Modular product design and customization

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Abstract

The paper deals with modular design architecture and its capabilities for easy and fast customization in products. The basic principles of modularity are mentioned and the most known methodologies and tools for modular product design are reported. The way modularity can facilitate a product's customization is being addressed. With the help of a modular real test case, a motorcycle helmet, the capabilities of modularity in customization are illustrated and a customization procedure is described. The conclusions drawn in the final section of the paper indicate that although many modular design methods exist none of them is capable to provide the optimum design solution. However, all of these methods undeniably facilitate the customization of products.

Keywords:
Modularity, customization, design

1   INTRODUCTION

In today's market of increasingly demanding customers, companies are compelled to focus on smaller and specific market segments of customer oriented products. The era of the so called "mass customization" is now emerging (Figure 1). The main requirement a product should meet in order to be customizable is to maintain its sensitivity to a change at the lowest possible level. The lower its sensitivity is, the higher its flexibility [1]. Therefore, flexible design architectures are utilized, so as to enable easy, low cost and fast changes in the product. Modularity is such architecture and considered as the most effective means of achieving these demands.
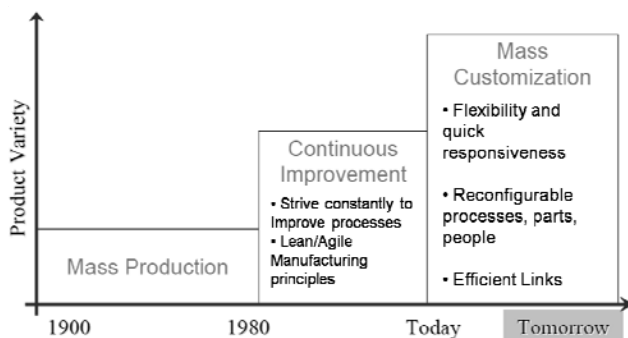

Figure 1: From mass production to mass customization [2].

Within the next sections of the paper, the principles of modularity and the basic design of modularity methods are initially described. Moreover, the way modularity facilitates customization is addressed. The main purpose of this work is for some of the existing methods to be applied to an existing case study, a modular motorcycle helmet, in order for the modularity of this product to be demonstrated and the ease by which it can be customized according to customer's needs. In the last section, conclusions are drawn and discussed.

2   MODULARITY AND CUSTOMIZATION

Ulrich [3] first distinguished two main architectures in product design: the integral and the modular one. In an integral architecture, the components of a product are designed to be assigned for more than one function and the interfaces among them are coupled. On the contrary, in a modular architecture, a one-to-one mapping exists between functions and parts and uncoupled interfaces are specified. However in the last years, modularity or integrality is not considered anymore as a binary characteristic. Products may therefore present varying degrees of one or the other architecture [4].

2.1   Design for modularity

A number of methods and tools, leading to modular design have been developed over the last years. Hereafter, the methods that are most widely used by design engineers are described.

Design Structure Matrix

Design Structure Matrix (DSM) is used for the better representation of a system's element structure. Through this visualization facility, a designer has the ability to better control the modularity of the product, with regards to the interface complexity.
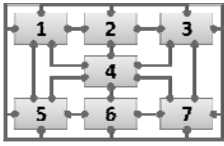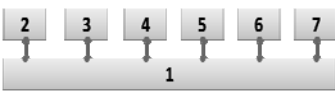
Interface architecture	Fully integral	Bus-modular	Fully modular
Graph			
DSM	$\begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

Table 1: DSMs for different interface architectures [4].

These matrices are binary in general, square and contain the system's elements, the name down the side (as row headings) and across the top (as column headings). While a link exists between node i to node j, the value of the ij element is unity or marked with X, otherwise the element value is either zero or it is left empty. Finally, the diagonal elements of such matrices have usually zero value or are left empty as well, since they do not play any role within matrix [5]. Holtta-Otto and de Weck [4] describe the DSMs of a fully "integral", a "bus-modular" and a fully "modular" system of seven components (Table 1).

Axiomatic Design Theory

Axiomatic Design Theory (ADT), developed by Suh [6], is a method that transforms Customer Attributes (CAs) into Functional Requirements (FRs) and subsequently to Design Parameters (DPs) and Process Variables (PVs). The design becomes interplay between the functional (FR domain) and the physical domains (DP domain). More than one result may arise from this procedure.

The interrelation among domains can be better demonstrated with the help of a Design Matrix (DM). By using vector notations for FRs and DPs (the same could apply for the pairs of the other domains), the relationship can be expressed in an equation of the following type:

$$FR = A \cdot DP \tag{1}$$

where A the DM.

ADT is governed by two axioms:

Axiom1 - The Independence Axiom

All FRs should remain independent throughout the design

Axiom2 - the Information Axiom

The information content of the design should always be kept at a minimum level

In order for the satisfaction of Axiom1 to be controlled, the DM is utilized. If the DM is diagonal, then Axiom1 is valid. This case corresponds to an uncoupled design. If the matrix is triangular, then the design is decoupled and may, under certain circumstances, satisfy Axiom 1. In all other cases, the design is coupled and each function is affected by more than one design decisions.

Axiom2, is utilized in case two or more designs fulfill Axiom1. By measuring the information content of each design it then selects the one that "carries" the minimum amount of information.

A correlation between ADT and modular design has been performed in [7]. According to this, an integral architecture can be compared with a coupled DM while the modular architecture can be modeled with an uncoupled one. Finally, a design characterized by an intermediate architecture, between integral and modular, may be represented with a "semi-coupled" design matrix, where some of its entries are not equal to zero and thus, coupling in design is caused.

Modular Function Deployment

Modular Function Deployment (MFD) is also a method performing functional decomposition. However, here the mapping takes place between the module drivers and the functions.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix}$$
Uncoupled design

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} x & 0 & 0 \\ x & x & 0 \\ x & x & x \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix}$$
Decoupled design

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} x & x & x \\ x & x & x \\ x & x & x \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix}$$
Coupled design

Figure 2: FR–DP relationship according to the design matrix [6].

MFD comprises five main steps:

1. *Define customer requirements*
   In this initial step, the characteristics of the product are defined, based on competition analysis and customer requirements.

2. *Select technical solutions*
   The FRs meeting the above demands are specified. These requirements are afterwards transformed into technical solutions.

3. *Generate concepts*
   This is the basic step of MFD, where the modules of the product occur, after the analysis of the technical solutions. The analysis is performed having as criteria twelve modularity drivers (carryover, technology evolution, planned design changes, different specification, styling, common unit etc.)

4. *Evaluate concepts*
   In this step, the interface relation between the modules is determined. Additionally, an economic evaluation of the modular concepts takes place.

5. *Improve each module*
   The final step of the method includes the definition of the modules' specifications (technical information, cost targets etc.). Based on these specifications, the detailed design and optimization of each module may take place.

Finally, MFD also indicates the ideal number of modules within a product, as the square root of the number of assembly operations in the average product. Furthermore, the interface design is also addressed taking into consideration parameters such as those of the fixation method, the number of contact interfaces, information exchange between modules (material flow, energy, signals etc.) [8].

Although several design methods, leading to modular architecture exist, as it was shown by Holtta and Salonen [9], each one of them gives different results with the same identical input. This happens, due to the different perception and application fields of each method.

2.2 Product customization

In order to perform product customization at low-cost, of high-quality and at the same time large-volume delivery, two are the basic requirements that have to be fulfilled. Firstly, technologies capable of performing the customization are needed. Reverse Engineering, advanced CAD techniques, Information Technology, non conventional manufacturing methods are some of these technologies. At the same time, the product's design complexity should be kept at a minimum level. This is accomplished by making the design modular, both as far as the functions mapping and the interfaces structuring is concerned.

A number of effective customized products already exist covering a wide range of industrial sectors, from cars and computers to software, toys, shoes and many others. In [10] - [14] such examples are reported.

3 TEST CASE: CUSTOMIZING A MOTORCYCLE HELMET

3.1 Helmet's design

The main parts of a motorcycle helmet are shown in figure 3:

Figure 3: Motorcycle helmet's basic parts.

In order to better illustrate the design architecture of the helmet, both in terms of functional decomposition and interface complexity, a DM with ADT and a DSM were formulated respectively.

Design Matrix formulation

The following main FRs-DPs are defined for the helmet:

Functional Requirements		Design Parameters	
FR1	Prevent penetration	DP1	Shell
FR2	Absorb energy	DP2	Expanded Polystyrene (EPS) foam liner
FR3	Provide comfort	DP3	Padding
FR4	Protect face/Visibility	DP4	Face shield

Table 2: FRs-DPs for motorcycle helmet.

The relation between these FRs with the DPs is described in the following design matrix:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 & 0 \\ 0 & A_{22} & 0 & 0 \\ 0 & 0 & A_{33} & 0 \\ 0 & 0 & 0 & A_{44} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \quad (1)$$

Design Structure Matrix formulation

The graph of the interface structure of the helmet's components as well as its corresponding DSM, are represented in Table 3.

Graph	DP4 — DP1 — DP2 — DP3
DSM	$\begin{array}{c} \\ DP4 \\ DP1 \\ DP2 \\ DP3 \end{array} \begin{array}{cccc} DP4 & DP1 & DP2 & DP3 \\ \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$

Table 3: Helmet's components interface structure.

Design evaluation

By analyzing matrix (1), an absolute one-to-one mapping that gives a completely uncoupled design, may be observed: this can be considered as a modular design, in terms of functional decomposition. Furthermore, Table 3 reveals a fully modular interface structure as well.

3.2 Helmet's customization

A generic customization procedure for products has been created in [15]. A motorcycle helmet is one of the test cases of the project, upon which this procedure was developed. This product was selected, since from studies performed within the project, it was shown that the 15-20% of all full face composite helmets were ill fitting and that 5% of the motorcyclists could not find helmets to fit their head geometry. Moreover, as the role of the EPS foam liner is to bring the head to a gentle stop, it is obvious that the smaller the gap is between the head and the liner, the less serious the injury. In Figure 4, this gap is illustrated.
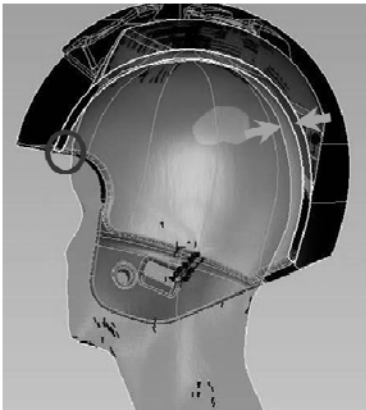

Figure 4: Gap illustration between head and liner.

In section 3.1, the helmet's design was defined as being completely modular. This means that a change in the "DP2 – EPS foam liner" would not affect the functionality of the other parts. Additionally, the interface between the liner and the shell is not altered in the customization procedure. Therefore, in order to minimize the gap and thus, maximize safety and comfort, the internal geometry of the EPS liner should be customized according to the rider's geometrical and non-geometrical features. The non-geometrical requirements define the interaction in the zones of contact, such as the pressure distribution between the product and the rider's head and the level of comfort felt by the rider.

The customization procedure developed consists of five steps:

1. *Capturing geometrical data*
   Scanned data from the rider's head are gathered with the help of a 3D body scanner.
2. *Capturing non-geometrical data*
   These data include the information about the pressure between the helmet and the user's head. For this reason, a customized recording system of static pressures has been developed so as to generate a pressure map.
3. *Designing the Custom-Fit inner liner*
   Geometric customer data, non-geometric data and the existing helmet geometry into which the liner has to be integrated, are required in the design phase. For this purpose, a design system was developed within the project that executes the required sequence of operations altogether automatically.
4. *Developing the manufacturing process for the inner liner*
   Rapid Manufacturing (RM) was selected for the manufacturing of the customized liner, due to the unique feature of this technology to build any shape that might be required. An RM system, capable of mimicking the material and properties of the EPS foam has been developed within the project.
5. *Manufacturing and assembling the inner liner*
   The STL files are generated from the design system and are imported in the RM machine. The inner liner is produced with the use of a straightforward honeycomb structure, which is a good compromise of mimicking the polyurethane foam and being cost effective in design and manufacturing Figure 5 [16].
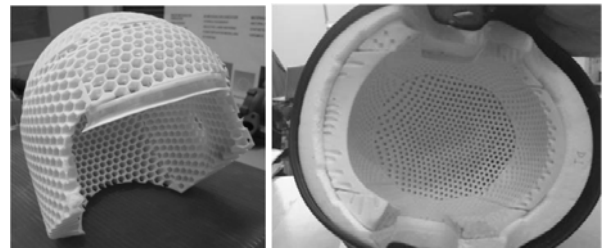

Figure 5: Customized helmet's liner.

4   CONCLUSIONS

Many modular design methods exist that may be useful to designers. None of these methods lead to an optimum design solution, as they all examine the design from a different perspective. However, all of them undoubtedly are capable to facilitate the customization of the product. With the help of a test case, the paper demonstrated how a modular product could be easily customized and a customization procedure was proposed.

Since the current trend is for products with combined design architectures, in order for the benefits that each architecture provides to be exploited, special attention should be given when assigning functions and interface structures to parts/modules, so as for couplings to be avoided in the parts to be customized.

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