Mass customization of shoes by automatically finding best-fitting shoes

Hans Grabowski, Ralf-Stefan Lossack and Matthias Wunsch

Author contacts:

o. Prof. em. Prof. E.h. Dr.-Ing. Dr. h.c. H. Grabowski
Universität Fridericiana, TH Karlsruhe
Institut für Rechneranwendung in Planung und Konstruktion (RPK)
Kaiserstr. 12, D-76128 Karlsruhe, Germany
Tel. +49 721 608 2984; Email: gr@rpk.mach.uni-karlsruhe.de

Dr.-Ing. Ralf-Stefan Lossack
Universität Fridericiana, TH Karlsruhe
Institut für Rechneranwendung in Planung und Konstruktion (RPK)
Kaiserstr. 12, D-76128 Karlsruhe, Germany
Tel. +49 721 608 3374; Email: lossack@rpk.mach.uni-karlsruhe.de

Dipl.-Ing. Matthias Wunsch
Universität Fridericiana, TH Karlsruhe
Institut für Rechneranwendung in Planung und Konstruktion (RPK)
Kaiserstr. 12, D-76128 Karlsruhe, Germany
Tel. +49 721 608 2985; Email: wunsch@rpk.mach.uni-karlsruhe.de

Acknowledgements:

This research was funded by grants form the European Commission (GRD1-2000-25761) and by grants from the German Federal Ministry of Education and Research.

Abstract:

How to meet the technological challenges of designing customized products? Typical customer products, such as shoes, seem to have a simple product structure and a quite low level of complexity. At least if one considers products, such as cars or airplanes. Modern truck factories customize and manufacture trucks, just in time and without being one truck similar to the other. How about shoes? Shoes have a simple product structure; approximately 10 or 20 parts, compared to 6000 parts in a car. Where are the difficulties, if not the number and the structure of its parts? One answer to this question is, that the complexity of a shoe, which is customized for a specific foot is hidden in its micro structure. The micro structure is the structure where the elements and their relationships are not parts as in typical product structures but single building blocks which together with their relationships determine the customer requirements. Designing customized shoes is a knowledge intensive process.

To meet customer requirements and the challenge of knowledge intensive design processes for customized products new technological concepts are necessary. The EUROSShoe project aims at realizing an Extended User Oriented Shoe Enterprise. And here, the individual shoe design to fulfill individual style, functional and comfort needs,
plays a fundamental role. In this paper we discuss some emerging techniques and solutions in order to meet the challenges. We present an architecture to manage and process product, customer and technological knowledge to design customized shoes according to individual customer requirements. The architecture consists of three components, which are basically based on a Case-Based Reasoning approach to reason, store, find and modify the necessary knowledge. Since the last is the main form-giving tool to manufacture shoes, its geometrical shape has to be chosen and adapted carefully for each customer to obtain best and custom fitting shoes. One result of our ongoing work is an architecture to automatically identify best-fitting shoes (lasts) for a customer’s feet out of a range of possible shoes (lasts). The concept, application and potential of the automatically finding of best-fitting shoes will be shown by an example.

1. Introduction

Over the last few years it has been recognized that apart from high quality products at low prices and short delivery times customers desire individual products of their own design. Nowadays, various examples for mass customized products can be found in the textile, automotive and leisure industry etc. In the early 90’s, JOSEPH PINE introduced the fundamental concept of mass customization (Pine, 1993), which is a customer driven approach of producing products. Mass customization (MC) is defined by the synthesis of mass production and the manufacturing of customized products by combining the positive characteristics of both: cheap mass produced products and expensive customized products with high quality and short delivery times (Pine, 1994; Tseng/Jiao, 2001). The borderline between MC and single-item production is determined by PILLER as a threshold value for cost per unit of output. If it is not higher than about 10-15 percent of a comparable mass product, it is referred to MC, otherwise to single-item production (Piller, 1998).

In order to implement the concept of mass customization it is of necessity to set up new concepts for product design, sale, procurement, production and distribution. An overview on how the process will be carried out by companies serving the market of individual products is given in Figure 1 (Rautenstrauch/Turowski, 1999).

![Figure 1 Overall process steps of Mass Customization](image)

According to the concept of mass customization, in the EUROShoe project (Extended User Oriented Shoe Enterprise) a radical renovation of the concept of the shoe as a product and of its production is targeted to satisfy the demand of custom-made shoes. Beside the individual chosen shoe style and functional requirements mass customized shoes offer high comfort by using best-fitting or custom-made shoe designs (Boer/Dulio, 2002). A good or optimal fitting shoe contributes to the maintenance of our feet and our healthy (Otto, 1984). Nevertheless, shoes are often produced only in one shoe width per size to reduce the price of the shoe. The size and width of shoes are oriented on average measurements and hence it is difficult or impossible to buy optimal
fitting shoes (a definition will be given in chapter 2). In consequence, the demand for mass customized shoes that fits better seems to be enormous (Pfi, 2002).

In the overall scenario of the customer driven process of producing mass customized shoes it can be seen in Figure 2 that a consumer is directly involved in the design of the shoe he is going to buy. Thus, one of the crucial points of manufacturing mass customized shoe lies in the individual shoe design.

Due to the general process steps of mass customization, the product with its customizable components must be designed in the Shoe-CAD system before a customer can initiate the sale process. In the shoe shop a customer chooses his/her individual shoe which is based on specific requirements. The customer selection criteria like style, color, material, shape, etc. are gathered by a product configurator (1), whereby incompatible configurations are excluded. A foot scanner (2) scans and extracts the characteristic foot measurements of a customer to enable the design and manufacturing of best and custom-fitting shoes. As a form-giving tool the last plays a significant role within the design and manufacturing of a shoe. The dimension of the last determines the size and shape of a shoe.

A best or custom fitting shoe will be automatically produced by a Shoe-CAD system (3) based on the product knowledge and biomechanical design knowledge. As result the customer receives a 3D graphical presentation of the shoe he/she is going to buy (hopefully). Delivery times as well as the specific price of the shoe will be suggested to the customer too. Through the customer order the customer specific geometrical data like the geometry of the shoe patterns and the last will be passed over to the

---

**Figure 2**  Simplified process of producing mass customized shoes

---
production to manufacture the shoes (4). Finally, the shoe will be distributed to the customer (5) by a standard delivery service such as UPS, DHL etc.

The time and cost-efficient production of mass customized shoes requires appropriate design and production technology that is able to produce and process customer individual design data. Both areas are part of the research work within EURO Shoe, whereas in the following the focus is on the design part.

2. Architecture of the Product Knowledge Management (PKM) System

The aim of the "Product Knowledge Management (PKM)" system architecture is to enable the mass customization of shoe designs by integrating and applying customer specific requirements on stored shoe (last) design knowledge. The shoe (last) design knowledge is gathered within the initial shoe design phase and must be stored in a way that it can be re-used for future shoe designs and quick adaptations. As an appropriate representation of the product-oriented design knowledge solution patterns has been chosen, which enable the application independent description of shoe knowledge and which can be adapted to customer specific requirements. Solution patterns consist of design knowledge, which is structured in elementary units that can be combined to more complex solutions. Further details about solution patterns can be found in (Suhm, 1993; Huber, 1993; Lossack, 1997).

Technically solution patterns are based on a Case-Based-Reasoning (CBR) approach, which has been emerged as an applicable powerful problem-solving technique to a wide range of tasks typically related to AI. CBR has been applied to provide numerous applications in many areas including prediction, diagnosis, design, process and the quality control, monitoring and for decision support etc. The philosophy of CBR is to “…solve a new problem by remembering a previous similar situation and by reusing information and knowledge of that situation” (Alhoff/Barletta/Manago/Auriol, 1995). Old problems and their solutions are stored in a so-called case base. For every new problem a CBR system recalls solutions of a similar old problem, which may be well adapted to the new one.

The PKM system consists of three components, which acquire, store and process shoe knowledge: a design knowledge component, a solution searching component and a solution adaptation component.

- **THE DESIGN KNOWLEDGE COMPONENT** enables the design and customization of shoes based on a methodological design process according to Pahl/Beitz, which is adapted to a computable representation (Pahl/Beitz, 1984). Characteristic for this design method is that all design solutions within the so called early design phases are gathered and stored in an integrated product model by requirement-, function-, principle- and embodiment models (Lossack, 2002). The solutions are related to each other using associations, which enable the systematical navigation through the shoe design knowledge.

- **THE SOLUTION SEARCHING COMPONENT** enables the automatically searching of a best-fitting last to produce best-fitting shoes by comparing anthropometrical foot dimensions like the length, width, ball girth etc. with the similar last dimensions of a selected shoe style. The component processes solution searching knowledge that enables the computer-based matching of a foot and a shoe (last). In the case of
custom-made shoes an identified last will be adapted in the following component according to customer specific needs.

- **THE SOLUTION ADAPTATION COMPONENT** enables the adaptation of an identified last matched by the solution searching component. The aim of the last adaptation component is to modify the shape of the last based on biomechanical design rules to obtain a custom made last and fit. The component processes characteristic foot measurements and usage experiences of the customer to modify selected areas of the last shape. The modification of the last takes place without changing the aesthetic shoe design.

The system components to design mass customized shoes are shown in Figure 3 on the right side. The left side shows the process contributing systems: the ShoeCAD-System and the Computer Aided Sale-System (CAS) with its components to configure a shoe and to acquire customer foot and usage knowledge. The data exchange between the systems is based on a XML/SOAP interface.

![Figure 3 Components of the “Product Knowledge Management (PKM)" system and contributing systems](image)

The components of “Product Knowledge Management (PKM)” system supports the computer-based shoe design process for either selling best-fitting or custom-made shoes. According to the definition of the best-fit approach (Boer/Dulio, 2002) a customer foot must match an available last and shoe, the result of the system is the work plan of a conventional manufacturing order that has the standard shoe size and
material. Whereas the custom-made method takes into consideration quick adaptation functions available in a Shoe-CAD system to produce a unique last and shoe design. The shoe design must merge the following requirements: style requirements that depend on the model chosen by the consumer, foot size requirements which depend on the morphology of the consumer's foot and biomechanical requirements that relate to the function of the shoe when used by the consumer. The output of the PKM-system for custom-made shoes is a complete product specification of the shoe including all CAD data of all its components.

3. Solution searching component

Ground for the system concept of the solution searching component is a general approach to automatically classify products (Grabowski/Lossack/Weiśkopf, 2001). The aim of the system is to automatically classify products and their product data enabling a cost- and time efficient product classification and product design. By accessing already known design solutions and re-using it the design of a new solution can be avoided (Grabowski/Lossack/Wunsch/Weiśkopf, 2000). One of the requirements was to develop a flexible system that can be applied in different application domains.

Thus, the system, which was extended by some specific requirements enables the automatically search and finding of best-fitting shoes (lasts). The solution searching process of an old, existing last is analogue to the problem of classifying objects, where the customer feet as objects are classified into a hierarchical class schema of lasts/feet by comparing their values. Each class of the hierarchical class schema contains knowledge by which the objects can or can’t be classified into the class of the hierarchical schema. In our case the solution searching knowledge is described and stored within the class schemas of a hierarchical structure by the characteristic last or foot measurements. In the following by solution searching knowledge it is understood the knowledge that enables a computer to match the foot data of a customer like the length, width, ball girth, etc. with a corresponding last. The values of the customer foot data are compared with the corresponding values of all available lasts. An existing last can be found if the values of the customer foot data correspond with the values of the last. Based on an identified last the adaptation takes place to obtain a custom-made shoe (last).

3.1. Architecture of the solution searching component

In the following the system architecture is described to illustrate the concept of automatically finding an existing shoe (last) for a customer foot. Basis for the application of this approach are characteristic last and foot data to be able to find the best fitting last for a specific customer foot. An overview of the system components is shown in Figure 4, which consists of three components: Usage Data, Classificator and Meta data.
The component for usage data stores and manages all specific data to be classified, which are often stored in distributed data sources i.e. the last and customer data. For example a PDM system contains the last data whereas the customer specific foot data are stored within a CAS-/CRM-System. Thus, the system concept foresees to merge the product, customer specific and other relevant data of various systems and classify these. The link is realized by the definition of a relation between objects, which have the same content in different IT-Systems. Through the mapping of all relations the automatically determination of the objects to be classified is possible. Currently, the system supports the following groups of IT-systems: CAD-/PDM- and ERP systems, Database system, MSExcel and Text documents. All data that is stored in one of these IT-systems can be accessed and classified. It is easy to implement interfaces for further IT-systems. The interfaces do not need very “intelligent” algorithms, as the interpretation system is provided by the PAK-system itself.

The meta data component provides a view on the information, which describes a product in a structure and information density that is suitable for classification. The meta data that is needed for classification – such as attributes, classes, class hierarchies and classification schemes – is held in an own database and is accessible to other system modules via an internal interface. In the meta data all classification relevant attributes like the foot length, foot width etc. as well as class hierarchies are specified, stored and managed:

- Within the system last or foot characteristics, that are stored in the usage data, are mapped to attributes that are organized in attribute structures. By defining calculation rules using other attributes, constants, variables and many different operator types such as math operators, boolean operators, compare operators and so on it is possible to create new attributes that may be needed for classification. For example the ball to heel and ball to toe of a foot object are stored in a data source, but not the proportion. Within the system it is possible to create an attribute called proportion that defines the calculation rule proportion = ball to toe/ball to heel.

- Ground for the creation of a classification system is the possibility to define classes. The most important characteristic of a class is the so-called defining rule. By
evaluating this defining rule the classification module decides whether an object stored in a usage data source has to be assigned to this class or not. The assignment of an object to a class does not have to be "sharp". The system allows to handle unsharp so called fuzzy-attributes to enable the usage of qualitative terms within the class definition. The assignment of an object to a class is described by a fuzzy value between zero and one that describes, how exact the object meets the classification criteria specified in the defining rule of the class.

- The specified classes can be hierarchically structured in class hierarchies. Within a hierarchy the characteristics of a class are inherited to the subclasses. This means, that an object has to meet the classification criteria of a class and the criteria of all super classes to be assigned to that class.

- Class hierarchies are flexible classification schemes that can be easily modified or extended to company specific requirements, if required. By assigning key numbers to the classes of a hierarchy the creation of the classification system is completed.

The aim of the solution searching component is the automatic finding of a best fitting shoe (last) by assigning last and foot data, which can be stored in various IT-systems, into a specified classification scheme. The task of the classificator is to execute the automatic classification of various usage data according to a chosen order scheme by using a so called meta structure. The meta structure is transformed out of the classification schema and is going to be filled by the usage data. The classificator requires here fore the classification relevant attributes and a defined class structure of a classification schema.

To give an overview on how the system operates as well as how the separated component interact, the main steps of a classification process are explained in brief:
The first step is the specification of the classification system (1) to enable the automatic classification of the usage data. The classes of the classification system distinguish lasts and feet by the knowledge specified within the defining rule. The defining rule of a class and the classification system can be modeled in the system simply by using graphical editors. All meta data (2) are stored in the meta data base and are accessible for the classificator module by the meta data interface (3). The second step is to inform the classificator (4) which classification system must be used for the classification. Usually, this step will be made from an external application system (5). Analogically to the classification system, which was modeled in the form of a class hierarchy, the classificator builds-up a structure that is indicated below as a meta structure (7). In the meta structure the usage data will be inserted. The data required to build-up the meta structure are provided to the classificator by the meta data interface. Within the next step, the classificator accesses the data base (usage data) (9) that are to be classified over the "common data interface" (8). By the properties of a class the determined usage data are assigned into the meta structure. Finally external application systems can access the classification results over the application interface (6) and can process them further.

3.2. Example of automatically searching a best-fitting shoe (last)

The flexibility of the system architecture allows to adapt it for the solution searching process to find a shoe (last) for a customer foot by specifying the classification schema based on last characteristics. To illustrate the possibilities of this approach, the classification schema will be structured by different lasts or last categories by size, width, ball girth and further last geometry data. The usage data are the customer foot
data that has to be classified into the specified classification schema. The output of the system is a set of minimum one class or last that corresponds to the customer foot data.

In the following the steps to search and find a last by the system automatically are described:

1. Determining the usage data to be classified (last data and customer foot data)
2. Specification of the last classification schema (corresponding to standard shoe sizes or an own size metric)
3. Presentation and application of the classification result

To 1) The data to be classified can be accessed easily by using available connectors to a variety of data bases like Oracle and MiniSql and to application systems such as CAD- and PDM-systems. Thus, also the data of the last database and the customer foot data can be accessed for the shoe (last) searching process. By the specification of the usage data source the classifier knows the location of the usage data, which he accesses during the classification process. The usage data source in Figure 6 contains a list of last and foot attributes like the last length, ball girth, instep girth, heel width etc. These attributes can be applied for the specification of the classification schema.

![Figure 6 Determination of the data to be classified](image)

To 2) The specification of the last classification schema can be made by graphical user interfaces. Hereby the attributes of the last database will be applied for the specification of the defining rule by which the foot and last data can be assigned to a class automatically. Figure 7 shows an example of a last schema for woman and man lasts. On the right side of the schema i.e. the defining rule for a last with Euro Size 41 and different widths A and B is shown. The characteristic attributes of a last are combined by using mathematical expressions like <, >, =, and, or etc. to specify the defining rule of each class. All specified classes are organized by using a class hierarchy browser, which allows copying and moving classes. By the specification of a hierarchical class schema the defining rule and class attributes are inherited to sub-classes.
As an example, the last matching rule for a men shoe size 41 is shown in Figure 8, which inherits the $(\text{TEXT: Gender} = \text{TEXT: "Men"})$ rule from the super class.

To 3) After running the classificator, which assigns last or foot data into the last classification schema, the obtained results can be viewed as shown on the right side of Figure 9. On the left side the usage data source is shown, which is an EXCEL sheet that contains 2000 generated customer data with foot length, foot width, ball girth, heel width, country, etc.
By the ID of a customer the system is able to name the corresponding classes to which the feet are assigned. In some cases a foot can be assigned to more than one class of the class schema since the classifier is able to process fuzzy attributes. The result of the solution searching process is a set of minimum one last that can be adapted to a customer specific last in the case of custom made shoes. In the case of best fit shoes the searching result will be offered to the customer to order his/her shoes in a standard shoe size.

4. Summary and conclusion

In this paper an architecture for the mass customization of shoes is proposed to effectively and economically design individual shoes. The architecture is based on the Case-Based-Reasoning approach and consists of three components. The components are processing shoe design and biomechanical knowledge to obtain a customized shoe. As part of the architecture, the developed and implemented solution searching component is described and verified in detail. This system component automatically matches a customer foot to a last according his/her foot measurements like the length, width, ball girth, etc. The presented component is appropriate to choose a best fitting shoe (last) out range of possible shoes based on a classification schema. The classification schema can be specified flexibly by using graphical editors and can be easily adapted to a specific shoe company. To obtain custom made shoes changes have to be made on the chosen last geometry corresponding to customer specific needs. The shoe (last) is adapted by applying biomechanical design rules on characteristic areas of the last shape to obtain a custom made shoe with perfect fit. This requires an integrated product model that combines the customer requirements with the geometry of the last. With our approach we can meet the challenges of customer requirements. Concerning geometry we consider standardization efforts, such as ISO-10303 (STEP) as perfectly suited.
References


Grabowski, H. / Lossack, R.-S. / Weißkopf, J. (2001): Automatic classification and creation of classification systems using methodologies of "Knowledge Discovery in Databases (KDD)"; In: Data Mining for Design and Manufacturing: Methods and Applications by edited Dan Braha; Heidelberg, Kluver Verlag, 2001


