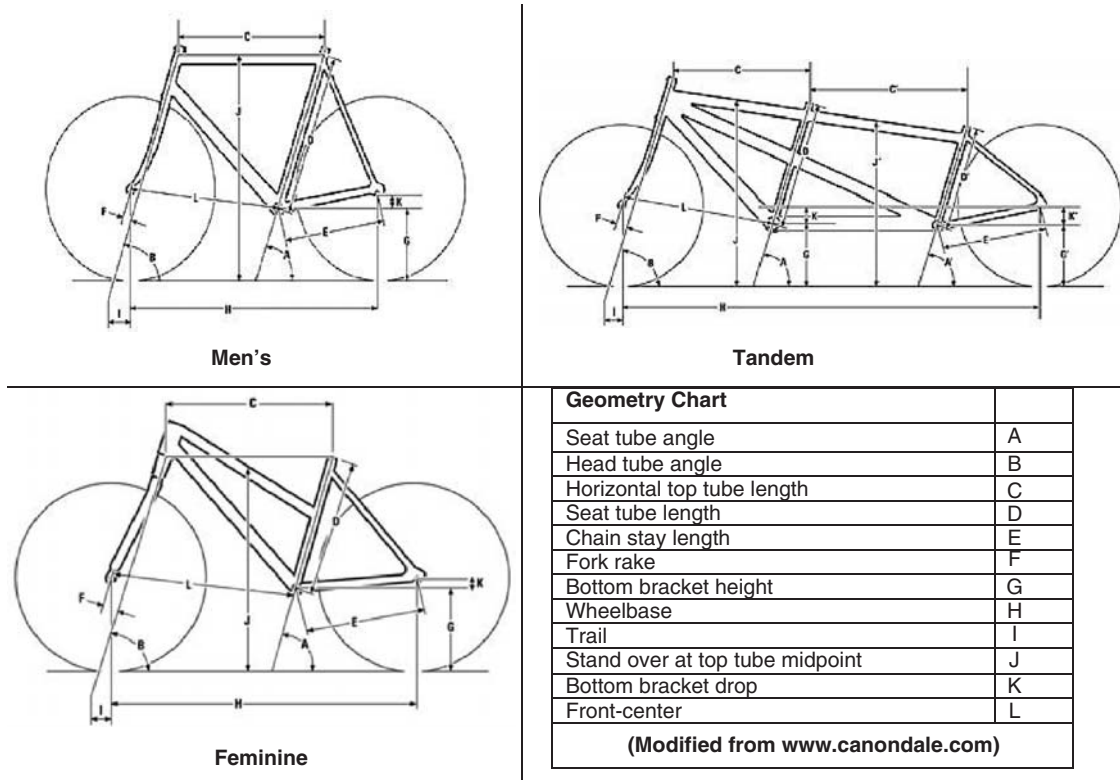


Figure 6. Geometry chart for men's, tandem, and feminine models.

the material for the frames. The solver is then called to perform the analysis and optimize the configuration. The APDL also provides features for capturing snapshots of results during post-processing. The results of the optimization are then written to a text file which is picked by ASP and passed on to the user in HTML format.

### 3.6 User-customized Variety

The implemented bicycle frame MC framework is demonstrated by customizing a bicycle frame through the developed user interfaces. First the men's model was selected by the customer and then values of parameters were specified to customize and design the frame. The values for the input parameters specified by the user are: (1) weight of the rider = 100 kg, (2) arm reach = 56 cm, (3) total length of frame = 98 cm, (4) total height of frame = 84 cm (5) height to seat = 84 cm, (6) clearance = 34 mm, and (7) wheel radius = 34 cm. The general optimization formulation for first iteration is:

Minimize: Mass of the customized frame.  
 Subject to: Von-Mises stress in the member  $\leq 82.7 \times 10^6$  Pa  
 $X_r = F(P)$  with  $X_r = (C, D, E, J, G, H)$  and  $F$  is a set of functions relating  $X_r$  with  $P$

$$72^\circ \leq A \leq 75^\circ, 70^\circ \leq B \leq 74^\circ$$

The initial optimization procedure did not result in a feasible configuration because the stresses in the structure were higher than the limiting value of  $82.7 \times 10^6$  Pa (Figure 7). On the second iteration, the parameters height to seat (HS) and arm reach (AR) were selected as the dimensions that can be varied. Hence the optimization formulation for this specific case is:

Minimize: Mass of the customized frame.  
 Subject to: Von-Mises stress in the member  $\leq 82.7 \times 10^6$  Pa  
 $X_r = F(P)$  with  $X_r = (E, J, G, H)$  and  $F$  is a set of functions relating  $X_r$  with  $P$   
 $72^\circ \leq A \leq 75^\circ, 70^\circ \leq B \leq 74^\circ$   
 $0.9 \times f_1(P) \leq C \leq 1.1 \times f_1(P)$ , with  $C = f_1(P)$   
 $0.9 \times f_2(P) \leq D \leq 1.1 \times f_2(P)$ , with  $D = f_2(P)$

The second iteration returned a feasible configuration with the altered values of: (1) HS = 45 cm and (2) AR = 56.76 cm. This small change in parameters resulted in a change in Von-Mises stress by  $13.8 \times 10^6$  Pa. The angles A and F also play a significant role in the resulting stresses, and the maximum Von-Mises stress is on the joint between lower tube and head tube.

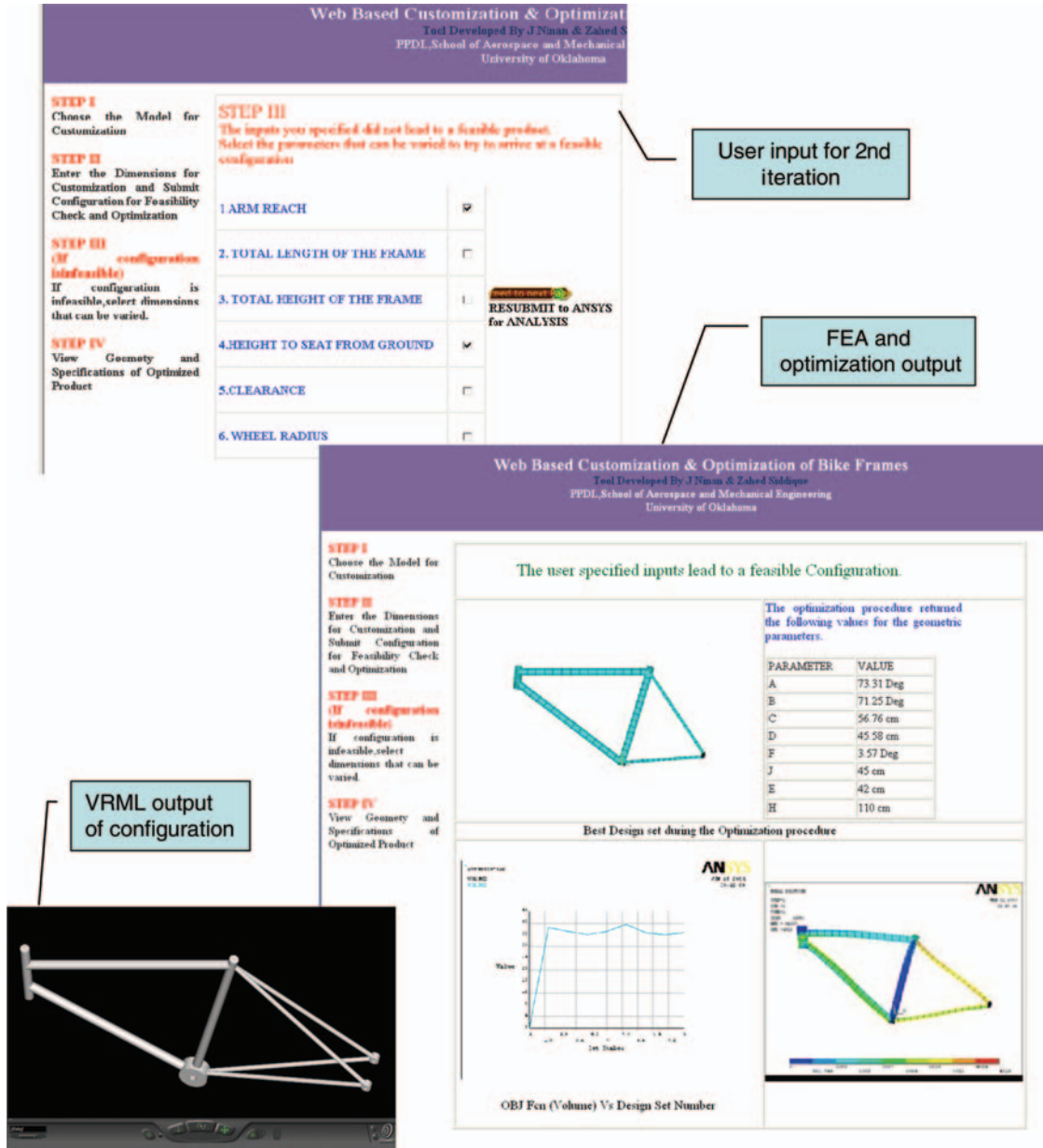


Figure 7. CAD model, FEA results, and parameters of optimized bicycle frame obtained after second iteration.

4. Conclusion

As more and more companies are embracing the product family approach for product development, the design tools and methodologies need to be altered to leverage the product family concept. The PP combined with the Internet-based design tools can provide means to manage customer requirements and facilitate integration of the customer during the design of the product. In this article, an Internet-based framework to better integrate customers into the design of mass-customized products was presented. The frame-

work supports automated design, analysis, and optimization of ETO products in real time. The CAD/FEA template presented in the article takes advantage of the commonality of the product family members and helps to automate the geometry generation and analysis of different configurations. The template can be applied to automate the design process of modular and scalable product families to support customization. The optimization of the customized product is a two-round iteration process – if the first round of optimization leads to an infeasible configuration, the customer is prompted to select those parameters which may be

altered. The second round of optimization includes these parameters also as design variables. The parameters are allowed to vary within a range of +10% of the original value. If the second optimization run also does not produce any possible configuration, the design process is not continued and the customer is just prompted about the infeasible product dimensions. The design iteration needs to be extended until a feasible configuration can be arrived at. The analysis performed here is a static linear analysis.

At present, no manufacturing parameters are considered in the optimization process. Since a 3D model of the customized product is generated by the framework, design for manufacturing and other concurrent engineering tools, which use 3D CAD models to perform manufacturing analysis, can be integrated with the framework.

## References

- Gilmore, J.H. and Pine, B.J., II. (1997). The Four Faces of Mass Customization, *Harvard Business Review*, **75**: 91–101.
- Duray, R. and Milligan, W.G. (1999). Improving Customer Satisfaction Through Mass Customization, *Quality Progress*, **32**(8): ABI/INFORM Global, p. 60.
- Thoben, K. (2003). Customer Driven Manufacturing versus Mass Customization, In: Tseng, M.M. and Piller, F. (eds), *The Customer Centric Enterprise – Advances in Mass Customization and Personalization*, pp. 71–84, Berlin, Germany: Springer.
- Wortmann, J.C., Muntslag, D.R. and Timmermanns, P.J.M. (1997). *Customer Driven Manufacturing*, London.
- <http://www.npd-solutions.com/prodconfig.html>
- Bin, S., Huang, G.Q. and Mak, K.L. (2002). Web-based Product Platform Development using Graph Theory, *International IEEE Engineering Management Conference*, Vol. 1, England: IEEE, pp. 107–112.
- Tseng, M.M. and Jiao, J. (1997). Case-based Evolutionary Design for Mass Customization, In: *Proceedings of the 21st International Conference on Computers and Industrial Engineering*, Puerto Rico, USA.
- Saxon, J. and Beaulieu, C. (2001). Combining the Power of ANSYS and the WEB – Automating Stabilizer Bar Analysis, *AET ANSYS News Letter 4Q2001ARVIN* URL: [http://www.aetchnology.com/aet\\_newsletter/SW4q01/AETSW4q01p1.html](http://www.aetchnology.com/aet_newsletter/SW4q01/AETSW4q01p1.html)
- Siddique, Z. and Zhou, Y. (2002). Automatic Generation of Product Family Member CAD Models Supported by a Platform using Template Approach, In: *Proceedings of Design Engineering Technical Conferences, Computers and Information in Engineering Conference 2002*, Montreal, Canada, DETC/CIE-34407.
- Siddique, Z. and Boddu, K. (2003). An Agent-based Framework to Automatically Generate 3D CAD Models of Customer-specified Products, In: *23rd ASME – Computers in Engineering Conference*, Chicago, IL, Paper No. DETC2003/CIE-48227.
- Siddique, Z. and Ninan, J. (2003). Internet Based Framework to Perform Automated FEA on User-customized Products, In: *29th Design Automation Conference*, Chicago, IL, Paper No. DETC2003/DAC-48719.
- Dahmus, J.B., Gonzalez-Zugasti, J.P. and Otto, K.N. (2000). Modular Product Architecture, In: *ASME 2000 Design Engineering Technical Conferences – Design Theory and Methodology Conference*, Baltimore, MD, Paper No. DETC2000/DTM-14565.
- Siddique, Z., Rosen, D.W. and Wang, N. (1998). On the Applicability of Product Variety Design Concepts to Automotive Platform Commonality, In: *Proceedings of DETC'98: 1998 ASME Design Engineering Technical Conferences*, Atlanta, Georgia, Paper No. 98-DETC/DTM-5661.
- Siddique, Z. (1999). Common Platform Development: Designing for Product Variety, PhD Dissertation, Georgia Institute of Technology, Atlanta, 1999.
- Siddique, Z., Rosen, D. and Wang, N. (1997). Investigations of Platform Commonality using Configuration Design Methods, Ford Motor Company Report.
- Messac, A., Martinez, M.P. and Simpson, T.W. (2002). Effective Product Family Design using Physical Programming, *Engineering Optimization*, **34**(3): 245–261.
- Sabbagh, K. (1996). *Twenty-first Century Jet: The Making and Marketing of the Boeing 777*, Scribner, New York, NY.

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