Laboratoire d'Analyses et Modélisation de Systèmes pour l'Aide à la Décision
UMR 7243

CAHIER DU LAMSADE

350

Mars 2014

Economic variety control and modularity

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***Abstract**: Since the industry revolution, companies have tried to standardize more their components, in order to allow mass production and to increase components' commonality between products. To remain competitive, companies always have to offer more variety to customers. Manufacturers of complex assembled products that are facing the challenge of mass customization are forced to increase simultaneously commonality of used components and the variety of end products. Variety control is more than ever an issue but seems to lack a complete economic insight. In this paper we propose a systematic economic optimization for variety control taking into account the whole total delivered cost (TDC) including investments and operating costs. It is clear that modular product architecture is a cornerstone to allow end product customization at low cost. Modular architecture facilitates variety control; thanks to interfaces standardization and appropriate architectures, the diversity of alternative modules can easily be controlled. On the other hand the decoupling of modules will always be limited due to inevitable technical combinatorial restrictions between modules. After a description of the main concepts of modular product, we will propose an extent to the model of variety control in order to take into account these constraints between modules.*

***Keywords**: mass customization, variety control, standardization, diversity, modular product*

It is generally admitted that the competitive position of a manufacturing company is mainly based on the diversity of its products, thus making it possible "to stick as closely as possible to the demand" with respect to characteristics such as price, quality and availability. The selling price depends on the cost, which is not independent of diversity, as increased diversity is often a source of an increase in costs. In order to remain competitive, companies must control their variety. The design's rationalization of new products makes it possible to obtain lower costs for the desired diversity that the customer will observe (e.g., the diversity as yielded by a car configurator). The structure's rationalization of a set of components ensuring the same whole of functional needs can be achieved with the techniques of standardization that were developed in the middle of the 19th century; we will bring to them the economic light that they are currently lacking (§1). The approach of achieving diversity through a combination of alternative modules (AMs) belonging to different sets of AMs (AMSs) mobilizes the concepts of platform and standardized interfaces. It is an approach that has been used for approximately forty years to enable the mass production of strongly diversified products. We will analyze (§2) the characteristics of this approach in which the economic vision is weak and propose to extend the model developed in §1, to the modular approach.

1 Rationalization of production by using variety control and product standards

Variety control aims at limiting the diversity of the components assembled in complex products. This approach is devoted to the rationalization of the design of these products and is supplemented by the use of product standards for selecting supplied components and defining the characteristics of a complex manufactured good.

1.1 Control of the components variety

First we will make a recap of the initial method of variety control of parts, then we will consider the economic insight that is missing out and finally, we will discuss some extends of this first model.

The initial approach

The efforts of rationalization of production arose at various times, when attempting to produce a set of identical products such as the production lines of the galleys in Venice at the beginning of the 12th century (Voss, 2007; Ciciliot, 2012). Manufactories were created to produce components or end products that shared the same morphological and functional characteristics. Within this framework, the produced components were interchangeable; this case may be considered as the first form of standardization.

. The problem of the economic relevance of the diversity of a set of components sharing similar functions quickly emerged. Unfortunately, the design of a new product often leads to the creation of a new component with the exact required specifications rather than to the use of an existing component that offers similar functionalities. The standardization of components constitutes a first stage in the rationalization of the production. To avoid increasing diversity, one can force the engineering center to consider using existing components. However, this solution presents the disadvantage of perpetuating a portfolio of alternative components whose composition may be economically not very efficient. It is then judicious to mobilize the techniques of standardization, defined here as the design rationalization of a set of partially interchangeable products created to meet a set of needs.

The modeling of the rationalization of the composition of a set of components that ensure the same functionality was proposed in 1877 by Colonel Charles Renard who was interested in the rationalization among cables of various diameters used for the stowing and constructing of captive military balloons. The excessive number of parts (425) posed serious logistic problems. The approach used made it possible to reduce the number to 17 to satisfy all requirements. This

solution rests on a relatively simple concept. In the posed problem, the unique functional characteristic of a cable is the maximum tensile strength *Y* that a cable of diameter *X* can withstand before rupturing. A test on cables of different diameters made it possible to construct Figure 1. It is then enough to cut out the y-axis in a certain number of intervals and to associate with any y_k tension request the diameter associated with the upper limit of the interval that contains y_k (i.e., in our example, a cable of diameter x_2 for any maximum tensile strength ranging between y_1 and y_2).

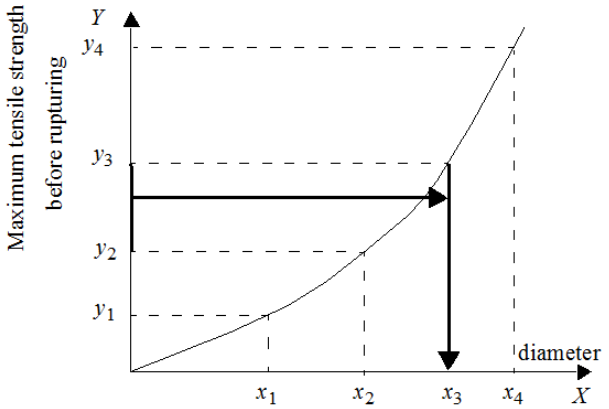

Figure 1: Rationalization of the composition of a set of components (Col. Renard)

The implementation of this relatively simple idea poses the problem of the determination of the number of intervals and of their upper bounds. Empirical studies of Renard led him to split the same range of values (10 to 100) in different predetermined numbers of intervals whose upper bounds were defined in a geometric progression. Known as the Renard series, they are still used in industry under the name of the Internationally Standardized Series (Standards ISO 3-1973, ISO 17-1973, SO 497-1973 and ANSI Z17.1-1973). This structured approach presents two important limitations as no economic tradeoff is regarded in this rationalization and it uses only one criterion, which is characterized by a continuous variable, in the characterization of the component.

Introduction to an economic insight

Giard (2001, 2003) proposes a generalization of the approach to address these two restrictions. The term of alternative module (AM) is used here in preference to that of alternative component of similar functionalities. These AMs belong to a unique set (AMS) of AMs. It starts from an AMS $\mathscr{E}_J$ of n_J AMs, such as a set of gasoline engines. This set includes n'_J existing AMs and $n''_J = n_J - n'_J$ new AMs. A set of *p* criteria corresponding to functional needs is retained. These criteria can be quantitative (weight, power, height, etc.) or qualitative (standard used, assembly interfaces, etc.). For example, the first engine has a weight of 176 kg, it delivers a power of 90 hp and is Euro 6 - compliant (Euro 6 is an European emission standard for new cars), etc. The list of criteria is the result of a consultation of experts, when defining the needs to meet (see here after). The dynamic evolution of the requirements may lead to some new criteria. To satisfy these new needs, new alternative modules may be required. As they didn't exist yet, their functional characterization should be based on the expected functional request.

		Criteria					
		1	2	…	*l*	…	*p*
Alternative Modules $\mathscr{E}_J$	1						
	2						
	…						
	j						
	…						
	n_J						

Table 1: Functional characterization of the AMs of the AMS $\mathscr{E}_j$

In addition, the set of *m* needs, which these components must satisfy is known. These needs are characterized by all the criteria introduced previously. For each quantitative criterion, a need is defined by a range of values (e.g., for the first need, the engine must deliver a minimal power of 80 hp and must weigh less than 150 kg). For each qualitative criterion, a need is defined by a list of qualitative items (e.g., for the first need, the engine must be Euro 6 - compliant). This information is the result of a consultation of experts, and can lead to certain revisions of specifications considered to be unnecessarily constraining. d_i is the annual demand of the need *i* that is to be satisfied.

		Criteria						Demands
		1	2	…	*l*	…	*p*	
Needs	1							d_1
	2							d_2
	…							…
	i							d_i
	…							…
	m							d_m

Table 2: Functional characterization and importance of demands to be covered by the AMS $\mathscr{E}_j$

The Boolean a_{ij} takes a value of 1 only if the component *j* is usable to satisfy need *i*, and 0, otherwise. In our example, the engine 1 meets all the requirements of need 1 ($\rightarrow a_{11} = 1$) only if the three criteria introduced previously are used

		Alternative Modules $\mathscr{E}_J$					
		1	2	…	*j*	…	n_J
Needs	1						
	2						
	…						
	i						
	…						
	m						

Table 3: Ability of the AMs to meet the needs (Boolean parameters)

The binary variable x_{ij} takes a value of 1 if the AM *j* satisfies the need *i*. This need *i* is assumed to be covered by a unique AM *j* but this AM *j* can meet several needs. Note that it is useless to create a variable x_{ij} if the corresponding parameter a_{ij} is null; this limits drastically the number of decision variables. Equation (1) enforces each need *i* to be satisfied.

$$\sum_j x_{ij} = 1, \forall i \quad (1)$$

The production of the AM *j* is $\sum_i x_{ij} \cdot d_i$.

The total annual delivery cost of a manufactured AM includes its production costs, the costs of the purchased parts that it includes in case of a new AM in project, an appropriate share[1] for the cost of design studies (which gives an economic advantage for the existing AMs). This total annual cost is easier to define if the AM is bought. In both cases, this total annual delivery cost is generally not proportional to the quantity produced (or bought) and can be regarded as linear for a quantity u_{k_j} belonging to the interval k_j (with $1 \le k_j \le K_j$) and bounded by the quantities M_{k_j-1} and M_{k_j} such as $M_{k_j-1} \le u_{k_k} < M_{k_j}$. In this formulation, $M_0 = 0$ corresponds to the possible nil production (or supply), and M_{K_j} corresponds to the maximum capacity of production (or supply) of the AM *j*. This maximum capacity may be increased ($\rightarrow$ new maximum capacity M_{K_j+1}) by an appropriate investment (machines…). Its impact on the total annual delivery cost is a fixed cost to bear when the first M_{K_j} unit is produced. This fixed cost is a share of the investment cost, calculated as suggested above.

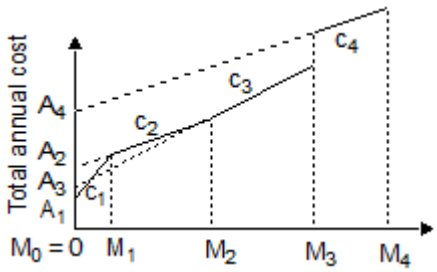

Figure 2: Example of a total annual cost of procurement

Let z_{k_j} be a binary variable that takes a value of 1 if a production (or supply) of the AM *j* is completed in the interval k_j, and 0 otherwise. The production (or supply) of the AM *j* may be null and is impossible on more than one interval, which is enforced by equation (2).

$$\sum_{k_j=1}^{k_j=K_j} z_{k_j} \le 1 \quad (2)$$

The variables z_{k_j} and u_{k_j} are linked by the constraints (3), preventing more than one positive u_{k_j}.

$$M_{k_j-1} \cdot z_{k_j} \le u_{k_j} < M_{k_j} \cdot z_{k_j}, \forall k_j \quad (3)$$

The production, possibly nil, of the AM *j* can then be written as $\sum_{k_j=1}^{k_j=K_j} u_{k_j}$, which leads to the equation (4)

$$\sum_{k_j=1}^{k_j=K_j} u_{k_j} = \sum_i x_{ij} \cdot d_i \quad (4)$$

The cost function of a positive quantity u_{k_j}, assumed to be linear on the interval k_j is $A_{k_j} + c_{k_j} \cdot y_{k_j}$. As only one interval k_j can be used, the cost function of the AM *j* is defined by relation (5).

$$\sum_{k_j=1}^{k_j=K_j} (A_{k_j} \cdot z_{k_j} + c_{k_j} \cdot u_{k_j}) \quad (5)$$

The optimal composition of an AMS is that which minimizes the sum of the total delivery cost of the selected AMs, given by relation (6).

$$\sum_{j=1}^{j=n_J} \sum_{k_j=1}^{k_j=K_j} (A_{k_j} \cdot z_{k_j} + c_{k_j} \cdot u_{k_j}) \quad (6)$$

Extensions of the model

The previous formulation assumes that optimal decisions can be taken for any AMS independently from decisions taken for others AMSs. This is not always the case. In § 2.2, we will examine the case of physical constraints that may link AMs belonging to two AMSs or more. Here we take into account global constraints that the set of AMSs' optimal solutions must respect. Those environmental constraints may lead to downgrade the optimality of solutions obtained for some AMSs. The first aspect deals with positive or negative cost synergy (Giard 2003). The second issue relates of the concern to avoid a dramatic change in the existing solution. The last point is the introduction of the possibility to cover a need with several AMs.

Let's examine the cost synergies.

- If more than κ AMs, whose index run from j_1 to j_2, are produced in the same plant ($\rightarrow \kappa > j_2 - j_1 + 1$), the annual total cost of procurement must be increased by the additional cost Γ^+, which may correspond to a share of an

[1] It can be calculated as the annual payment, equivalent to the investment (design studies) cost, using the company discount rate and the number of years of use of this investment.

investment used by all these AMs. Then the term $(+\gamma \cdot \Gamma^{+})$ is to add to relation (6), where γ is a binary variable; the constraint (7) enforces γ to takes a value of 1 if at least κ of those AMs are produced.

$$\sum_{r=j_1}^{r=j_2} \sum_{i=1}^{i=m} x_{ir} < \kappa + n_j \cdot \gamma \quad (7)$$

- Conversely, if this production yields an economy of Γ^{-}, the term $(-\gamma \cdot \Gamma^{-})$ has to be added to relation (6) and the equation (8) enforces γ to takes a value of 1 only if this condition is met.

$$\sum_{r=j_1}^{r=j_2} \sum_{i=1}^{i=m} x_{ir} > \kappa \cdot \gamma \quad (8)$$

The concern for avoiding a dramatic change in the existing situation justifies the presence of the existing components in the list of candidates to the selection. From this perspective, one can decide that based on the set of the $n' < n$ AMs currently used (top of the list of the *n* candidates), one will retain at least $n'' < n'$ AMs, which leads to the equation (9).

$$\sum_{j=1}^{j=n'} \sum_{i=1}^{i=m} x_{ij} \geq n''_J \quad (9)$$

One can also replace this relation (9) by a constraint on a total volume of AMs to be kept or on a valorization of the total volume.

It may be interesting to cover the need *i* with several AMs rather than with a unique AM. Then, x_{ij} becomes continuous $(0 \leq x_{ij} \leq 1)$ because of certain constraints on production or supply capacities.

At last, this formulation can also be adapted easily to go beyond the annual average requirements by introducing the forecast evolution for these demands, based on trade or technical reasons. Then d_i becomes $d_{it}\,(1 < t \leq T)$ and the cost function to be minimized becomes a sum of the discounted annual costs[2]. The AMS for the selection evolves over time, which makes it possible to introduce AMs that are not immediately available (x_{ij} becomes x_{ijt}) and to gradually relax the constraint on a set of current AMs to retain (n'' becomes n'''_t where $n'''_{t_2} \geq n'''_{t_1}$, for $t_2 > t_1$).

Two remarks are pertinent to the scope of this approach.

- The reduction in the variety of an AMS is without interest when that set is created to offer a visible differentiation of the end product (design problem). This is the case, for example, regarding the hubcaps or the seats of a car. Thus, it is useful for those AMSs that the customer does not see or is not interested in, such as radiators.

- Some AMs can differ from others based solely on their interfaces with some AMs that pertain to other AMSs with which they will be assembled (gearboxes and engines, for example). The problem of the standardization of the interfaces is not sufficiently addressed in the approach described above. Indeed, this approach treats the rationalization of the composition of an AMS independent of other AMSs used in the same product range. The optimality of the decisions proposed pursuant to this approach with various AMSs must be reconsidered due to the need to create some junction components or because it is physically impossible to connect the considered AMs. Taking into account this interfacing is explicit in the modular architecture (see §3) and will lead to a broader approach of this economic rationalization.

1.2 **The standardization**

The International Standard Organization defines (ISO, 2004) standardization as an activity that "consists of the processes of formulating, issuing and implementing standards", and it defines a standard as "a document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context". The ISO adds two additional definitions, however. A product standard is defined as a "standard that specifies requirements to be fulfilled by a product or a group of products, to establish its fitness for purpose", and an interface standard is a "standard that specifies requirements concerned with the compatibility of products or systems at their points of interconnection".

These two last definitions explain the interest of standardization in the rationalization of the design of the products. Indeed, a complex product includes components or AMs designed and manufactured by the company (or by a subcontractor) as well as components or AMs that have been purchased. The technical description of the latter is accompanied by the mention of standards of products and/or of interfaces. Accordingly, the research department can then more easily select the components or AMs to be integrated in a new product, thereby limiting the risks of dysfunction of the end product. If the end products are sold as components to be integrated in an end product by another company and if the information that this component adheres to certain standards constitutes a selling point, these standards define a set of constraints that restrict

[2] The discount rate must be the one used for calculating the annual share of investment in development studies of a new module or in capacity extension.

the space of design and speed up the product design.

2 Rationalization from a modular perspective

Industries with scholars seek to manage efficiently the design, production, sales and updates of products that incorporate a degree of diversity to attain mass customization. In this way, the modular approach is a powerful tool for companies:

- First, because the division into independent modules allows for parallel designs, the total time for a design is reduced and modifications or upgrades of products can be implemented more often and at lower costs, thus facilitating innovation (Baldwin & Clark 1997, Ulrich 1995, Dahmus 2001, Pandremenos et al. 2009).

- Because the division can simplify the management associated with the diversity in production, the standardization between products may improve the robustness of assembling factories as they will be able to produce a greater variety of products on the same line and they will be less impacted by frequent product changes over time). Furthermore, independency between modules simplifies forecast management (Lamouri & Thomas 2000, Sali 2012).

In this section, we first introduce the concept used by the modular approach, and we then propose a generalization of our method of rationalization within the particular framework of modular architecture.

2.1 Fundamental Concepts

We define a modular system as a set of interdependent sub-systems or modules that are smaller than the entire system and can therefore be managed (designed and/or produced and/or sold and/or updated) independently (Baldwin & Clark 1997). This independency results from a prior division (Baldwin & Clark 1997, Ulrich 1995) ad hoc (unique for each system and each organization) of the system and the definition of decoupled interfaces (Ulrich 1995) between modules. Ulrich (1995) adds that a module must correspond to, at the most, a unique function (but a function may be the result of a set of modules) to have an efficient division. Modular architecture permits the generation of alternative modules (AM) that will offer customization to the customer (Pine II 1993, Baldwin & Clark 1997). A component, defined as a separable sub-system (Ulrich 1995), is a module only if it addresses a unique function and if its interfaces are decoupled, that is, if they permit the generation of alternative modules. In the following situation, we reserve the term “component” to sub-systems that are not modules.

The functions are intrinsic characteristics of a product that contribute to the global service provided by the product (Ulrich & Eppinger 1995, Eggen 2003). The definition of a unique but complex function rather than a set of functional elements allows us to define modules at a more economically pertinent aggregate level. For example, in automobile one of the most complex modules is the powertrain. We can associate a unique function to the powertrain as it: permits the autonomous moving of a vehicle. In fact, this function could be decomposed through a functional tree whose first level would be composed of creating energy and transforming this energy into motion. This functional decomposition leads to precise functional elements that are traduced in the component or module (e.g., to create the spark in the cylinder, spark plugs).

Thus, there are certain relevant points to be made:

- Going deeper into the tree, the functional study is already making technical choices (localization of the engine in the vehicle, alimentation type, etc.).

- A consequence of the first point is that it reduces the possibilities for innovation (at level 0 or 1 it is possible to develop the electrical engine, but it is impossible to do so at the level of functional elements).

- These choices arise partially from choices the company has made in the past. That is, we can define a brand-new car using a new powertrain that is based on an existing engine.

- The boundary level between the component made and the components purchased defines the functional element level. That level evolves over time and is specific to an organization and sometimes to a specific product/manufacturer couple.

- Therefore, the definition of the modules is not a simple objective functional division, as it takes necessarily into account different life cycles, such as those of the product and the architecture, as well as the make or buy frontiers in the supply chain (Campagnolo & Camuffo 2010).

The definition of modules calls for the definition of standard interfaces. We define interfaces as any interactions between two components (Chen & Liu 2005, Erens & Verhuslt 1997). To simplify the exhaustive determination of the interfaces, since 1994, Sanchez has differentiated five main types of interactions:

- Attachment interfaces (how components are connected/plugged)

- Transfer interfaces (how energy is transferred)

- Control interfaces (how information signals are transferred)

- Spatial interfaces (packaging constraints and precise localization)

- Environmental interfaces (effects between components such as thermal and magnetic)

The standardization of interfaces is a concept older than that of modularity. For example, the standardization has been used for decades in the construction of costless custom-made electrical and plumbing networks. Two objectives can lead a company to standardize its component (modules or not) interfaces:

- At the product range level, the objective is to re-use the modules developed for one product on other products (Ulrich 1995). This approach, which aims to reduce diversity, is often proposed in the literature design as it reduces development time and the need for additional resources. This approach, however, runs the risk of cannibalization between products if we reuse a module that is visible to the customer (Eggen 2003). On the other hand, this can also be a marketing strategy, as is the case with the Ikea group.

- At a module level, it is easy to create diversity with respect to performance for a given function (Sanchez 1996, 2002, Baldwin & Clark 1997, Pine II 1993). This approach, which aims to simplify the management and the creation of strong diversity, is present in the literature focused on mass customization. Our work regarding rationalization of the number of alternative modules is consistent with this use of modularity.

Thus, a module can be described as a collection of AM for a sub-system associated with a function. Each AM represents a specific level of performance or a peculiar technical solution to accomplish the considered function, and accordingly, the standardization of the interfaces is the cornerstone of a good modular vision (Sanchez & Mahoney 1996).

The very early definition of the interfaces in a new project generally does not include their concrete design. In fact, the definition of the standard interfaces is the explanation of design rules and specifications that will serve as input constraints in the further designs of AM. The early definition of those standards, which must be stable over time, implies a huge expertise regarding the products and a solid understanding of their forward evolutions (Erens & Verhulst 1997, Chen & Liu 2005, Eggen 2003, Ulrich 1995).

The definition of the modules, based on their functional division and by the description of their interfaces, is a strategic activity for companies that is usually referred to as the architecture phase. Ulrich (1995) defines the architecture as:

- the arrangement of functional elements,

- the mapping from functional elements to physical components, and

the specification of the interfaces among interacting physical components.

The definition of the modular architecture of a product is the moment when the functions that will be realized by the modules are identified. Indeed, it is incorrect to consider that a product is necessarily either modular or integral with respect to its architecture (Ulrich 1995). Thus, the architecture defines the frontiers between components that will be developed using modular architecture from those that will be developed using integral architecture (Ulrich 1995, Chen & Liu 2005).

As Erens & Verhulst (1997) emphasize, the architecture of a product facilitates the identification of the components (which may be modules) that will be chosen as stable, that is, without diversity. For example, when Renault develops a new car, despite the huge diversity of products generated by the customization decisions made by the customer, a substantial number of used components is common. This approach gives a first definition of the concept of platform. Indeed, the platform can be defined as the set or sub-set of stable modules or components within a range of products, including the interfaces (Chen & Liu 2005, Dahmus et al. 2001). Once the platform is built, it represents both the architecture of the product and a certain number of stable modules or components. Thus, a product family is defined as the set of products belonging to different market segments but sharing the same platform.

Ulrich (1995) describes 3 possible types of modular architectures:

- Bus type: The platform includes a physical support element on which all of the modules are plugged. The interfaces are standardized within the range of products and are common for all modules. While this approach is often used in personal computers, it seems unusable in the automobile industry.

- Slot type: The platform includes a physical support element on which all modules are plugged. The interfaces are standardized within the range of products but are specific for each module. This type of architecture is the historical automobile platform form of architecture. For us, the modular approach aims to exceed this vision.

- Sectional type: The physical support no longer exists. The modules are assembled to obtain the overall complex system. The interfaces are standardized within the range of products but are generally specific for each module. This architecture seems to be the one most commonly used in the automobile industry with the modular approach (for example, the gearbox is plugged on the engine that is plugged on the chassis).

With the first type, it seems easier to reach an independency between AMSs, because modules are essentially only interfaced with the platform. Thus, this architecture may be more compliant for the economic standardization model proposed above (§1.1). With the second type, modules often have more interfaces (with more AMSs) and in practice remain technically dependent. For example all gearboxes will not be assembled with all the engines. Thus this approach calls for a generalization of our model which takes into account those constraints. We will propose it in §2.2.

Given the modular approach, the platform can appear at the level of a given product family, as a set of modules without diversity, or at the level of the range of products, as a group of alternative module sets. The concept of product family is then defined by the finite diversity of interchangeable variants for the rest of the alternative modules (Dahmus et al. 2001).

Modular architecture is based on module independency. This independency simplifies the use of the method of rationalization at the level of each set of variants of modules. In practice, this independency is difficult to achieve, and at best, it is limited to the application cases anticipated (Ulrich 1995). Thus, the independency between modules is real only for a delimited range of use. Given that the technical and economical optimization is opposed to the absolute independency between modules, firms rightly do not seek to reach optimization (Ulrich 1995, Eggen 2003). All gearboxes are not compatible with all engines of a car manufacturer. Therefore, the rationalization of diversity within each module must, in practice, take into account the interdependency between modules.

2.2 Rationalization of the modular architecture

The approach described in § 1.1 is used without issue to rationalize the composition of an AMS having no dependent links (Chatras et al. 2013) with other AMSs. When two AMs *j* and *h* pertaining to two different AMSs $\mathscr{E}_J$ and $\mathscr{E}_H$ are physically dependent (engine and gearbox, for example), these AMs can be assembled only if the interface between these modules allows for it. One can note that the AMS $\mathscr{E}_H$ can correspond to a set of alternative platforms on which the AMs can be mounted. It is preferable to start with a set of elementary AMs (engine rather than powertrain) and take into account the postponement possibilities in the definition of these AMs.

This interdependence implies an adaptation of the concept of need that cannot be defined any further at the level of an AMS, but rather at the level of a set of interdependent AMSs. For example, an independent list of 20 needs can be associated with the engines and another independent list of 4 needs can be associated with the gearboxes. The simultaneous determination of the engines and gearboxes to be used can be based on a combined list of 31 needs (less than the combinations without restrictions, 4x20), making it possible to obtain by aggregation the two independent lists. One preserves index *i* for this broader list with which the needs requirements d_i are associated.

		Alternative Modules $\mathscr{E}_J$						Alternative Modules $\mathscr{E}_H$						Demands
		1	2	…	*j*	…	n_H	1	2	…	*h*	…	n_H	
Needs	1													d_1
	2													d_2
	…													…
	i													d_i
	…													…
	m													d_m

Table 3: Ability of the AMs $\mathscr{E}_J$ and $\mathscr{E}_H$ to meet the needs' (Boolean parameters) and needs' annual demands

The introduction of the new AMS $\mathscr{E}_H$ implies the creation of the binary variable v_{ih} ,which takes a value of 1 if the AM *h* satisfies the need *i*, assumed to be covered by only one AM *h* (it can meet several needs). As previously noted, it is useless to create a variable v_{ih} if the corresponding parameter a_{ih} is null, to limit the number of decision variables. Equation (10) enforces each need *i* to be satisfied.

$$\sum_h v_{ih} = 1, \forall i \quad (10)$$

The production of the AM *h* is $\sum_h v_{ih} \cdot d_i$.

The Boolean parameter b_{jh} formalizes the dependence between $\mathscr{E}_J$ and $\mathscr{E}_H$; it takes a value of 1 if the AMs *j* and *h* can be directly coupled, and 0 otherwise. To take into account the problems of interfaces, it is necessary to prevent the variables x_{ij} and v_{ih} (introduced only if $a_{ij} = 1$ and $a_{ih} = 1$) to take a value of 1, if $b_{jh} = 0$, it is enough to add the constraint (11), constraint, created only if $a_{ij} = 1$ and $a_{ih} = 1$.

$$x_{ij} + v_{ih} \leq 1 + b_{jh}, \forall i, j, h \quad (11)$$

The cost function to be minimized is then the sum of all of the cost functions, defined by relation (6), of the AMS selected in these two AMSs.

$$\sum_{j=1}^{j=n_J} \sum_{k_j=1}^{k_j=K_j} (A_{k_j} \cdot z_{k_j} + c_{k_j} \cdot u_{k_j}) + \sum_{h=1}^{h=n_H} \sum_{k_h=1}^{k_h=K_H} (A_{k_h} \cdot z_{k_h} + c_{k_h} \cdot u_{k_h}) \quad (12)$$

The coupling between the modules *j* and *h* not having the same interface can be possible due to a junction component with a unit cost e_{jh} . Thus,

taking into explicit account the junction components is not justified if their costs are negligible compared to the costs of the AMs that they assemble. The Boolean parameter f_{jh} takes a value of 1 if this coupling is only possible through a junction component, and 0 if the interface is standardized or if the coupling is impossible (which implies $b_{jh} + f_{jh} = 0$). Then relation (11) becomes relation (13).

$$x_{ij} + v_{ih} \leq 1 + b_{jh} + f_{jh}, \forall i, j, h \quad (13)$$

Moreover, it is necessary to introduce a new Boolean variable u_{ijh} that takes the value of 1 if the junction component between the components *j* and *h* is to be supplied to satisfy need *i*. This is carried out through constraint (14), created only if $a_{ij} = 1$ and $a_{ih} = 1$.

$$u_{ijh} + 1 \geq f_{jh} \cdot x_{ij} + f_{jh} \cdot v_{ih}, \forall i, j, h \quad (14)$$

This leads to a new cost $\sum_{j,h} e_{jh} \sum_i u_{ijh}$ to add to the cost function defined by relation (12), which gives relation (15).

$$\begin{aligned} &\sum_{j=1}^{j=n_J} \sum_{k_j=1}^{k_j=K_j} (A_{k_j} \cdot z_{k_j} + c_{k_j} \cdot u_{k_j}) \\ &\quad + \sum_{h=1}^{h=n_H} \sum_{k_h=1}^{k_h=K_H} (A_{k_h} \cdot z_{k_h} + c_{k_h} \cdot u_{k_h}) \\ &\quad + \sum_{j=1}^{j=n_J} \sum_{h=1}^{h=n_H} e_{jh} \sum_{i=1}^{m} u_{ijh} \end{aligned} \quad (15)$$

The generalization of this approach to several AMSs physically dependent does not pose a particular problem of formalization as long as the number of dependent AMSs is low. The main problem lies within the definition of the needs as it must be common to this dependent AMS.

3 Conclusion

The mass customization is the paradox of modern manufacturing companies. Firms succeed in offering increasingly more products within an increasingly shorter time to market at an always lower cost. To overcome this challenge, a good understanding of the different levels of diversity is necessary. Indeed, diversity has different meanings because it can be measured at different levels of needs or at different levels in the bill of material. Therefore, companies want to find ways to maximize the offered diversity of the end product while they rationalize the diversity of components or modules that constitute the products. This rationalization goes through a product standardization approach for a given function. Modular architecture, which is based on a precise functional division of the products, permits not only the simplification of the generation and management of the needed diversity, but it also offers a strong framework for portfolio analysis, thus accentuating standardization. Given that modules are complex components, standardization based on a single parameter is no longer acceptable. In addition, the complexity of the overall products prevents companies from reaching the desired independency. As a result, the standardization of alternative modules cannot be performed freely without taking into account the choices of standardizations in other alternative module sets. In this paper, we first proposed a model of diversity rationalization that allows the optimization of the total delivery cost regarding a set of technical parameters. This approach takes into account the architectures and components developed in the past and can be easily generalized to take into account the dynamic evolution of demand. We propose an approach that extends the product standardization approach to a range of alternative modules sets with explicit compatibility restrictions.

This variety control approach should be introduced in the design phase during the range renewal. It requires economic information that is available only during a late stage in the development of alternative modules. Generally, especially with respect to the increase in modularity, at this later stage, each cell of the organization is highly specialized. This contributes to complicate the global approach that takes into account the interdependencies between modules. Therefore, the question of optimal organization, which permits greater control regarding relevant variety among the overall range of products, seems to be a fundamental question that future research should address. Numerous studies have emphasized that one of the main impacts of the modular product architecture is the functional division of the organization (Baldwin & Clark 1997, Sako & Murray 1999, Galvin & Morkel 2001, etc.). If, in a certain way, modular architecture facilitates product standardization, the consequences of the organizational trends on product standardization remain unclear.

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