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CONCEIVING MODULAR SOLUTIONS IN EARLY CONCEPTUAL DESIGN ACTIVITIES

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Abstract

Literature acknowledges modular architectures to give rise to a series of positive effects, and advantages given by considering modularity early in the design process have also been inferred. As a matter of the fact, many attempts have been made to develop modularization methods and tools. However such methods mainly support redesign tasks focused on modifying the architecture of an existing solution, i.e. operate only after, at least, a preliminary conceptual design process. Anyway, it is well acknowledged that product success is strongly influenced by the quality of the underlying concept. Such an observation leaded the authors of this paper towards a research activity aimed at the development of new design tools, for supporting the designer in facing modularity issues during the conceptual design phase. In particular, the present paper shows some preliminary results concerning the development of a new design approach capable of taking into account modularity issues since early concept generation activities.

Keywords: Modularity, Product architecture, Conceptual design, Design methods

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1 INTRODUCTION

During the last two decades, many contributions concerning product modularity have been written, including literature reviews dedicated to the comparison and classification of existing definitions and methods. Such an interest of engineering design scholars is motivated by the common assumption that, despite some not negligible detrimental effects, modularity gives rise to several benefits (e.g. Gershenson et al. 2003). More precisely, these benefits leads to the reduction of costs involved in design, production, and retirement product life cycle phases.

Many attempts have been made to develop modularization methods and tools, and a careful literature analysis has revealed that three main approaches may be considered as the most representative of the current state of the art, since they are well acknowledged in academia and have been successfully tested through industrial case studies. However, such methods mainly support redesign tasks focussed on modifying the architecture of an existing solution that, therefore, represents the starting point of the design activity (Fiorineschi et al. 2014a). Such a peculiarity implies that the positive effects of modularity can be fully exploited only by considering a further step in the design process, i.e. the modularization. It means that, in case of new product design activities, when conceiving conceptual solutions it can be very hard to foresee if the adoption of a specific working principle can be detrimental for future modularizations. Anyway, it is acknowledged that the starting concept strongly influences product success. Starting from this observation, the aim of the work performed by authors arises, which consists in the development of a new design approach capable of taking into account modularity issues since early concept generation. In particular, this paper presents a first version thought for non-structured conceptual design activities.

The content is organized as described in the following. The relationship between conceptual design and current modularization methods is shortly described in Section 2, while the new proposal is presented in Section 3. Section 4 is dedicated to the description of the test performed to evaluate the proposed approach. Section 5 reports an analysis of the most relevant results and introduces final remarks and future developments. Eventually, Section 6 is dedicated to the conclusions.

2 ABOUT MODULARIZATION APPROACHES AND THEIR RELATIONSHIP WITH CONCEPTUAL DESIGN TASKS

Several attempts can be found in literature to develop methods for supporting the designer in reorganizing the product architecture towards modular configurations. However, the Design Structure Matrix (DSM) (Eppinger and Browning, 2012), the Modular Function Deployment (MFD) (Ericsson and Erixon, 1999) and the Function Structure Heuristics (FSH) (Stone et al. 2000) can be considered as the representative sample of the most acknowledged methodologies for product modularization (Borjesson, 2010), (Daniilidis et al., 2011). In this section, due to space limits, only a short introduction on the above mentioned approaches is reported, together with some considerations about their relationships with the conceptual design phase (as defined in Pahl et al. 2007). However, the reader can find a more comprehensive analysis of the three methods in Fiorineschi et al. (2014a).

2.1 Methods based on the Design Structure Matrix

One of the possible DSM typology, i.e. the so called Component-Based DSM, is used to manage the modularization of products thanks to its capability to reorganize the architecture by using matrix manipulation algorithms. This type of DSM is also called “Product Architecture DSM” (Eppinger and Browning, 2012). The application of the method generally starts from the decomposition of an existent system, in order to identify elements and then to form the starting matrices. It is evident that, at least, a reference product concept is required, then these methods can be used only after a preliminary design activity devoted at creating system elements. Therefore, since DSM-based modularization methods use a component-based analysis of the product architecture, they cannot be used in early concept design phase, due to the lack of information regarding the system structure (Daniilidis et al., 2011).

2.2 Function Structure Heuristics

The FSH method (Stone et al. 2000) is constituted by five steps, i.e. “gather customer needs”, “derive functional model”, “identify product architecture”, “generate modular concepts” and finally “embody design”. The second and third steps are the main contributions of the method, where the functional structure of the system forms the starting point of the module identification, and three heuristics have been developed in order to find modules operating on such a functional structure. More precisely, the functionalities of the product are modelled by means of the Energy-Material-Signal model (Pahl and Beitz, 2007).

Then it is possible to assert that the core of the FSH method is based on the achievement of a comprehensive functional model of the product in order to apply the three heuristics and to find module concepts (Stone et al., 2000). In other words it means that the method can be applied only after a first concept generation step whose outcome is a representation of the product, at least, in terms of functions.

2.3 Modular Function Deployment

MFD has been developed by (Erixon and Ericsson, 1999) and is a structured method developed to find the optimal modular product design, taking into considerations company's specific needs. In the first step, customer needs are linked to product properties; then, in step two, functions are identified and corresponding technical solutions are selected. In step three the previously selected technical solutions are investigated so as to evaluate their possibility to form a module. The last two steps are dedicated respectively to the generation of module concepts and to the preparation of technical document to be used for the improvement of modules.

As for FSH, MFD is based on a comprehensive function modelling of the system which has to be modularized. As explicitly reported in the step two of the method, in order to operate the functional decomposition, it is fundamental to know the technical solutions adopted for the function implementation. Then, it is possible to assert that the method is best suited for a redesign of an existent product.

2.4 General considerations

According to the brief survey above presented, modularization methods cannot manage issues related to the definition and choice of the working principles (or the behaviour) of a system, because they have been thought only for rearranging functions and/or structures of existent solutions. This kind of general approach is surely useful and the considered methods have been successfully tested in that sense. However, it is possible to claim that in this way the outcomes of the design activity are strongly influenced by the solutions which constitute the original product concept. In other words, if on the one hand the current modularization methods are capable of modifying the architecture of products, on the other hand the two following considerations can be expressed:

- Currently, there is the need of a further design step in order to reach the desired product architecture in a structured manner, since modularization methods require, at least, a functional representation of the product as input.
- According to Ulrich and Eppinger (2007), the success of a product is heavily influenced by the quality of the underlying concept. Then, starting from a poor concept, it can be very hard to achieve product success only through subsequent manipulations of its architecture.

Here, the main objective of the research activity arises, i.e. defining an alternative approach to be used in the early concept design phases, for supporting the designer in achieving the optimal product architecture.

3 FUNDAMENTALS OF THE PROPOSED APPROACH

In order to achieve the objective introduced in Section 2, the authors developed an approach aimed at individuating the opportunity of using modularity as well as supporting the designer in using it, even in early concept generation activities. The proposal can be summarized into two main parts:

- Identification of modularity needs.
- Support in generating modular solutions for each identified modularity need.

In this section, a detailed description of the two parts is reported.

3.1 Identification of modularity needs

The first part of the proposal takes inspiration by the benefits attributed to modularity, which have been highlighted by several literature contributions, e.g. Gershenson et al. (2003). A list of fifteen

benefits, grouped according to the main product life-cycle phases, is reported in Fiorineschi et al. (2014a, 2014b) while an excerpt of it is reported in Table 1.
More in particular, the recalled benefits are considered here as potential instruments to be used in order to better satisfy the fulfilment of specific design requirements through modularity. For instance, considering a requirement concerning the lowering of the product manufacturing costs, the "Economy of Scale" and/or the "Logistic optimization for production/assembly" benefits, (see Table 1), can give a potential help. Since these benefits are associated to modularity, it means that in order to fulfil the specific requirement, the use of modular solutions has to be, at least, considered.
It is worth of notice that, for identifying relationships between requirements and modularity benefits, it is sufficient to analyse the requirement list, thus this task can be performed even before to start generating concept ideas.

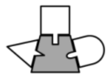
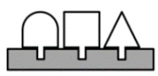
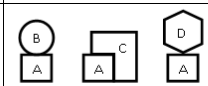
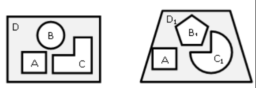
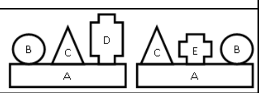
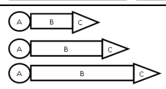
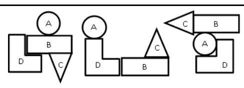
Table 1. Excerpt of the Modularity Benefits listed in Fiorineschi et al (2014a, 2014b).

BENEFITS	DESCRITPION
Logistic Optimization for Production/Assembly	The opportunity to optimize the production process from a logistical point of view.
Economy of Scale	Possibility to use standardization to reduce the cost of the components.
Reconfiguration/Flexibility in Use	The possibility to add or modify functionalities of the product
Variety	The possibility to obtain different product models with a set of standardized parts.
Customization	The possibility to obtain different product models by means of customized parts.

3.2 Generating modular solutions

Once the opportunity to use modularity has been identified through the logic introduced above, the designer should conceive befitting modular solutions. The procedure introduced in the following aims at giving a support for performing this activity, and takes inspiration from the literature contributions concerning the classification of modularity types (Table 2).

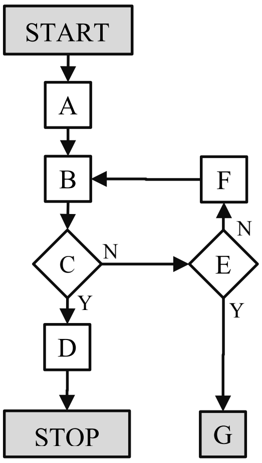
Table 2. Modular characteristics (Fiorineschi et al. 2014b)

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

The considered modularity types are those reported in Table 2, and they are grouped by the following criteria:

- Interfaces types of the modules. Describing the characteristics of the connectivity among components of the system.
- Interactions within the system. Describing how the modules are matched together in order to form the system.
- Supply type of modules. Describing the way by which the components of the systems are provided.

A similar classification has been done also by (Salvador et al. 2002) where the modularity types are almost the same here described, but with some differences regarding the way they are clustered.
Table 2 is then used as a sort of design catalogue in order to inspire the designer during the development of the concept. More precisely, for each design requirement in relationship with one or more modularity benefits, the designer is asked to follow the roadmap of activities described in Fig. 1.



A	Select a group of modularity type.
B	Consider one of the possible type variants belonging to the same grouping criterion (Table 2).
C	Does the modularity type variant inspires any idea?
D	Conceive solution details concerning the other two modularity groups by considering related standard type variants.
E	All the three modularity groups have been already considered for generating the solution?
F	Select one of the remaining modularity groups.
G	Proceed without considering modularity for this requirement.

Figure 1. Logic of the experimental modular solution generation process to be followed for each requirement of the design task.

4 PERFORMING THE TEST

The test was aimed at evaluating the proposed approach, in particular concerning the generation of modular solutions. The test consisted in administering a case study regarding the design of a product starting from a limited set of given requirements, to a sample of convenience composed by eighty-two engineering students. The expected outcome was the sketch of a solution and a short description of it.
The considered sample of student was randomly subdivided into the following two groups:

- Analysis Group (AG). Formed by forty students equipped by a specific material developed to support them in using the proposed approach.
- Control Group (CG). Formed by forty-two students, leaved completely free in the development of the concept. Such a group constitutes a reference in order to evaluate if the developed approach, used by the AG group, is capable of generating impacting results in terms of modularity.

A common case study has been assigned to both the groups, concerning the concept development of a multifunctional and customizable pen. More precisely, the functionalities to be implemented were the pencil, the pen and the eraser. Two main requirements, i.e. "multifunction" and "customization", have been considered since they can be linked to the modularity benefits. Indeed, the fulfilment of the "multifunction" requirement can take advantage by modularity, as expressed by the "Reconfiguration/Flexibility in use" benefit introduced in Table 1. Similarly, the "customization" requirement is linked to modularity thanks to the "Customization" and "Variety" benefits.
Besides the recalled requirements, further specifications have been furnished in order to better frame the design task. For what concerns the class of the product, an intermediate level from medium to luxury pens has been given as a reference and, moreover, concerning the "ease of use", the

manoeuvrability of standard pens and the absence of additional tools for using it, were given as expected characteristics of the final product.
Eventually, the students involved in the test were not learned about any type of systematic conceptual design process as well as they didn't receive any training about modularity before.
Here in the following, detailed descriptions are reported about the supporting material given to the AG and the metrics used to validate the results.

4.1 Supporting material for the analysis group

As CG, also AG was equipped with a description of the two main requirements and a description of the form through which the results were expected to be delivered. Also a pre-printed sheet to be used for drafting and describing the solution was distributed to each student of the two groups.
However, since the AG was supposed to follow the proposed approach for the fulfilment of the two main requirements, additional instructions were furnished. More precisely, authors delivered the following set of information and supporting material:

- Explicit request to AG of following the approach to fulfil the two main requirements. In order to ascertain that students followed the approach, they were also asked to indicate how they used the modularity types in order to fulfil the two main requirements.
- Detailed instructions for a correct use of the process shown in Figure 1.
- Three tables containing simplified descriptions and generic examples of each modularity type (Table 3 shows one of the examples in the table concerning the "interface" modularity group).

Table 3. Two of the generic examples reported in the modularity tables furnished to the AG.

Sectional modularity	Modules can be connected each other by mean of the same interface.	
Bus modularity	All modules have the same interface with a bus component.	

4.2 Evaluation of the concepts

The outcomes of the test, for both AG and CG, were assessed according to the following criteria:

- Degree of fulfilment of the two main requirements to assess how much the concept matches the design task.
- Degree of feasibility and/or usability of the solutions, to purge the results of unfeasible and/or unusable solutions.
- Modularity level to assess modularity of the concepts, and evaluate the impact of the approach.

The generated solutions have been ranked through a score assigned according to the level of satisfaction of each criterion. In the following subsections the above introduced criteria are described in detail.

4.2.1 Fulfilment of the two main requirements

In order to evaluate how much the concepts fulfil the main requirements, two specific metrics have been formulated (Table 4). By means of them, authors aimed at ranking the generated concepts and verifying the hypothesis performed in section 3.1 and, thus, the reliability of the approach. Indeed, by observing the relationship between modularity level and degree of fulfilment of the main requirement, it is possible to observe the existent link (if any) between modularity and related benefits.

4.2.2 Feasibility and usability of the concepts

Due to the limited time available for the test and the skill of the involved students, authors foresee the possibility to obtain conceptual solutions affected by feasibility or usability problems. For this reason, a specific metric has been developed in order to rank the generated concepts in terms of their potential feasibility and ease of use. A rough scale composed by three levels has been considered in order to rank the concepts, i.e. not feasible (score = 1), existence of some doubts concerning feasibility or usability (score = 2), no feasibility or usability problems detected (score = 3).

Table 4. Metrics and score (S) used to evaluate the fulfilment of the two main requirements

S	Multifunction	Customization
4	Possibility to use the three functions without any need of assembly or disassembly	Possibility to completely change the aspect by changing also specific aesthetic components
3	Possibility to implement only two functions concurrently. The third function obtainable as alternative of one of the others, by means of single connection or disconnection.	Possibility to completely change the aspect by changing components aimed at implementing the three functions, by means of a simple connection or disconnection.
2	Possibility to implement only two functions concurrently. The third function obtainable as alternative of one of the others, by means of more complex operations.	Possibility to partially (completely) change the aspect by changing components aimed at implementing the three functions, by means of a simple connection or disconnection (by mean of complex operations).
1	Not possible to implement Eraser and Pencil concurrently.	Not possible to change the aspect of the system

4.2.3 Modularity level of the concepts

This metric aims at assessing the modularity level of the solutions developed by the students through the observation of the sketches representing the structure of the generated concept.

Many definitions of modularity can be found in literature, belonging to different engineering domains and based on different perspectives (Salvador, 2007). Some of these definitions may differ when using terms like, module, chunk, component and element. Then, in order to avoid ambiguity and to 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 and which is identifiable with the modularity definitions given in Section 3.

Literature offers many types of modularity metrics (Hölttä-otto et al., 2012), however many of them consider a number of details that are not available in the concept sketches produced by the students.

For such a reason, an elementary measure has been considered for assessing the levels of modularity of the outcomes and ranking them. More precisely, one of the two metrics proposed by Mattson and Magleby (2001), as reported by Hölttä-otto et al. (2012), has been taken into account. In particular, only the number of functions and modules are considered to assess modularity:

$$\text{Modularity} = \frac{\text{number of modules}}{\text{number of functions}} \tag{1}$$

Taking (1) as reference, the following three levels of modularity have been formulated for the specific case study of the test:

- The pen, the pencil and the eraser functionalities are implemented by components that cannot be used independently from the rest of the system (score = 1).
- Only one of the three requested functions is implemented by a component that can be used independently from the whole system (score = 2).
- All the three requested functions are implemented by distinct components that can be used independently from the rest of the system (score = 3).

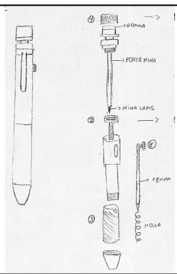
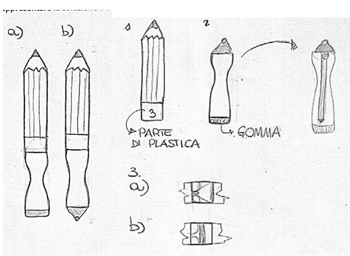
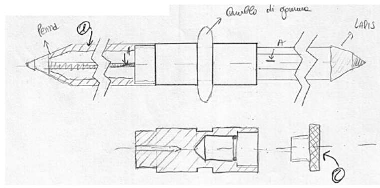
The above mentioned metric is intended to be applied considering the whole product as the "System".

5 ANALYSIS OF THE RESULTS

An evaluation is shown here in the following about the concepts produced by students belonging to both the groups, according to the above described criteria.

Concepts ranked as "unfeasible" have been discarded, reducing the sample from eighty-two to fifty-eight persons (thirty-one for the control group and twenty-seven for the analysis group). Such a not negligible reduction is probably due to the limited time available for the test and to the level of expertise characterizing the sample, i.e. beginners. Three examples of solutions conceived by students, independently from the group, are shown in Table 5. In addition to sketches, students produced a written description of each concept, by means of which the scores have been assigned. However, it is not possible to report these details in the paper, due to length limits.

Table 5. Three examples of concepts and the related scores

Sketches of the concepts			
Modularity	1	2	3
Feasibility	2	3	3
Multifunction	4	3	4
Customization	2	3	4

5.1 Effect of the proposed approach on the concept modularity level

By comparing the scores assigned to the concepts belonging to the CG and the AG, a not negligible difference arises. Indeed, considering the mean values obtained for each group, the AG is characterized by a higher score (+16,8%). Such a value is even doubled if only concepts characterized by the highest level of feasibility are considered (+33%). However, it is worth of notice that if considering only such a level, the sample is reduced to fifteen and twelve people, respectively for the CG and the AG.
In order to evaluate the statistical reliability of the observed difference, a two-sample t-test (Sheskin 2003) has been executed on the modularity mean values of the two groups.
In the first case (feasibility levels 2 and 3) comparing the modularity mean values of AG and CG leads to a p-value of 0,076. Instead, if repeating the t-test by considering only most feasible solutions (feasibility level 3), the p-value becomes 0,005. Considering a reference p-value of 0,05 to accept the alternative hypothesis, it is possible to observe that in the first case the p-value is slightly out of limits, but it only means that the null hypothesis (mean values are equal) can be discarded only with a slightly higher uncertainty value. Differently, in the second case the difference between the two mean values is validated by the test with a confidence level of almost one hundred percent.
The difference between the two groups in terms of modularity of the concepts can be considered a first evidence of a not negligible effect of the proposed approach.

5.2 Link between modularity and the two considered benefits

Considering only the fulfilment of the main requirements, it is not possible to find significant differences between the mean values of the AG and the CG. However, also CG students develop modular concepts, confirming that modularity may arise informally during the conceptual design phase (Ulrich and Eppinger, 2007).
Here in the following, the effect of modularity on the satisfaction of the main requirements is evaluated on the whole sample, i.e. composed by AG and CG together, and on AG and CG separately. First of all, Chi-squared (X^2) tests of independence (Sheskin 2003) has been performed on modularity against the satisfaction level of the two main requirements. Such a kind of test is capable to assess the probability of association (or independence) of two variables, analysed through the considered sample of data. The critical X^2 has been obtained for the degrees of freedom characterizing the variables (six), and a probability level of 0,05. If the X^2 calculated for two variables is lower than the critical X^2, then it is not possible to reject the null hypothesis, i.e. the absence of any relationship. On the contrary, if the calculated X^2 is higher than the critical one, it is possible to assert that a relationship between the two variables exists. Table 6 shows the results of the test performed between modularity and the satisfaction level of the two requirements. It is possible to observe that both the two variables are related to modularity when considering the whole sample.

Instead, considering the groups separately, it has not been possible to reject the null hypothesis for modularity vs customization.

Table 6. Results of the X^2 independence tests performed on the sample

TEST	X^2 (AG+CG)	X^2 for AG	X^2 for CG	Critical X^2
Modularity VS Multifunction	32,56	18,32	14,57	12,59
Modularity VS Customization	13,49	12,45	3,34	

However, even when it is possible to observe a relationship with modularity, the X^2 test does not highlight how the variables are interrelated. In order to estimate the trend, the mean values of each of the two variables have been calculated for each modularity level. Results are shown in Figures 2 and 3, respectively for the whole sample and the separated groups. In Figure 2 it is possible to observe different behaviours of the requirements satisfaction in relation to the considered modularity level of concepts. Moreover, for what concerns modularity vs multifunction, a difference can be observed also between the two groups (Figure 3). The reason of such a difference is not clear, however, the presence of concepts characterized by an intermediate level of feasibility may introduce some noise. However, it should be observed that if only the best concepts in terms of feasibility (level 3) are considered, two not negligible problems arise, i.e. the previously mentioned reduction of the sample, and the absence of data at the lowest level of modularity for the AG. For that reasons, such an incomplete set of results has not been considered here.

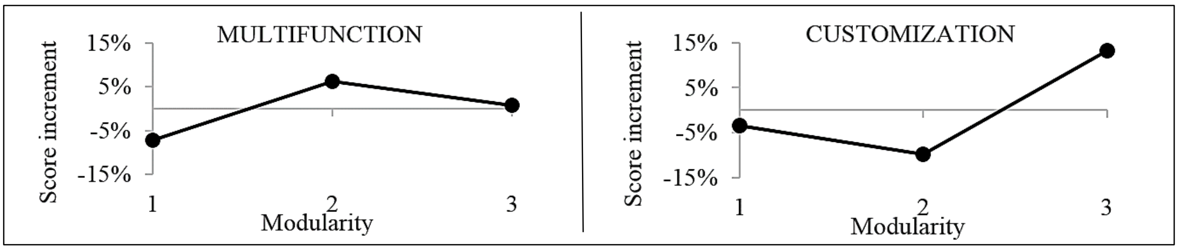


Figure 2. Influence of modularity on the main requirements satisfaction. The values represent the difference among mean scores calculated for concepts characterized by specific modularity levels, and the global mean scores, i.e. 2,78 for Multifunction and 2,34 for Customization.

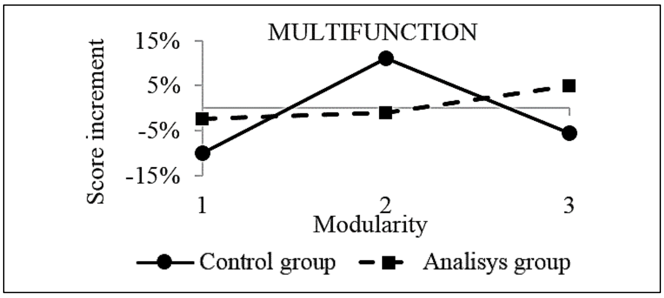


Figure 3. Differences observed between the AG and the CG, about the influence of modularity on the Multifunction requirement satisfaction. As for Figure 2, the global mean scores are 2,78 for Multifunction and 2,34 for Customization.

5.3 Final considerations about results

The results presented in this section substantially show that the proposed experimental approach is capable of producing a not negligible effect in terms of modularity level of the concepts. Moreover, the evaluation of the effect of modularity on the main requirements satisfaction confirms the existence of a relationship between modularity and the considered benefits; however more data are needed to understand the real trend, which seems to be not linear. Nevertheless, such possibility is in accordance with similar observations performed by other scholars (Collado-ruiz and Capuz-rizo, 2013).
Thanks to these promising results, this first experience constitutes a basis for future research activities devoted to the development of an upgraded version of the proposed approach to be integrated in structured conceptual design processes.

6 CONCLUSIONS

One of the common peculiarities of the most acknowledged modularization methods is the practical impossibility to be used before of a preliminary concept design, performed at least in terms of functions.

In order to fill such a gap, authors propose an approach capable of identifying potential opportunities to employ modular solutions, and to give support in their conception since early creative design activities. A first version for non-structured conceptual design processes has been tested on a sample of eighty-two engineering students, which has been randomly subdivided in an Analysis Group, and a Control one. In order to evaluate the impact of the method, students were asked to conceive a conceptual solution for a specific case study. Moreover, a set of metrics has been formulated for the analysis of results. Obtained results show a not negligible effect of the proposed approach in terms of modularity level of generated concepts. In addition, also the effect of modularity level on requirements satisfaction has been evaluated. Such an observation confirms the existence of a relationship between modularity and benefits, whose real trend can be difficult to assess, which however seems to be not linear.

For what concerns future developments of the work, the obtained results partially confirm the applicability of the proposal on conceptual design activities, and then it forms the basis for the development of a more structured version of the approach.

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