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MODULAR PRODUCTS AND PRODUCT MODULARITY - IMPLICATIONS FOR THE MANAGEMENT OF INNOVATION AND FOR NEW PRODUCT DEVELOPMENT

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1. Introduction

"Modular products" have become a hot topic in a number of industries, and particularly in automotive [AW 2001]. For instance, Volkswagen reports that, in its Resende factory in Brazil, it has adopted a modular approach to manufacturing. In this factory, industrial vehicles are made by assembling a limited number of "modules" which are locally pre-assembled by suppliers. A similar approach characterizes the way the Smart city car is made by DaimlerChrysler. In current automotive manufacturing practice it has become customary to use pre-assembled modules for elements such as cockpits (incorporating dashboard, sound system, ventilation pipes and the numerous controls and gadgets that clutter the front area of a car interior), devices associated with vehicle doors (including latches, power windows and loudspeakers) and for bumpers (incorporating headlights and park distance control). Although the degree with which such approach is economically advantageous is not very clear [Sako and Warburton 1999], it appears that car manufacturers are pushing ahead because they perceive that, by increasing the level of outsourced labor and manufacturing equipment, they may take advantage of suppliers' cheaper labor costs and, above all, increase their return on assets employed.

From the perspective of the engineering design scholar, this use of the word "modular" seems strikingly inaccurate. Pre-assemblies incorporating heterogeneous functionality and technology seem to negate the essence of "product modularity", which instead implies functional separation and mutual independence [Ulrich 1995]. This mismatch has not gone unnoticed, and a number of researchers have pointed out that there are different perspectives to modularity [Camuffo 2001]. While the engineering design literature focuses upon product modularity, which is associated to functional independence, modularity can also be viewed from the perspective of the manufacturing system and that of the structure given to the supply chain.

The relevance of these alternative viewpoints suggests that, in product development, functionality is not the only aspect that should be taken into account when defining product architecture. As a matter of fact, the car industry is clearly using a criterion which is instead related to assembly. As a side note, it should also be noticed that, from the engineering design perspective, the architecture of today's automobiles is integral and not modular at all. The interlinking among functions and components is very tight, as is the one among performance aspects and components. In other words, there are few components to be found which are individually responsible for a given function or performance indicator. From the perspective of manufacturing, instead, cars seem to lend themselves quite well to a modular architecture with a limited number of large "building blocks" which may facilitate the final assembly process. The following section of this paper will discuss how the product development process is affected when a modular architecture is not built by using functional separation as a lead criterion. Section 3 discusses the impact that technological innovation may have upon the definition of product architecture. Finally, section 4 proposes a tool that has been developed within a research project in cooperation with a leading automotive manufacturer. The tool supports the multi-criteria evaluation of alternative product architectures in conjunction with different technological scenarios.

2. Implications upon product development

In order to discuss how product development may be affected by adopting module-creating criteria which are different from the functional separation advocated by engineering design, it is necessary to discuss some broader implications.

In first instance, modular products based upon assembly-related criteria will entail rather strong transformations in industry structure. In general, the final assembler (or OEM – Original Equipment Manufacturer) will tend to outsource both the development and the manufacturing of modules in order to exploit cheaper labor cost and reduce its amount of capital expenditure. In the case of the automotive industry this seems to be the continuation of a decade-long trend towards greater degrees of outsourcing. The case of modules is quite special, however, since modules incorporate heterogeneous functionality and technology. It follows that the development and manufacturing of an entire module will not be carried out by an individual organizational entity. Such operations will generally be performed by temporary associations of suppliers acting as a consortium (in such cases it is today fashionable to talk about “virtual enterprises”), or by different business units of a single large supplier.

The structure of modular products will also be affected. Bills of materials will become “narrower” and “deeper”, since OEMs will buy a smaller number of components of greater complexity. Deepening the bill of materials has the potential to reduce the complexity of assembly operations, but increases the problems related to manufacturing management, especially when products need to be adapted to suit customer needs. In the case of automobiles, which are nowadays partly built-to-order, information related to customer choices currently remains within the car manufacturer. OEMs assemble cars by “reading” a specific customer order and by picking the required components from inventory, which is then generally replenished with Just-In-Time techniques. Only in a very limited number of instances, such as seats, customer-specific information must be fed upstream to suppliers in order to make them prepare the “right” component to fit in a specific car. With more complex modules, instead, customization will have to occur at module level, and this will require order-specific information to be given to suppliers.

Modular products will also reshape manufacturing facilities. With products being assembled by a limited number of rather complex modules, assembly lines will assume a “fishbone” structure. In such configuration, there will be a shorter section for final assembly, since fewer modules will have to be put together. This line will be fed by rather long assembly lines producing each of the modules. In order to improve logistics, plants will probably be reorganized in order to accommodate this entire structure within a same building, within which personnel from different firms will be operate the corresponding elements of this “fishbone” assembly line.

Finally, modular products will affect product development in a substantial way. In first instance the product development process will occur among the OEM and the consortia dealing with the development of individual modules. Moreover, the process will continue among the firms associated to each such consortia. Among the main implications of such organizational arrangement one can list:

- the need for both OEMs and first-tier suppliers to develop stronger coordination capabilities in systems engineering. In current practice vehicle manufacturers are accustomed to operating as the “systems integrators” of a two- or three-tiered structure. Immediately below them operate suppliers which are essentially focused upon individual subsystems (e.g., electrical, interiors) which fulfill specific functions and are based upon a single technology. Further below them one can find sub-suppliers which generally provide simple custom-made parts or off-the-shelf components. In this way, systems integration tasks are essentially performed by the OEM. With the shift to modular solutions, systems integration is pushed further down at the level of the lead contractors of each of the supplier consortia. In turn, OEMs will have to learn how to “coordinate” the “coordinators”. In addition, the specification of components and interfaces will become a more complex task because assembly-oriented modules incorporating different functions and technology will be very closely interlinked to one another. For example, a car’s sound system will be split among the “interiors” and the “cockpit” modules and it may be difficult to write specifications allowing a good overall performance when the two modules are “plugged together”;

- the ability to correctly design responsibilities and incentives at the levels of the supplier consortium and of the individual supplier, so that performance targets are effectively met. In current practice, performance is ensured by having the OEM take direct responsibility in design or by associating performance indicators to an individual supplier and making the supplier accountable for it. If systems responsible for a given performance indicator are split among modules it becomes quite difficult to make sure that each consortium puts the appropriate effort in meeting targets, since there would be a natural tendency to “take a free ride” upon others’ effort. As an extreme example one may take the case of braking systems. In current practice, braking performance is managed by having a single supplier deal with the braking system and then by initiating extensive iterations in order to fine tune the system when the rest of vehicle design changes in a relevant way (for example, when mass distribution is altered). If the car were to be split in a “front module” and a “rear” module, it would be more difficult to ensure that the consortia in charge of developing such modules design the appropriate “braking performance” into their modules at each design change iteration;
- the ability to break organizational, cultural and technological barriers among different firms. As highlighted by Henderson and Clark [1990], product architecture shapes organizational structures and routines. It follows that architectural innovation, where the core technology of a product is unchanged, but is arranged in a different way, becomes one of the most difficult transitions to be managed by a firm. The transition to modular products clearly is an innovation of this kind, and is made even more demanding by the fact that it requires the reconfiguration of an entire supply chain, rather than that of an individual firm. Specifically, it remains to be seen how suppliers, used to be coordinated through the OEM, will be able to create now organizational routines with which to coordinate themselves within a consortium and to be further coordinated by the OEM.

3. The design of product architecture and the management of innovation

The last issue raised in the previous section, related to the complexity of managing the innovation of product architecture, is probably the crucial point in ensuring a successful transition to modular products. By looking at recent literature one can notice that there has been significant effort in developing tools which may be used to define product architecture in the most appropriate way. Examples of such tools include the analysis of flows reported in block-diagram functional schematics of the product [Stone et al. 1998] and the block-diagonal rearrangement of matrix-based representations of intercomponent interactions [Pimmler and Eppinger 1997], [Huang and Kusiak 1998], [Lanner and Malmqvist, 1998]. Such tools have been presented in academic literature, but have also been reported to be used in practice (for example, [Rushton and Zakariah 2000]). To the best of the authors’ knowledge, however, they have always been applied to rather simple products or at subsystem level and never to the overall architectural redesign of a complex product.

In this context it must be remarked that product architecture rarely changes because of endogenous determinants. Following the well-known model of innovation by Abernathy and Utterback [Utterback 1994], product architecture changes rapidly during the initial phases of the product life-cycle because firms experiment with alternative - and generally rather different – architectural solutions. However, once one of these solutions eventually emerges as the “dominant design”, an event which is due to a mixture of technical, economic and commercial factors, product architecture ceases to change and innovation in the product becomes incremental and localized.

Under this perspective it is difficult to explain the current move towards modular architectures developed by using criteria which are related to manufacturing and less to functional separation. This change cannot be justified by the hypothesis that a “smart idea” has suddenly emerged in industry, with everything else being kept constant. Even in the absence of formal methods for designing product architecture, evolutionary mechanisms would already have led industry to such kind of architecture, provided it really is superior. An explanation can instead be found by looking at innovation in background technology, which provides both the occasion and possibly the appropriateness of such architectural innovation. In many instances, innovations which are seemingly localized alter the relationships between components and thus relax some of the constraints which had previously led to specific architectural solutions. For example, the introduction of low-power electronic devices may at first glance appear to affect only the amount of energy consumed by a personal computer. Such innovation may instead have a more profound effect upon the product architecture. For example, it may eliminate the need to provide ventilation, thus allowing to remove the related system, or it may allow a tighter packing of the components, thus leading to layout arrangements which had previously been impossible to achieve. In a similar way, the introduction of “steering by wire” systems in automobiles may allow to eliminate the steering column and relax the constraints that currently force to position the steering wheel in a given position, or even allow to use alternative ways of controlling the vehicle’s direction.

From this perspective the design, or the redesign, of product architecture should not be viewed from the viewpoint of a constant technological regime. By missing this factor, the proposed architectural solutions are bound to be no better than the extant ones under current technology, and to miss out important opportunities within the future technological scenario. This, connected to the organizational difficulty of changing product architecture once it is established, implies a rather poor result. On the contrary, if product architecture is designed by taking into account some kind of technology roadmap which looks into the future, it is possible to plan in advance a product architecture whose appropriateness may jointly be high and persistent.

4. A multicriteria method for evaluating product decompositions

The previous discussions have outlined a scenario in which manufacturing firms have the need to actively manage the architecture design process with a close link to the management of innovation. When dealing with the overall product, rather than with subsystems, discussions with industry have shown that the main problem is not so much related to automating the synthesis of architectural solutions. The grouping of components into architectural chunks will more often than not be done “by sight” both because some solutions are fairly obvious and also because the firm would not easily trust a purely algorithmic solution to be problem. The problem is rather:

- to document the relationships among components from a number of technical and non-technical criteria, in order to create a self-standing knowledge base related to the design of product architecture. Examples of such criteria include functional separation, technological homogeneity, ease of assembly, availability of capable suppliers, etc.;
- to document the foreseen impact of the results of innovation projects upon these same relationships;
- to support the process of manually grouping components into chunks. This may be done by identifying “natural groupings” built by iteratively aggregating those component couples which under all or most criteria appear to be suitable for inclusion in a same module;
- to highlight the obstacles to a desired modular configuration and to eventually take action for their future removal. Such obstacles may come from “bottleneck criteria” (i.e. criteria which lean against a specific grouping) or from the fact that some “critical technology” is not yet available (i.e. the results of an innovation process which could increase the suitability of a currently impossible grouping);
- to support an objective evaluation of alternative architectural solutions by taking into account multiple criteria and the possible change enabled by the incoming stream of technology.

Such requirements have led to the development of a method which builds upon well-known matrix-based methods for product architecture design, such as [Pimmler and Eppinger 1997] and especially the “suitability matrix” by Huang and Kusiak [1998]. The method consists of six steps, namely the decomposition of the product bill of materials, the drafting of a technology roadmap, the definition of a criterion hierarchy, the elicitation of architectural information and, finally, its use for supporting the design and evaluation of product architecture (figure 1).

The first step requires to decompose the product bill-of-materials to a convenient degree, approximately down to the level of "functional elements", i.e. elements which have some kind self-contained functionality. More detailed checklists have been designed in order to verify the opportunity of further "exploding" each single item on the bill of materials, but they are not reported here due to lack of space.

The definition of a criteria hierarchy, in step 2, is associated to the need of including a wide enough number of criteria in assessing product architecture but, at the same time, not to disperse attention too widely. In this respect, arranging criteria hierarchically is a standard approach in multiple criteria analysis [Saaty 1980]. Figure 2 reports a possible decomposition of criteria.

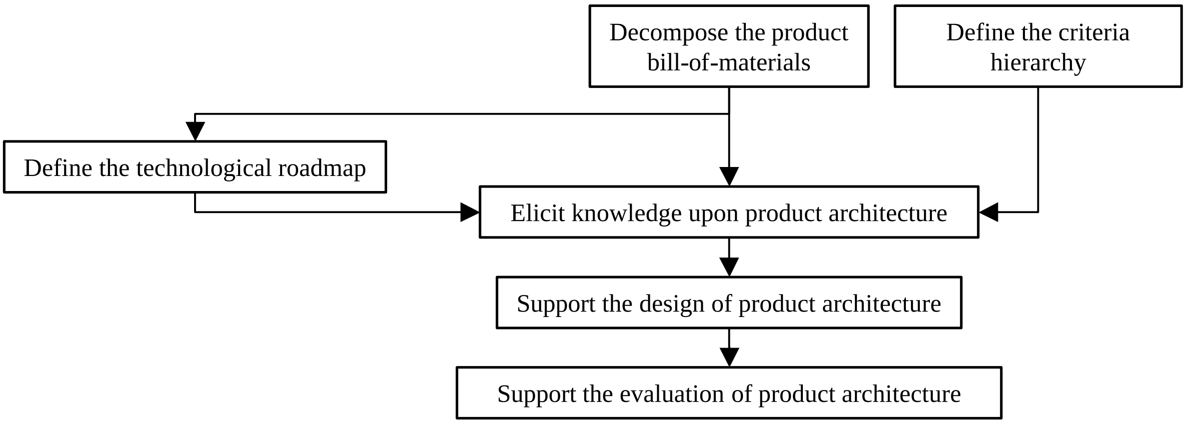


Figure 1. Structure of the proposed method

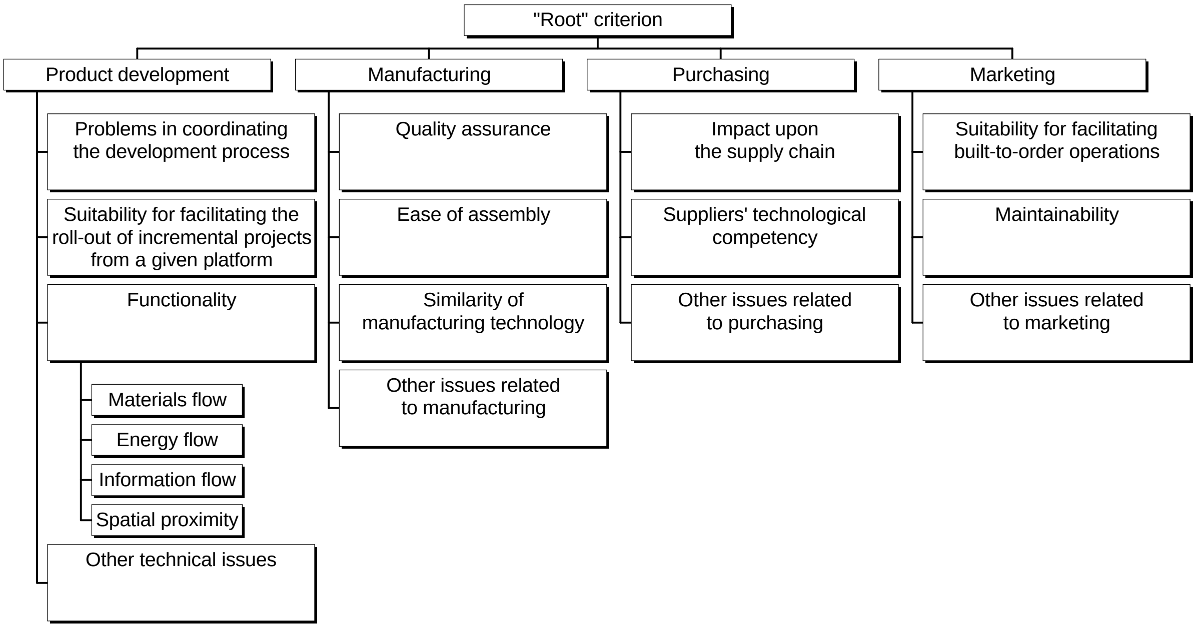
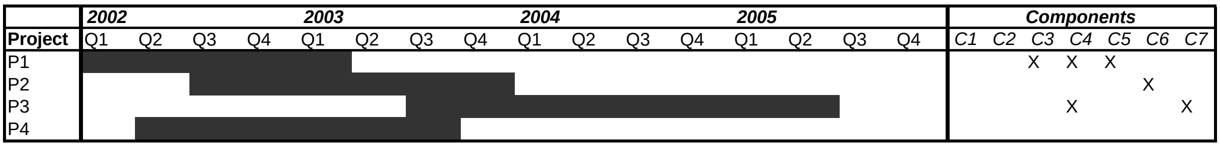


Figure 2. Example of a criteria structure

The third step, i.e. developing the technology roadmap, consists in describing the innovation projects which are foreseen within the planning horizon, in plotting them against time and in spotting their relationship to affected components (figure 3).

The fourth step consists in the knowledge elicitation phase. This step requires to firm to systematically evaluate, with reference to the current technological state of the art and per each main criteria, the suitability of including each component-component couple in a same module. One can represent such information with parameter $s_{ii'j0}$, expressing the suitability, under criterion *j*, of grouping components *i* and *i'* together. Such information may be coded on a numerical scale, with the due attention being paid that such information is ordinal in nature and not cardinal. To this purpose it is necessary to stress that the objective here is not to perform precise calculations but, rather, to provide qualitative kind of support to the system architect. Following previous proposals by other authors, a range from –2 to +2 may be suitably adopted, with negative numbers expressing that the two components should not stay together, with positive numbers indicating that they should, and null values indicating indifference. In order to limit the amount of data to be gathered, when dealing with complex products with a large number of components it is appropriate to record parameters $s_{ii'j0}$ for the top-level criteria only. The way with which the related subcriteria have been used in order to set this aggregate-level parameter should however be recorded in some way, in order to document the rationale followed by the analyst.

At this point, it is necessary to assess how each innovation project relevant to either of the two components may affect such suitability, by increasing or decreasing the value of $s_{ii'j0}$. One can indicate such information with parameter $\Delta s_{ii'jk}$, expressing the impact of project *k* upon parameter $s_{ii'j0}$. Again, a numerical scale ranging from –2 to +2 may be used, with the meaning that the innovation respectively decreases, increases, or does not affect the suitability.



	2002				*2003*				*2004*				*2005*				***Components***						
Project	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*
P1	■	■	■	■	■														X	X	X		
P2			■	■	■	■	■	■														X	
P3							■	■	■	■	■	■	■	■						X			X
P4		■	■	■	■	■	■																

Figure 3. Example of a technology roadmap

This data collection task is obviously quitedemanding and requires close cooperation from the different organizational functions involved, especially when the number of components becomes large. Previous applications of matrix methods to the design of product architecture however show that the resulting matrices are rather sparse (i.e., with few nonzero elements). In order to decrease the burden of data entry, the analyst may therefore reduce the number of component-component couples to be analyzed by spotting in advance those couples which clearly do not make sense. The Entity-Relationship diagram in figure 4 specifies the database required to accommodate the information now presented.

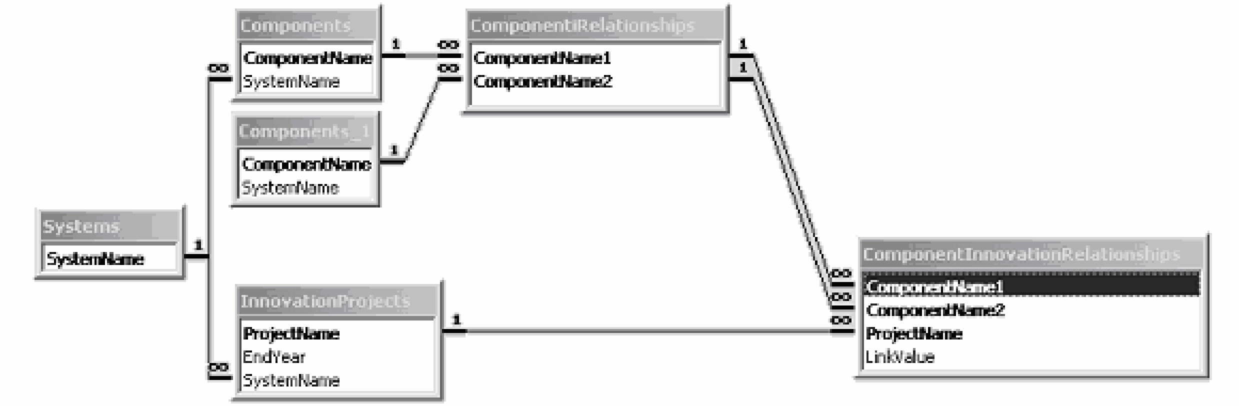


Figure 4. Database schema for supporting the proposed method

In the last two steps of the method, the information thus gathered may be used in order to support the design of product architecture, or to assess the validity of proposed solutions. This may be done at first by setting a given technological scenario, i.e. by hypothesizing that a subset of the projects in the roadmap are active. This may be epxressed by associating each project with a booelan variable, a_k which is set to “1” or to “0” in case project *k* is respectively active or not. With a given technological scenario, defined by the vector $[\ldots, a_k, \ldots]$, one can construct suitability matrices, one per each main criterion, by calculating the suitability index

$$SI_{ii'j} = s_{ii'j0} + a\sum_{k}\Delta s_{ii'jk} \tag{1}$$

where $SI_{ii'j}$ is the overall suitability, under criterion j, of keeping components i and i' within the same module and a is a scaling factor.

With a given technological scenario it is now possible to support the grouping of components by looking for the component couples that score the highest value. Moreover, it is possible to evaluate a given proposal for product architecture by computing overall scores per each criterion. One simple metric which is currently being used to this purpose is given by summing together the suitability scores $SI_{ii'j}$ for components which are grouped in the same module, and by subtracting the same scores for components which are not grouped in the same module. If one introduces a boolean variable $m_{ii'}$ which is set to “1” if components i and i' stay in the same module and “0” in the opposite case, one can calculate the score S_j as

$$S_j = \sum_{i<i'}\sum_{i'} SI_{ii'j}\, m_{ii'} - \sum_{i<i'}\sum_{i'} SI_{ii'j}\left(1 - m_{ii'}\right) \tag{2}$$

In this way, keeping together modules with a high suitability helps to increase the score, while keeping them apart reduces it. Conversely, keeping together modules with a negative suitability reduces the score and keeping them apart increases it. This method is of course very rough, but suitable to provide a ballpark assessment of proposals for product architecture.

Having thus obtained scores with respect to the main criteria, standard multicriteria evaluation techniques may be used in order to obtain a final ranking of alternatives. Without going through details, such techniques will involve at first the elimination of dominated solutions (i.e., solutions which score lower than other ones on all of the the main criteria), followed by the determination of relative weights among the top-level criteria, possibly through the AHP algorithm or using alternative methods.

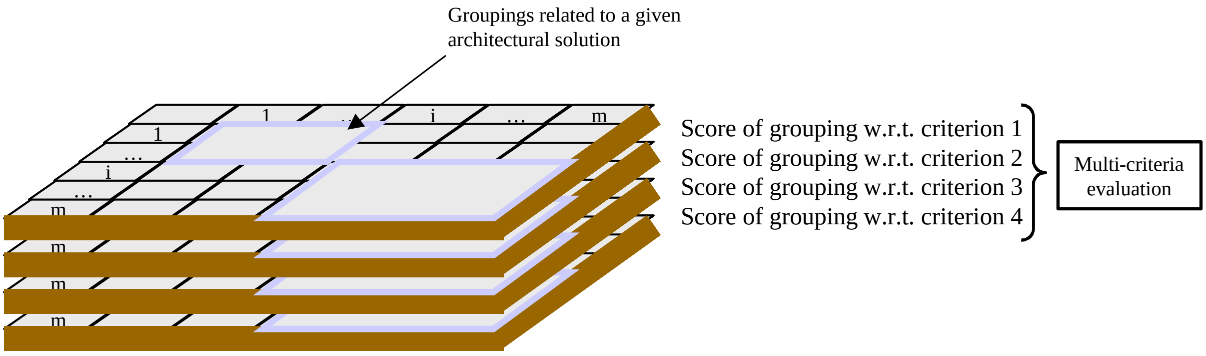


Figure 5. Conceptual model of the proposed evaluation method

5. Conclusions

The paper has tackled the problem of designing product architecture when a number of heterogeneous criteria, both technical and non-technical, are taken into account. The paper has considered the case of the automotive industry as the background scenario, but its contents should retain their validity in other domains as well. The choice of the automotive industry is due to the fact that the research project upon which the paper is based is actually dealing with such domain, and because there currently is a significant trend towards the development of “modular cars” in which modules are defined by considering criteria related to manufacturing, rather than to functionality alone.

The paper has attempted to show that the design of product architecture can and should occur by considering a wide range of criteria and especially the stream of innovations that will presumably affect the product within the planning horizon. To this purpose, the paper outlines a method for product architecture design which is currently being tested in industry. The purpose of the method is to document knowledge upon the relationships among components and upon the change that will occur because of technological evolution. In addition, to support the multiple criteria evaluation of alternative product architectures. The method presented in the paper is to be considered as a conceptual proposal which will need further refinement following its deployment in an industrial setting.

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