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A PRELIMINARY PROPOSAL TOWARDS UNAMBIGUOUS DEFINITIONS FOR MODULAR INTERFACES AND INTERACTIONS

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ABSTRACT

Modularity is acknowledged to provide benefits across the whole product lifecycle. Accordingly, many literature contributions can be found about modularization methods, metrics and definitions. In particular, recent studies focused on the development of heuristic principles for exploiting modularity early in the design process. However, to design modules it is necessary to define their mutual interactions, the related interfaces and their production strategies. Concerning interfaces and interactions, this paper highlights that current definitions are often ambiguous and overlapping each other. Therefore, extracting univocal information about interfaces and interactions of existent modular products could be difficult. This could hinder the identification of comprehensive heuristic design guidelines, about how to design modules from a structural point of view. This paper proposes a new set of interface and interaction definitions, which allows to overcome the flaw observed for current ones. The proposed set and the classical one have been applied on 110 products identified on the web, showing that the new definitions allow to extract more reliable information.

Keywords: Modularity, Product architecture, Early design phases, Conceptual design, Modular design

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1 INTRODUCTION

The potential benefits that modular architectures can bring to the whole product life-cycle make them one of the most important arguments in the field of product design. Accordingly, many research works have been produced, among which, the methodological contributions aimed at supporting the designer in reorganizing the product architecture towards optimal modular configurations (Greve and Krause, 2018). Moreover, a variety of contributions have been proposed for assessing the modularity degree of products (e.g. Chiriac *et al*. (2011), Heilemann *et al*. (2013), Hölttä-otto *et al*. (2012), Holtta-Otto and De Weck (2007)).

Nevertheless, understanding when and how to adopt modularity still is a non-trivial task, especially in early design phases. Indeed, while modularization methods provide a comprehensive support in reorganizing the architecture of existing (or partially designed) products, it can be difficult to identify earlier opportunities to exploit modularity. More precisely, methodological contributions about heuristic approaches have been proposed in literature (Niutanen and Otto, 2017) but the identification or the suggestions of suitable interfaces and interactions among modules is not comprehensively supported in conceptual design phases. However, to exploit modularity it is necessary to implement it in specific ways, which imply the selection of certain interfaces, interactions and production strategies. Unfortunately, the definitions of modular interfaces and interactions currently available in literature are often overlapping each other, leading to ambiguous representations of the actual modular architecture. Therefore, any attempt to provide a systematic support for the identification of the preferred interface-interaction configuration is hindered.

The aim of this paper is to propose a new set of definitions, which allows to identify and univocally represent any possible modular architecture in terms of interface and interactions among modules. The expected benefits from this new set, include the possibility to retrieve information from existing products, in order (for example) to extract heuristic indications about preferred interfaces and interaction among modules. Both the classical and the new sets of definitions have been applied on a sample of 110 products, whose (partial) information has been extracted mainly from the World Wide Web, with the aim of comparing the assessments performed by two different evaluators in terms of inter-rater agreement.

The paper contents are structured as follows. Section 2 reports a brief description of the fundamental definitions considered in this paper. In Section 3, the new set of definitions is introduced and compared with the classical ones to show how classical definitions can be univocally represented by means of the new proposed set. Section 4 reports a preliminary comparison between the new set and the old set, while Discussions are reported in Section 5, introducing potential future research hints and practical implications. Eventually, Conclusions are reported in the last section.

2 BACKGROUND

2.1 Modules

Concerning the meaning of the term "module", different definitions exist in literature (e.g. Campagnolo and Camuffo,2009; Fixson, 2007; Gershenson *et al*., 2003; Salvador, 2007). Some of them focus the attention on functional aspects (e.g. "function units" or "building blocks" (Pahl *et al*., 2007)), while some others also consider structural aspects (Allen and Carlson-Skalak, 1998). Unfortunately, the meaning of the term "function" is far to be standardized (Eckert, 2013; Eckert *et al*., 2011; Eisenbart *et al*., 2013; Vermaas and Eckert, 2013). Consequently, the identification of modules in existent products needs detailed and high quality information, and is affected by ambiguous definitions of the interaction among function carriers (Bonvoisin *et al*., 2016).

For the scope of this work, where only partial information about products is available, modules are identified by considering only pure structural aspects. More precisely, modules are considered here as particular components or assemblies, showing the following characteristics:

- Easily separable and re-combinable to the rest of the system (Cabigiosu *et al*., 2013)
- Self-contained and isolable (Cabigiosu *et al*., 2013)
- Once interfaces are identified, can be designed and developed independently but must be connected to the rest of the system for implementing their functions completely (Baldwin and Clark, 2006).

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For instance, by following the above mentioned indications, a drill bit is considered here as a module because it is a component of the system "driller", it can be easily disconnected and reconnected, it is self-contained and isolable, but it must be connected to the driller to exploit its unique function, i.e. removing material.

2.2 Granularity levels

The considered level of granularity, i.e. the decomposition depth at which the system is analysed, is an important parameter to identify the product's architecture, and then its modules. Indeed, the same product may show different modularity traits at different levels of granularity (Chiriac *et al*., 2011) and then, it is possible to infer that different modular configurations can be observed at different decomposition levels. Some approaches to deal with "granularity levels" have been proposed in literature (Maier *et al*., 2016). However, due to the limited information available for the set of products considered in this work (see Section 4), we refer here to the following elementary recursive model for the identification of the decomposition levels (Fiorineschi *et al*., 2014):

- System: Any part or assembly belonging to a determined level of granularity may falls under this definition. At the highest level, the system corresponds to the product.
- Component: With this term, any physical element is identified, intended as single part or assembly that constitutes the system at the succeeding level of granularity.

Moreover, a component can be identified as "module" if it owns the characteristics listed in Section 2.1.

2.3 Current modularity definitions based on structural aspects

By focusing the attention on structural aspects, it is possible to find well-known modularity definitions focused on the physical configuration of modules, i.e. their structural characteristics and the way they interact each other (Salvador *et al*., 2002). For the scope of this paper, we cluster the recalled definitions under three main categories:

- Interfaces of the modules. Describing the connectivity among the 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 how standard components might interact with customized ones.

The recalled framework has been used here to list the most acknowledged definitions of modularity types (Table 1).

In some cases, the same product, at the same granularity level may show different interaction types, depending on the problem solved by modularity. More precisely, Component Swapping and Component Sharing cannot be distinguished only by observing structural product characteristics but it is fundamental to know how modules are used, i.e. which is the design problem solved by modularity. However, besides this particular but correct distinction, the available modularity types (Table 1) are sometimes overlapping and/or ambiguous, thus neglecting the univocal identification of "how" modularity has been applied.

A first minor issue can be identified if considering the "Sectional" modular interface (see Table 1), where, quoting (Ulrich, 1995): "… all interfaces are of the same type and there is no single element to which all the other components attach". In this definition, not only information about interface is provided, but also the interaction is specified. Accordingly, Salvador *et al*. (2002) split the definition in two parts, both under the name of Sectional modularity, but other cases exist where the same interface type is used across modules, even if the sectional interaction is not involved. One of the most evident example is that related to the "Bus" modularity, where modules are connected to a bus via identical interfaces. Even in this case, two different definitions are considered for interfaces and interactions, i.e. one for interfaces (Ulrich, 1995) and one for interactions (Ulrich and Tung, 1991). However, the original interface definition of Ulrich (1995) reports: "there is a common bus where the other physical components connect via the same type of interface". Therefore, the same definition provides both interface and interaction information, partially overlapping the second "Bus" definition, which concerns interactions only. Moreover, Salvador *et al*. (2002) consider the "Bus" interaction modularity type as a special case of the Sectional "interface" definition, where the interaction information makes the difference. Therefore, if considering an architecture composed by a bus element where other modules are connected through identical interfaces, both, Bus and Sectional types could theoretically be selected for identifying the modular configuration.

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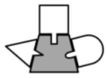
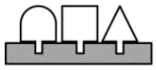
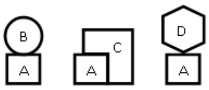
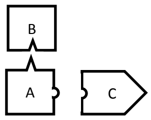
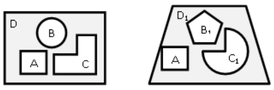
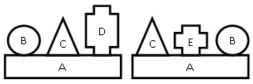
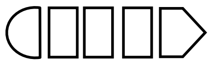
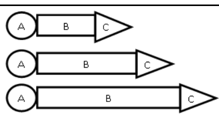
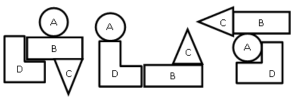
Salvador *et al*. (2002) also introduced the "Combinatorial" modularity type as an extension of the well-known "Component-Swapping". Accordingly, it is possible to infer that "Combinatorial" modularity belongs to the interaction category, as acknowledged for the "Component-Swapping". However, the definition of "Combinatorial" modularity is strictly related to interface aspects, because components (or modules) variants can be interchanged only within the same component families that, by definition, have specific different interfaces. Consequently, "Combinatorial" interaction type is implicitly linked to the "Slot" interface type of Table 1.

Table 1. Current modularity types

Group	Short description	Schematic representation
Interface type	**Slot Modularity** (Ulrich 1995): all the interfaces between different components are of different type.	
	Bus Modularity 'a' (Ulrich 1995): it is possible to individuate a common bus that connects other components by the same type of interface.	
	Sectional Modularity 'a' (Salvador *et al*., 2002): all the interfaces between different components are of the same type.	
Interaction type	**Component-swapping Modularity** (Ulrich and Tung 1991): two or more components can be interchanged in a system in order to create product variants.	
	Combinatorial Modularity (Salvador *et al*., 2002): each module belongs to a specific component family and have a specific set of interfaces. Component variants can be interchanged only with those belonging to the same family.	
	Component-sharing Modularity (Ulrich and Tung 1991): two or more systems share the same basic component in order to provide product variants.	
	Bus Modularity 'b' (Ulrich and Tung 1991): where a component can be matched with any number of other basic components.	
	Sectional Modularity 'b' (Salvador *et al*., 2002): product variants are obtained by mixing and matching in an arbitrary way a set of components as long as they are connected at their interfaces	
	Stack Modularity (Miller and Elgård 1998): product variants can be obtained by connecting a different number of modules on a unique direction.	
Supply type	**Fabricate-to-fit** (sometimes called also "Cut-to-Fit") modularity (Ulrich and Tung 1991): standard components are combined with customizable ones.	
	"Mix" Modularity, where a set of standard components can be matched together in order to form a variety of products (Stone 1997).	

Moreover, at certain granularity levels, some products present architectures constituted by two modules only (e.g. Figure 1).

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Figure 1. Screwdriver composed by two components or modules. The bit module is available in different variants

For instance, in reference to the screwdriver shown Figure 1, the interface type cannot be univocally identified (e.g. a "Slot" from a "Sectional" interface), because only one interface is present. More precisely, the use of definitions where interfaces are "all" equal or different has no sense and it is definitely more obvious to observe that only a "unique" interface is present. Similarly, the identification of the actual interaction type is difficult when only two modules are present. For instance, the use of different bit variants is certainly a valid solution for achieving the required variety of geometries and it can be easily associated to the "Component-Swapping" modularity. However, in presence of a solution like the one represented in Figure 2, "Component-Swapping" modularity is no longer useful for describing the interaction type because no bit variants are present. Both, "Bus" and "Sectional" interaction types should be considered, but, once again, it is not possible to discern the most suitable among them.

Figure 2. Screwdriver composed by two un-variant modules

Furthermore, classical definitions only consider "static" interfaces. More specifically, in a common electrical drill, bit variants are used to allow a variety of configurations in terms of bore diameter and material to be processed. At the highest level of granularity, the drill main body, comprising the mandrel, can be considered as a single module that interacts with the bit variants and the battery pack. However, the bit variants have different interface dimensions, but instead of using a different mandrel for each bit variant, an adaptable and self-centering mandrel is adopted for matching any bit interface. Therefore, although a "Component-Swapping" modularity can be reasonably used for identifying the interaction, no interface types are currently available for representing the case.
The above considerations led the authors to conclude that the available modularity types definitions cannot be used for extracting univocal information about interfaces and interactions of all modular products.

3 THE NEW SET OF UNAMBIGUOUS MODULARITY DEFINITIONS

As a viable solution for the issues explained in Section 2, we propose the new set of definitions summarized in Table 2 and described here in the following. It is worth to notice that the old definitions concerning the supply-type (see Table 1) are considered still valid in this work, whilst interface and interaction definitions have been redefined.

3.1 New modular interfaces definitions

The "Unique" and "Multiple" types respectively represent those cases where only one interface type is used across modules in a system (like in the Bus 'a' and Sectional 'a' definitions of), and where different interface types are considered (as for the Slot or the Combinatorial modularity types of). However, interface types are now completely independent on the interactions, and allow a more intuitive identification.
A new interface type, i.e. the "Adaptable", has been conceived for representing those cases where modules can be connected via adjustable interfaces, not currently represented by classical definitions. Differently from the "Adjustment" architecture principle proposed by Mesa *et al*. (2015), where a specific module can be modified during its use, the Adaptable type proposed here does not consider the adaptation of the whole module, but only of its interface.

3.2 New modular interaction definitions

Classical Component-Swapping and Component-Sharing are still valid for the new set (we refer at "Swapping" or "Sharing" without "Component" when considering the new types), while the Bus definition has been modified. Furthermore, the overall meaning of classical "Bus" remains unchanged, but it is now

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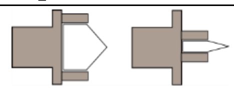
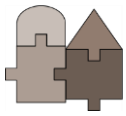
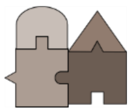
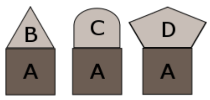
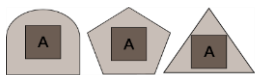
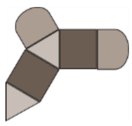
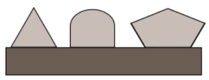
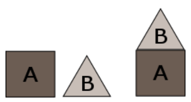
strictly related to cases where "more than one" component is connected to the bus. This specification is fundamental for avoiding ambiguities with the "Single" interaction type, where only two products are connected each other and "no variants" are considered for them (e.g. Figure 2). Moreover, in the "Single" interaction definition, the absence of module variants avoids ambiguities with the Sharing and Swapping ones, where (at least) one module foresee some variants (e.g. Figure 1).
When in presence of only two modules, and without comprehensive information about the product development history, distinguishing between Swapping and Sharing modularity could be difficult. However, while Swapping is a potential solution for increasing product variety without any expressed control on the number of module variants (i.e. for increasing firm-external variety (Pil and Holweg, 2004)), Sharing can be considered as a solution for limiting the variety of modules needed for achieving product variants (i.e. for reducing firm-internal variety (Pil and Holweg, 2004)). Therefore, it is assumed here that, even in case of simple binary architectures, the most suitable modularity type can be identified only through the related problem type.
Eventually, the "Reciprocal" interaction type represents all the cases where it is not possible to identify a common bus and where all modules can be modified, interchanged and/or substituted with variants. Such a new definition has been thought for eliminating the overlapping definitions of Sectional and Combinatorial modularity where, as stated in Section 2, both interaction and interface information was involved together.

Table 2. The new set of structural modularity types.

Group	Short description	Schematic representation
Interface type	**Adaptable**: the interface can be adjusted for connecting different modules.	
	Unique: a unique interface type is present amongst the modules constituting the system.	
	Multiple: multiple interface types are involved in the connection of modules constituting the system	
Interaction type	**Swapping**: two or more components can be interchanged in a system in order to create product variants.	
	Sharing: two or more systems share the same basic component in order to provide product variants.	
	Reciprocal: it is not possible to identify a main body on which other modules are connected, but all modules can be modified/substituted.	
	Bus: it is possible to identify a common bus that connects other components (more than one).	
	Single: a component connected to another one. No variants of the modules are foreseen.	

3.3 Representing classical modularity types with the new set

The very first check to be performed on the new set, is necessarily focused on verifying its capability to univocally represent the definitions listed in Table 1 (see Table 3).
As shown in Table 3, also current definitions containing information about both interface and interaction, are univocally represented by specific combinations of the new interface and interaction definitions. Component-Swapping and Component-Sharing do not provide any information about the interfaces, therefore only the new interaction types can be used to represent them. Similarly, concerning the Bus

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modularity where no information about interfaces is provided (Ulrich and Tung, 1991), it is sufficient to use the new Bus definition. Differently, for the Bus definition of Ulrich (1995), it is necessary to indicate both the new "Unique" interface type and the new "Bus" interaction type.
Referring to Table 1, it is worth to notice how the Sectional modularity differs from the Combinatorial only in terms of interfaces, while the Stack modularity can be considered as a particular Sectional modularity, where modules of the same type are disposed along a preferred dimension (Miller and Elgård, 1998). Both, Sectional and Combinatorial, do not allow the presence of a main body (Bus), but the number of possible combinations among modules is strongly dependent on the nature of interfaces. Indeed, a Unique interface type (i.e. for the Sectional) allows a theoretically infinite number of possible matching (e.g. Lego® toys), while, in case of Multiple interface type (i.e. for the Combinatorial), the variability is reduced to a finite set of combinations of components belonging to specific families.
In conclusion, the new proposed set is capable of representing classical modularity types and univocally representing any possible combinations of interface and interaction types.

Table 3. Classical Interface and Interaction definitions represented with the new set.

Classical modularity types (see Table 1)	Representation with the new set	
	Interface	**Interaction**
Slot Modularity (Ulrich 1995)	Multiple	-
Bus Modularity 'a' (Ulrich 1995)	Unique	Bus
Sectional Modularity 'a' (Salvador et al., 2002)	Unique	-
Component-Swapping (Ulrich and Tung 1991)	-	Swapping
Combinatorial modularity (Salvador *et al.*, 2002)	Multiple	Reciprocal
Component-Sharing (Ulrich and Tung 1991)	-	Sharing
Bus Modularity 'b' (Ulrich and Tung 1991)	-	Bus
Sectional Modularity 'b' (Ulrich 1995)	Unique	Reciprocal
Stack modularity (Miller and Elgård 1998)	Unique	Reciprocal

4 COMPARING NEW DEFINITIONS WITH OLD DEFINITIONS

In this section, a comparison is shown between the new proposed set of definitions and the classical one. The aim of the activity described in this section, is to perform a preliminary verification about the actual contribution of the new set in terms of disambiguation.

4.1 Collecting the sample

To collect the sample of products to be assessed in terms of interfaces and interactions, the authors and five other colleagues searched for any possible product showing modules at a certain level of granularity, according to what introduced in Section 2.1. Since no particular restriction was provided for this preliminary application, any available source has been used to identify products and to retrieve the related information. In other words, everyday home/office/hobby physically available products were considered, as well as those identified by means of specific web searches (e.g. simply by searching for "modular product" in internet search engines). In any case, detailed information from designers and manufacturers of each considered product was neglected here, because only pictures and/or short textual descriptions (online-available datasheets) were available. Nevertheless, in order to distinguish the different interactions types (Table 2) for each modular product, we tried to infer the potential problems solved by the adoption of modularity. Indeed, in the example reported in Figure 3, it is possible to observe how the identification of the interaction can be strictly related to the problem to be solved. More precisely, although the two saws appear to be very similar from a structural point of view, the number of blade variants is different (multiple variants for the first saw, no variants for the second saw). Such a difference is fundamental for discerning a "Swapping" interaction from a "Single" interaction. Accordingly, since each product could show different modules at different granularity levels and since different problems could be solved by the same modular solution, we

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extracted a sample of 140 different problems solved by modularity, from about 110 different products (see at https://goo.gl/xsuqc6).

4.2 Identifying modular configurations with the two definitions sets

The two sets of definitions are compared in terms of Inter Rater Reliability (IRR) score, calculated for the interface/interaction assignments performed by two different evaluators. More precisely, a first assignment session has been performed with both the sets, on a 20% of the products constituting the sample. This session was performed to check the alignment among the evaluators in reference to the correct interpretation and application of the definitions provided in Table 1 and Table 2. Afterwards, the two evaluators independently processed the whole sample, firstly with the old definitions, and then with the new proposed ones. Once gathered the results of the two assignments processes, Krippendorff Alpha tests (Hayes and Krippendorff, 2007) have been performed to check IRR.
The assignments performed with the new set led to an Alpha value of 0,75 for interfaces types and 0,81 for interaction types. The latter value means that a good reliability exists among evaluators for the interaction types, while the first value implies a low reliability (Krippendorff, 2013) for interfaces. Anyway, these values can be considered sensibly higher than those obtained with the definitions listed in Table 1. Indeed, the assessments performed with classical definitions (Table 1), led to an Alpha value of 0,53 for interfaces assignments, and 0,44 for interactions. The performed assignments can be seen at https://goo.gl/MzEE7C.

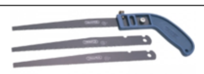
SYSTEM LEVEL	MODULES	SOLUTION PICTURE	EXTRACTED PROBLEM DESCRIPTION	MODULAR SOLUTION DESCRIPTION	INTERFACE-INTERACTI Evaluator 1		
					INTERFACE	INTERACTION	
wood saw	handling, blades		how to allow different cutting styles?	same handling module with interchangeable blades	UNIQUE	Swapping	
wood saw	handling, blades		how to rapidly recondition the cutting tool?	same handling module with detacheable blade	UNIQUE	Single	

Figure 3. Excerpt from the set of 110 products, the problems solved by modularity, and the assessment performed with the new set of definitions.

5 DISCUSSION

5.1 Achieved results and practical implications

The obtained results show that the new set of definitions listed in Table 2, together with the description of the problem solved by modularity, can be successfully used to extract unambiguous information about the modularity types characterizing any specific product.
The proposed set can lead to more comprehensive and detailed investigations about possible heuristic relationships between modularity types and design problems. This argument is currently emerging in literature, where the concept of "modular design rules or principles" is under investigation by scholars. Indeed, Bonvoisin *et al.* (2016) focused the attention on the concept of design principles for supporting designers in fulfilling specific design objectives where modularity can bring some benefit. Similarly, Fiorineschi *et al.* (2014b) observed that certain types of design problems suggest the adoption of modular solutions, i.e. physical solutions presenting specific combinations of interfaces, interactions and supply types. Accordingly, the same authors investigated about how to conceive modular solutions in early concept generation phases (Fiorineschi *et al*., 2015). Eventually, also Mesa *et al.* (2015), which focused the attention mainly on reconfiguration and product portfolio aspects, have investigated the concept of design principles for achieving modularity.
Considering well-known systematic conceptual design (SCD) approaches based on function structures (Eder and Hosnedl, 2008; Pahl *et al*., 2007), the future availability of design rules or guidelines for the identification of the most suitable interface-interaction combination, could improve current methodology. Indeed, while methods like FSH (as well as the indications provided by Pahl *et al*. or the German VDI (Beitz *et al*., 1987)) somehow suggest "when" to use modules across function structures, the outcomes expected from the proposed investigation strategy could provide design stimuli or suggestions about "how" to conceive interfaces and interactions among of modules. The possibility to

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identify suitable interface-interaction configurations early in the design process, could reduce detrimental design iterations that are acknowledged to lead toward delays and costs overruns (Helmer *et al*., 2010).

5.2 Limitations and future research hints

Maybe the most evident limitation of this work is that the actual motivations that led designers and manufacturers to consider modularity, were unknown for the products considered for the comparison. This limitation hindered the possibility to extract realistic information about potential relationships between design problems and modularity types. To this purpose, future research should be focused on samples where more detailed information can be retrieved about product's design history. Indeed, in this way, besides a more comprehensive identification of modular problems, interfaces and interactions, it would be possible to work on the definitions related to supply-type. Moreover, with a comprehensive identification of the product variants, it would be possible to understand if a particular module or set of modules can be considered as product platforms (Meyer and Lehnerd, 1997; Ostrosi *et al*., 2014; Voordijk *et al*., 2006).

Another limitation is related to the limited number of evaluators (two) involved in the IRR test. Similar tests should be repeated with more evaluators, preferably with different technical backgrounds. Furthermore, also the number of products considered in this paper is quite limited. Differently, with huge samples of products, the identification of a comprehensive set of "modular problems" (or problem categories) that can be actually solved by the adoption of specific combinations of modularity types, is the starting point for the identification of "heuristic design rules" suggesting the physical configuration (in terms of interfaces and interactions) of solutions.

6 CONCLUSIONS

Investigating about the presence of possible relationship between design problems and modular solutions could lead to important methodological results, which could support designers also in early conceptual design phases. Unfortunately, some current overlapping and redundant paradigms sometimes make impossible the univocal identification of the modular configurations. To bridge this gap, we proposed a new set of unambiguous definitions, constituted by three interface types and five interaction types, capable to represent many different configurations of interfaces and interactions, comprising those already described in literature. The proposed set and the classical one have been applied on a sample of 110 products, where only limited and fragmental information was available. Nevertheless, the outcomes of the comparison revealed that the new proposed set of definitions allows to perform more reliable identifications of modular interfaces and interactions in examined products. More precisely, interaction types can be identified when the problem solved by modularity is clearly expressed, while only structural information is sufficient to identify interface types. This contribution paves the way for future research activities devoted to the identification of heuristic approaches for the suggestion of suitable modular solutions for solving specific categories of design problems.

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