INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

INVESTIGATING ON THE RISE OF MODULARITY DURING THE CONCEPTUAL DESIGN PHASE

L. Fiorineschi, P. Rissone and F. Rotini

Keywords: modularity, conceptual design, design process

1. Introduction

According to the model proposed by [Pahl and Beitz 2007] and several other scholars, the conceptual design can be considered the phase of the design process where functionalities, physical principles, and preliminary sketches of the system physical structure are defined. The importance of the recalled design phase is well acknowledged by the literature, especially in reference to the impact it has on the overall design costs [Akay et al. 2011] as well as on the success probability of the design outcomes [Ulrich and Eppinger 2003]. Moreover, since the way in which functions are allocated in the components constitutes an important part of the architecture of the product [Ulrich and Eppinger 2003], it is possible to assert that defining a product concept means also defining a draft of its architecture.

Despite the presence of side effects, literature acknowledges modular type architectures to give rise to a series of positive effects. In confirmation of this, several contributions aimed at supporting the designer in reorganizing the product architecture towards modular configurations can be found in literature. However, advantages given by considering modularity early in the design process have been already inferred [Stock et al. 2003], [Graedel and Allenby 1995].

As claimed by [Hölttä-Otto 2005], [Borjesson 2010], [Daniilidis et al. 2011], the Design Structure Matrix (DSM) [Eppinger and Browning 2012], the Function Structure Heuristics (FSH) [Stone et al. 2000] and the Modular Function Deployment (MFD) [Ericsson and Erixon 1999] can be considered the representative sample of the most acknowledged methods for assisting product modularization. However, it is worth of noting that the cited contributions have been developed to suggest modular reconfigurations of an existent product concept. Indeed, according to [Daniilidis et al. 2011], since the DSM-based modularization methods use a component-based analysis of the product architecture, it cannot be used until product components are determined. Concerning FSH, as stated by [Van Wie et al. 2001] the method can be used during concept design for determining the product architecture. In fact it is based on the Energy, Material and Signal (EMS) functional model [Pahl and Beitz 2007], and uses three euristics based on the EMS flows to suggest potential modules. However, the physical principles implementing the functions must be already known otherwise it results impossible to identificate the EMS flows needed for the application of the heuristics. Lastly, the MFD method has been developed to suggest potential grouping of the technical solutions composing the product, but do not give any support for their identification.

In consideration of these evidences, it is possible to claim that the results obtained by the application of the considered methods are strongly influenced by the solutions adopted in the starting concept which however has been developed without considering modularity. In fact, it can be inferred that the available modularization methods can assist concept design activities only with a trial and error approach, where a product concept has to be formerly developed. Nevertheless, [Fixson 2003] observed that the need for a modular architecture may arise during the definition of the requirement list as well as early in the design process. Furthermore, [Ulrich and Eppinger 2003] state that modularity issues may arise even during the concept design phase, although only informally. Such a statement requires further investigations aimed at verifying when and why modularity issues emerge during conceptual design. The outcomes of such an activity could contribute to the understanding of how modularity issues can be managed during the conceptual design of a new product. Thus, they can constitutes a base of knowledge for the development of systematic approaches to assist the management of modularity in early concept design tasks. According to the just introduced objective, the aim of the present paper, is to perform some preliminary investigations about a research approach aimed at verifying and analysing the "informal" occurrences of modularity issues during the concept design phase of a new product.

In Section 2 the issues that characterize the investigation activity are introduced, together with the basic principles adopted to develop the proposed research method. Sections 3 and 4 are dedicated to the explanation of the fundamental elements on which the method is based, while the logic of the suggested approach is described in Section 5. It has been tested on a set of three real case studies concerning the design of working prototypes and the related results are reported in Section 6, where the potentialities of the proposed approach are discussed. Eventually, Section 7 is dedicated to conclusions and future developmetns.

2. Investigation issues: Problem to be solved

The objective of this work, introduced in the previous section, involves the necessity to analyse many design processes and the related outcomes. Substantially, there is the need to identify the adopted technical solutions, assess them for finding modular characteristics, and somehow go back to the reasons which leaded the designer to adopt such characteristics. Such a process requires the mapping of the solutions that appear during the conceptual design activity and the linking of these ones to the original problems. To this purpose, the Network of Problem (NOP), derived from the OTSM-TRIZ base of knowledge [Khomenko et al. 2007], constitutes a valid tool since it allows to visualize relationships between problems and solutions belonging to different level of detail of the system.

Consequently, a problems-solutions analysis has been chosen to develop the proposed approach. Accordingly, the following two parameters have been defined:

- *Modular problems*: this parameter refers to those design problems in which their resolution could take advantage from one or more modularity benefits acknowldeged by literature. A list of modularity benefits is reported and shortly described in the following Section.
- *Modular solutions*: they represent solutions whose characteristics can be attributed to well acknowledged types of modularity (see Section 4). Thus, every investigated solution which presents one or more characteristics belonging to a category of modularity presented in Section 4 is assumed as a modular solution. It is worth to notice that a modular solution may also be something not completely identifiable in a module.

The modular problem definition is used to identify design problems potentially solvable with modularity, while the modular solution definition is employed to discern modularity in the technical solutions adopted in the considered product.

A not negligible problem to be faced for the implementation of the analysis is represented by the need of collecting and managing a big amount of data related to real case studies whose design processes, requirements and outcomes must be well known. For this scope, two possible solutions arise, i.e. the observation of design processes in real time and the analysis of already performed design tasks. The first chance privileges the completeness and exhaustivity of the data, but direct observations may involve too time to obtain the required amount of information. The analysis of already performed design processes potentially involves a minor amount of time resources for its implementation, however there are some important drawbacks to be considered. First of all, the success of this approach is strongly dependent on the completeness of the information that can be gathered from the sample of case studies. Furthermore, there is the need to verify and ensure that the design intent wasn't explicitly oriented towards the search for modular solutions, otherwise the results of the analysis miss the meaning. A way to solve this problem is to consider only design processes where the designer or the design team were not learned about modularity. Morevoer, there is the necessity to relate modular problems with the corresponding solutions but, since the design process cannot be directly observed, the relationships between problems and solutions must be reconstructed using a sort of "reverse engineering" approach. The coevolving path involving problems and solutions can be recreated by interviewing the designers that have carried out the examined case studies. To the scope of this work, the authors decided to adopt the analysis of already performed design tasks as way of investigation, since they have the availability of three case studies whose design processes are sufficiently characterized in terms of requirements, outcomes and main design problems faced by designers in the concept development phase. It is worth to notice that every design problem related to the identification of the functions, the physical principles and the basic forms of a part of the product, are considered here as belonging to the conceptual design phase. The considered sample of convenience is sufficient to show how the method described in Section 5 works, as well as to obtain preliminary outcomes to be discussed. However, the same method can be adapted and subsequently adopted also for investigations performed through the direct observation of the design activity.

3. Benefits of modularity

The interest of scholars towards modularity is motivated by the common assumption that despite some inevitable disadvantages, "modularization" of products can give rise to benefits under many points of view. Many of these benefits have been highlighted by several literature contributions which show the advantages of modularity [Newcomb et al. 1996], [Gu and Sosale 1999], [Huang 2000], [Gershenson et al. 2003], [De Weck and Hölttä-Otto 2005], [Krause and Eilmus 2011], etc. In Table 1 a list of these benefits is reported and grouped according to the four main product life-cycle phases.

Table 1. Modularity benefits

Life-Cycle phase	BENEFITS
DESIGN	a) Parallel Development b) Design Reuse c) Design Team management
PRODUCTION	d) Ease of Assembly e) Logistic Optimization for Production/Assembly f) Economy of Scale g) Late Point Differentiation/Customiz. or Postponement
USE/OPERATION	h) Ease of Maintenance/Repair Operations i) Reconfiguration/Flexibility in Use j) Variety k) Customization l) Upgrades/Part Changes
RETIREMENT	m) Material Recycling Facilitation n) Disassembly Time o) Part/component Reuse

That list of benefits have been defined by interpreting and generalizing the contributions currently available in literature. According to what introduced in the previous Section, the list of the benefit serves to identify which problems should be defined as modular. For the sake of brevity, only a short explanation of each benefit is reported in the following.

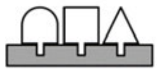
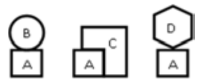
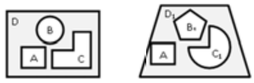
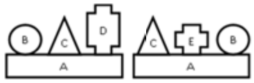
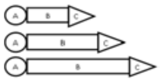
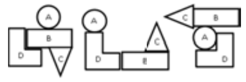
The "Parallel Development (a)" term means the possibility to subdivide the product development task into different and independent development sub-tasks. With "Design Reuse (b)" the possibility to reuse a part of the design work performed to develop a product whitin other design tasks is intended. "Design Team Management (c)" identifies the opportunity of reducing communication and coordination efforts into a structured design team. The "Ease of Assembly (d)" and "Disassembly time (o)" benefits represent respectively the possibility to reduce assembly and disassembly operation costs. The "Logistic optimization for Production/Assembly (e)" benefit identifies the opportunity to optimize the production process from a logistical point of view. The effect of standardization on component costs is well acknowledged, e.g. Ulrich (1995) assert that usually standard components are less expensive than custom-made ones, primarily because the standard component is produced in higher volumes. On this principle is based the meaning of the “Economy of scale (f)” benefit. With “Late Point Differentiation/Customization or Postponement (g)” is intended the delay of the assembling of some components in order to optimize delivery costs. The “Ease of maintenance/Repair operations(h)” the benefit related to the reduction complexity and costs of maintenance operations. “Reconfiguration/Flexibility in Use (i)” identifies the possibility to add or modify functionalities of the product. With “Variety (j)” is intended the possibility to obtain different product models with a set of standardized parts. As for the previous benefit, “Customization (k)” identifies the possibility to obtain different product models, but by means of customized parts. “Upgrades/Part Changes (l)” represents the possibility of a product to be upgraded by changing components. “Material Recycling facilitation (m)” identifies the possibility to reduce the complexity of the procedures needed to recycle some parts of the product. Finally, the benefit “Part/Component Reuse (o)” identifies the possibility to recover some parts of the product after the retirement, in order to be re-used in other products.

4. Modular characteristics

Many definitions of modularity can be found in literature, belonging to different engineering domains and based on different perspectives [Salvador 2007]. Some definitions may differ when using terms like, module, chunk, component and element. In order to avoid ambiguity and supply a reference for the scope of this work, the following key concepts have been considered, which are based on the consideration that different levels of detail can be identified in a product:

- *System*: Every part or assembly belonging to a determined level of detail may falls under this definition. At the highest level of detail the system corresponds to the product.
- *Component*: With this term any physical element is identified, intended as single part or assembly which constitutes the system at the succeeding level of detail.
- *Module*: It is intended here as a particular component connected to rest of the system by means of decoupled interfaces and which is identifiable with the modularity definitions given in this Section.

Table 2. Modular characteristics

Interface type	Slot Modularity: all the interfaces between different components are of different type. [Ulrich 1995]	
	Bus Modularity ‘a’: it is possible to individuate a common bus that connects other components by the same type of interface. [Ulrich 1995]	
	Sectional Modularity: all the interfaces between different components are of the same type. [Ulrich 1995]	
Interaction type	Component-swapping:modularity: two or more components can be interchanged in a system in order to create product variants. [Ulrich and Tung 1991]	
	Component-sharing modularity: two or more systems share the same basic component in order to provide product variants. [Ulrich and Tung 1991]	
	Bus modularity ‘b’: where a component can be matched with any number of other basic components. [Ulrich and Tung 1991]	
Supply type	Fabricate-to-fit (sometimes called also “Cut-to-Fit”) modularity: standard components are combined with customizable ones. [Ulrich and Tung 1991]	
	“Mix” modularity, where a set of standard components can be matched together in order to form a variety of products. [Stone 1997]	

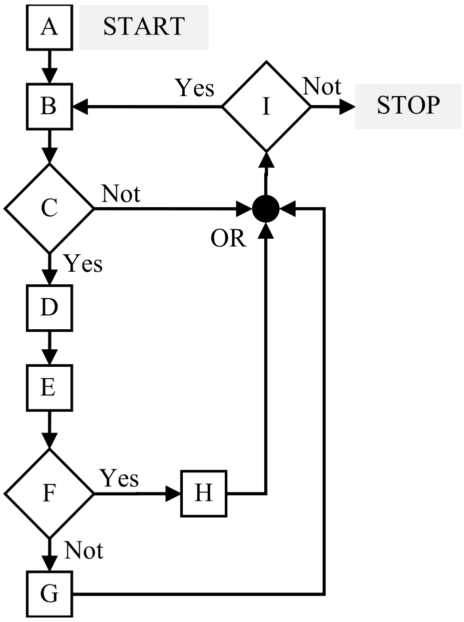
Well known definition concerning modules and modularity are based on functional aspects [Stone et al. 2000], [Pahl and Beitz 2007]. However, the function-based definitions of modules [Pahl and Beitz 2007] have not been considered in this type of “reverse engineering” analysis. This because, for the aim of this investigation, it is not important to classify modules (when present) from a functional point of view. Indeed it is sufficient to identify traces of modularity in the adopted solutions. More precisely, only modular characteristics related to the physical structure of the product have been taken into account (Table 2). The following criterion has been used by authors to classify the modularity types:

- *Interfaces types of the modules*. Describing the characteristics of the connectivity among the components of the system. The definitions of Slot modularity, Sectional modularity and Bus modularity belong to this class.
- *Interactions within the system*. Describing how the modules are matched together in order to form the system . Swapping, Sharing and Bus modularity fall into this class.
- *Supply type of modules*. Describing the way on which the components of the systems are provided. Fabricated to fit and Mix modularity belong to this last classification group.

A similar attempt to classify modularity types has been done also by [Salvador et al. 2002] where the considered modularity types are almost the same introduced here, but with some differences in how they are grouped. Strictly for the aim of this work, such a differences have been considered as a possible cause of ambiguity.

5. Method of investigation

The proposed investigation method is constituted by four main activities that are here described in detail, while the logic of the suggested approach is shown in Figure 1.



A	Retrieve the conceptual design problems list
B	Compare one problem with the modularity benefits
C	Is the problem compatible with modularity benefits?
D	Identify the related solution
E	Compare the solution with the modularity types
F	Is the solution associable to a modularity type?
G	Assign null score
H	Assign unitary score
I	Are other conceptual design problems still present?

Figure 1. Logic of the design processes investigation approach

The first step consists in the acquisition of design problems which characterize the design process under investigation. For that purpose, designers involved in the investigated project are asked about the followed design process and faced problems. The main design problems are tipically related to the fulfillment of the functional requirements of the system, while the others are related to more detailed aspects. Once the list of design problems has been obtained, the subsequent step is the identification of the modular problems by performing the comparison with the modularity benefits introduced in Section 3. This is a fundamental activity, since it allows the emerging of the linkage between informal occurrence of modularity and specific modularity benefits.

This step is carried out with the presence of the designers involved in the examined case study. In this way it is possible to avoid eventual misunderstanding due to the use of improper or incomplete descriptions of the problems. To give an example, for the design of a biomass grinder, a problem encountered by designers was: “How to allow to process different raw materials?”. Only after a confrontation, the modularity benefits which fit with this problem definition have been identified in “Variety (j)” and “Customization (k)”. Indeed, both the benefits are related to the diversification of the product model, although the first suggests the use of standardized parts while the second considers the use of custom-made ones.

Conversely, design problems like “how to increase reliability” and “how to reduce energy consumption” do not match with any of the benefits, so they have not been considered in the analysis since, according to the classification introduced in Section 2, they are not modular problems. This is in accordance with the literature since performances aspects of the product are optimized moving towards integrality [Ulrich 1995], [Hölttä-Otto and De Weck 2007].

The third step of the method is the retrieval of the solutions adopted to solve the modular problems identified in the previous step. As for Step 2, the active participation of the designers that have carried out the activity is required to perform the task. Subsequently, the identification of modular solutions, among the retrieved solutions, is performed by searching for decoupled interfaces and module characteristics belonging to the three groups defined in Section 4. In order to show how the modular solution identification is performed, one of the investigated cases is considered and a description of the process is reported in the following. The solution (Figure 2) belongs to the design process related to an innovative biomass grinder, where the considered modular problem is that previously mentioned in this Section, i.e. “How to allow to process different raw materials”.

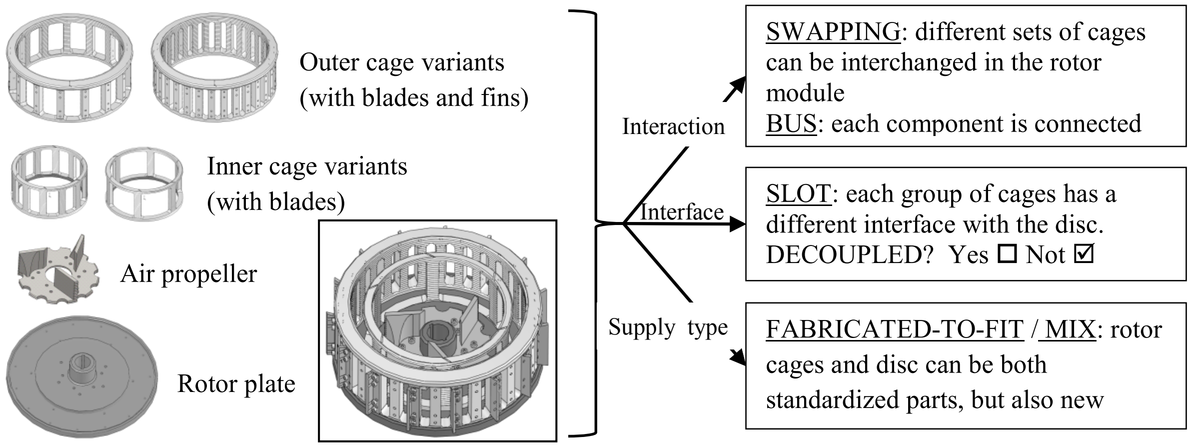


Figure 2. Identification of the modularity characteristics involved in the solution related to the problem: “How to allow to process different raw materials?”

Referring to the example of Figure 2 and considering the rotor assembly as the “system”, the results of the comparison with the modularity characteristics are explained in the following:

- **Interface type:** the modularity type is “SLOT”, because each component has a different interface with the rotor disc. This solution resembles the definition of “Slot Modularity” reported in section 4, i.e. “all the interfaces are of different type”. It can be observed that the interfaces are not decoupled, in fact, a variation of the internal diameter of the inner rotor cage implies a modification on the plate. The same for the other components, but for other diameters.
- **Interaction type:** the modularity type is “Swapping” because different components can be interchanged in the same rotor assembly. It is in fact equivalent to the definition of “Swapping Modularity” reported in Section 4, i.e.“two or more components can be interchanged in a module in order to create product variants”. Moreover, in the adopted solution there is a “Bus” component, i.e. the rotor plate, to which the others are connected, allowing to obtain rotor variants by changing the part version or by eliminating the outer cage.
- **Supply type:** the modularity type can be considered congruent with the definitions of both the “Fabricated-to-Fit” and the “Mix” modularity given in Section 4, because rotor cages can be both standardized parts (internally to the firm) or custom made parts.

Eventually, the last step of the method consists in the assignment of a binary score (1 or 0) in order to use the results to evaluate how modular solutions are related to modular problems. More specifically, a unitary score is given to each modularity benefit whenever it is involved in the identification of a modular problem that is associated to a modular solution. Conversely, a null score is given to the benefit when the related solution is not modular. Taking again as a reference the example of Figure 2, even three modular characteristics have been found then, given the definitions of Section 2, it has been possible to consider the solution as modular, and consequently a unitary score is assigned to both the benefits involved in the identification of the related modular problem.

6. Testing of the method

Before starting with the contents of this section, it is worth to highlight that due to the restricted amount of data considered in this work, it was not possible to obtain a statistical reliability of the results. However they have been successfully used to develop and evaluate the potentialities of the proposed investigation method and, furthermore, they allowed to rise some not negligible research questions.

6.1 Case studies

The case studies chosen for the investigation are a system to grind wet biomass, a platform for performing stratospheric ballooning experiments (Gondola) and a hydraulic pole driver for excavator's heads. It is worth to highlight that the three considered cases concern the development of experimental prototypes, where no explicit intent to obtain modularity were considered. The list of the considered conceptual design problems which have been identified as modular is reported in Table 3.

Table 3. Modular problems of the three considered case studies and related benefits of modularity

Case	Design problem	Associated Modularity benefit
Biomass grinder	How to ease the maintenance of the cutting elements?	Ease of maintenance.
	How to allow to process different raw materials?	Customization; Variety.
	How to allow different output size of the processed material	Customization; Variety.
	How to allow upgrades of the cutting elements	Allow upgrades/part changes .
	How to allow to test different impact blades configurations	Customization.
Stratospheric platform	How to ease of multiuser management	Design team management.
	How to reduce the design costs of the gondola	Design reuse.
	How to increase the reuse the gondola after landing?	Component reuse.
	How to ease the transportation and recovery operations?	Disassembly time.
	How to ease of the assembly process?	Ease of assembly.
	How to obtain different shapes for the same gondola?	Variety; Customization.
	How to allow different positions of the Pivot axis?	Variety; Customization.
	How to reduce manufacturing costs	Economy of scale.
Pole driver	How to allow compatibility with different crane heads?	Customization.
	How to allow compatibility with different poles?	Customization.
	How to ease the maintenance of sliding parts?	Ease of maintenance.
	How to allow upgrades?	Allow upgrades/part changes .
	How to split the project into two distinct sub-tasks?	Parallel development.

The project of the biomass grinder was originally born to improve the wood pellet manufacturing process [Cascini et al. 2008], trying to introduce a new technology capable to eliminate some shortcomings in the current wood grinding systems which fail when they handle wet raw materials. In order to develop such a system, a design activity was engaged with the aim to develop a prototype of a totally new system for performing experimental activities. The second project concerns the design of an innovative platform to support the devices for performing stratospheric experiments by using probe balloons. The design task was focused on the search of a new solution aimed at reducing flight costs [Boscaleri et al. 2009]. Eventually, the last case study consists in a design activity aimed at developing a pole driver system prototype for excavators heads, capable to preserve the integrity of the wooden poles since in the current systems some problems emerge during the process.

6.2 Results

As shown in Table 3, the set of design problems considered for the investigation are those which, in their formulation, present the possibility to be solved with modularity. In the sample it has been found that 14 out of 18 considered problems were effectively solved with a modular solution. More in detail, and considering that sometimes more than one benefit may be involved in the identification of a modular problem, the outcomes of the test are reported in Figure 3. That graph, developed considering the scoring results, shows the comparison between the occurrence of modularity benefits involved in the identification of modular problems, and the number of times in which the related modular problem was solved with a modular solution.

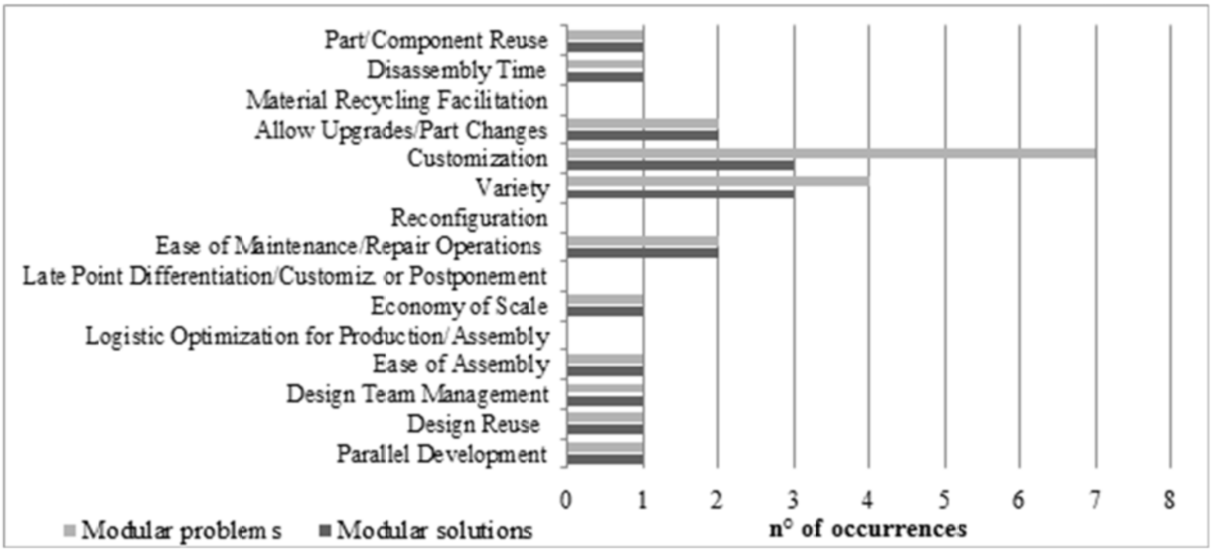


Figure 3. Comparison between the occurrence of modularity benefits used for identification of modular problems, and the number of times in which the related modular problem was solved with a modular solution

Despite the limited amount of data, the results depicted in Figure 3 show the existence of a link between the informal occurrence of modularity and certain types of design problems. However, the way to confirm such a kind of evidences is to consider a more extended sample of design processes. In reference to the scope of the paper, such preliminary results are encouraging and suggest that the proposed method can be used to verify the informal occurrence of modularity during conceptual design and to obtain information to investigate on the mechanisms which lead to this phenomenon.

Moreover, the identification of the modular solutions also allows to highlight the modular characteristics that were the objectives of the solution development. For instance, it has been found that for all the three times where “Customization” and the “Variety” benefits were involved in the identification of the modular problems related to the modular solutions (Figure 3), the “Swapping” interaction type was indicated as the driver that guided the designer. This means that the proposed method also allows to investigate on the existence of a direct relationship between each modularity benefits and specific modular characteristics.

Furthermore, it can be noticed that in four of the eighteen modular problems, none of the modularity characteristics was observed in the adopted solution. In these cases another coincidence can be observed, i.e. the modularity benefit involved in the identification of the modular problems was the “Customization” one (in one case together with “Variety”). What stated above means that the proposed method could also allow to investigate when different types of non-modular solutions can be used as a valid alternative to modular ones.

Looking to the modular solutions of the considered sample, only an half of them presents modularity characteristics belonging to all the three categories. For instance, in the solution of Figure 2 the implemented interface between the rotor plate and the other componets is not decoupled. The analysis of the solutions performed together with the designers during the application of the proposed method highlighted that, a posteriori, the adoption of a decoupled interface would have been preferable. In fact, the interfaces between the rotor plate and the other components were thought only to ensure the correct positioning, neglecting the explicit need to obtain different configurations of the rotor and to allow drastic modifications of the prototype. This is a case in which, because of the lack of a specific support in the concept design phase, the designer attained a wrong or, at least, an incomplete result in the development of a required modular solution. Althought this evidence cannot represent a proof due to the limited number of design process that have been analysed, this kind of outcomes suggest that further researches are needed to develop design methods and tools capable to guide the designer in the identification of suitable modular solutions whereas modular problems arise. However it is worth to notice that in any case, also in presence of a modular problem, modularity has to be considered only as "potential" solution. So the last decision concerning the choice of the best solution must always be performed by considering the set of product requirements.

7. Conclusions and future developments

In this paper, the importance of integrating conceptual design with modularity issues have been introduced. However, despite the potential advantages in defining modularity early in the design process, some limits concerning the applicability of current modularization methods to early concept design phase have been highlighted. Anyway, it has been found that, although informally, modularity arises during the early phases of the design process. Such an evidence leads the authors to investigate about this phenomenon, with the aim to verify the real informal occurrence of modularity in conceptual design processes and to provide an approach to study the mechanism which unconsciously may lead the designer toward modularity. Then, an investigation method has been proposed and tested on a set of three real cases of study. The considered cases consist in already performed design processes where no explicit attempts to manage modularity aspects have been operated.

Results of the performed test have been reported and potentialities of the proposed investigation method have been discussed. More in particular, the possibility to investigate on further details related to the definition of modular solutions arose.

The experimental activity has suggested important hints for future developments. Indeed, it has been highlighted that in order to differentiate modular problems from non-modular ones, the design process has to be represented in terms of problems and related solutions. In this way, a structured approach to analyse the design process allows the application of the proposed investigation method to a statistically relevant set of case studies.

References

Akay, D., Kulak, O., Henson B., "Conceptual design evaluation using interval type-2 fuzzy information axiom", Computers in Industry, vol. 62, no. 2, 2011, pp. 138–146.

Borjesson, F., "A Systematic Qualitative Comparison of Five Approaches to Modularity", International Design Conference, 2010, Dubrovnik - Croatia, pp. 147-156.

Boscaleri, A., Castagnoli, F., Rissone, P., Corti, M., "Stratobus: A Multiuser Platform System for Making access to LDB Flight Easier and Cheaper", Proceedings of 19th Symposium on European Rocket and Balloon Programmes and Relates Research, ESA-SP-671, 2009, pp. 209-213.

Cascini, G., Rissone, P., Rotini, F., "Business re-engineering through the integration of methods and tools for process innovation", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 222:12, 2008, pp. 1715-1728.

Daniilidis, C., Enßlin, V., Eben, K., Lindemann, U., "A Classification Framework for Product Modularization Methods", International Conference on Engineering Design, ICED11, Technical University of Denmark, 2011.

De Weck, O., Hölttä-Otto, K., "Tradeoff Between modularity and performance for engineered systems and product", International Conference on Engineering Design ICED 05, Melbourne, 2005.

Eppinger, S. D., Browning, T. R., "Design Structure Matrix Methods and Applications", MIT Press, 2012.

Ericsson, A., Erixon, G., "Controlling Design Variants. Modular Product Platform", Society of Manufacturing Engineers, Michigan, 1999.

Fixson, S. K., "The Multiple Faces of Modularity. A Literature Analysis of Product Concept for Assembled Hardware Products", Technical Report 03-05. Industrial and Operation Engineering. University of Michigan, June 2003.

Gershenson, J. K., Prasad, G. J., Zhang, Y., "Product modularity: Definitions and benefit", Journal of Engineering Design, Vol. 14:3, 2003, pp. 295-313.

Graedel, T. E., Allenby, B. R., "Industrial Ecology", Englewood Cliffs, Prentice Hall, New Jersey, 1995.

Gu, P., Sosale, S., "Product modularization for life cycle engineering", Robotic and Computer Integrated Manufacturing, vol. 15, 1999.

Hölttä-Otto, K., "Modular Product Platform Design", Doctoral Dissertation, Helsinki University of Technology, 2005.

Hölttä-Otto, K., De Weck, O., "Degree of Modularity in Engineering Systems and Products with Technical and Business Constraints", Concurr. Eng., vol. 15, no. 2, 2007, pp. 113–126.

Huang, C. C., "Overview of Modular Product Development", Proc. of the Natl. Sci. Counc., Republic of China, vol. 24, no. 3, 2000, pp. 149-165.

Khomenko, N., De Guio, R., Lelait, L., Kaikov, I., "A framework for OTSM TRIZ-based computer support to be used in complex problem management", International Journal of Computer Applications in Technology Vol 30, Issue ½, 2007.

Krause, D., Eilmus, S., "A Methodical Approach For Developing Modular Product Families", International Conference on Engineering Design, ICED 11 Stockholm, 2011.

Newcomb, P. J., Bras, B., Rosen, D. W., "Implications Of Modularity On Product Design For The Life Cycle", ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, California, 1996, pp. 1–12.

Pahl, G., Beitz, W., "Engineering Design", 3rd ed., Springer-Verlag, London, 2007.

Salvador, F., "Toward a Product System Modularity Construct : Literature Review and Reconceptualization", IEEE Trans. Eng. Manag., vol. 54, no. 2, 2007, pp. 219–240.

Salvador, F., Forza, C., Rungtusanatham, M., "Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions", Journal of Operation Management", vol. 20, no. 5, 2002, pp. 549–575.

Stock, M. E., Bohm, M. R., Stone, R. B., Hubing, N. E., "Using Product Architecture-Based Design Methods to get smart in the battlefield", International Conference on Engineering Design. ICED 03 Stockholm, August 19-21, 2003.

Stone, R. B., "Towards a Theory of Modular Design", Doctoral Dissertation. Faculty of the Graduate School of the University of Texas at Austin, 1997.

Stone, R. B., Wood, K. L., Crawford, R. H., "A heuristic method for identifying modules for product architectures", Design Studies, Vol. 21, Issue 1, 2000, pp. 5-31.

Ulrich, K. T., Eppinger, S. D., "Product Design and Development", 4th ed. McGraw-Hill, Irwin, 2007.

Ulrich, K., "The role of product architecture in the manufacturing firm", Research Policy, Vol. 24, no. 3, 1995, pp. 419-440.

Ulrich, K., Tung, K., "Fundamentals of product modularity", Proceedings of the 1991 ASME Design Engineering Technical Conferences—Conference on Design/Manufacture Integration, Miami, FL, 1991.

Van Wie, M. J., Greer, J. L., Campbell, M. I., Stone, R. B., Wood, K. L., "Interfaces and Product Architecture", ASME Design Engineering Technical Conference Proceedings, DETC01/DTM. Vol. 21689, 2001.

Eng. Lorenzo Fiorineschi, Research assistant
Università degli Studi di Firenze, Industrial Engineering Department
Via Santa Marta, Firenze, Italy
Telephone: +39 055 4796 514
Telefax: +39 055 4796 525
Email: lorenzo.fiorineschi@unifi.it
URL: http://www.dief.unifi.it