Standardization, Commonality, Modularity: A Global Economic Perspective

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Abstract. This paper deals with the problem of simultaneous standardization of a set of modules and of multiple sets of components that may be combined in these modules. The aim is to minimize future costs. The components and modules, whether already existing or yet to be created are not related to predetermined BOMs. The problem takes into account coupling constraints between components because not all components included in a module may be coupled (coupling restriction), although some of the restrictions can be lifted through "junction components". Our approach is readily implemented and significantly improves decisional consistency when compared to the standardization approaches that deal with the problem in isolation as opposed to globally. It also matches the level of detail used in large organizations for forecasting purposes. This approach is illustrated with a real case study of great dimension.

Keywords: Standardization, management of diversity, optimization, product design, BOM definition

1 Introduction

Standardization is a process aiming to rationalize the definition of a set of components with different functional features that are used to satisfy a number of needs of similar nature (Rutenberg 1969, Fisher et al. 1999, Dupont and Cormier 2001, Perera et al. 1999, Baud-Lavigne et al. 2012…). We call these components 'alternative components (ACs)' and related sets 'set of alternative components (SAC)'. In general, when this process is in place, a SAC already exists and can be completed by a set of components that are still in the pre-development, study phase. The functional features of the related ACs are of the same nature as that which currently define the needs to which demand is associated. The proposed rationalization exercise generally results in reducing the number of components as well as the expenses committed to satisfy the needs. Standardization, therefore, is key to improving competitive advantage, particularly in the context of mass production. In practice, the combination of different SACs is limited by technical restrictions that affect the efficiency of models that standardize each SAC separately. We propose a solution to lift some of these restrictions and the related interfacing issues between two ACs through what we call "junction components".

Modules are particular components that combine elementary ACs belonging to multiple SACs. Modules may exist physically and be delivered to an assembly plant, or virtual and be set up at the production line. Standardization, therefore, can occur at module level, with "alternative modules (AMs)" being selected from a set of AMs (SAM). The modules match needs that we call "services" while the different kinds of needs are called "alternative services (ASs)". These represent the diversity of combinations of functions delivered to customers via such devices as web configurators. The set of ASs must be covered by the relevant SAM. By introducing modules one is able to use the sales forecasts usually prepared at AS, aggregated level. This level of aggregation moreover is adequate to make reliable forecasts down to AC level, where most of the cost saving opportunities are.

A particular AC can be mounted on several AMs, thus creating a commonality, from which valuable economies of scale may be derived. In this context, standardization must be handled jointly at AM and AC level, it being understood that AC demand stems from demand for the relevant AMs. This aspect is all the more valuable as demand forecasts may be limited to an aggregate level and as, in the approach we use, the BOMs for the AMs remain to be defined. The simultaneous optimization of SAM and component SACs standardization is the first contribution of our paper. Its other contribution relates to the cost savings opportunity. We shall show that the cost-benefit analysis enabled by the model covers both the time horizon and spatial dimensions.

Our paper opens with a review of literature on standardization as circumscribed to the relevant scope (Section2). This shall highlight a number of gaps that our model proposes to close. The next section shall present our model which builds on the work described in the literature we reviewed and enables a simultaneous standardization of AMs and their component ACs to be performed (Section 3). We end the paper with a a quantified case study and a conclusion.

2 Literature review

Our article is geared to standardization models and we therefore reviewed papers proposing prescriptive methods to reduce diversity. Accordingly, our analysis excludes both papers dealing with diversity management methods as well as descriptive papers (Martin and Ishii, 2002; Fonte, 1994; Sered and Reich, 2006; Perera et al., 1999).

We reviewed research into ways of standardizing components, modules or both. Our definition of modules is compatible with that expounded in the body of reference literature (Ulrich, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 1997; Dahmus and Otto, 2001…). We are not seeking to define an optimal modular architecture, a matter we consider settled, but rather to define AM diversity in a way that is relevant for any particular SAM. We found two distinct approaches in the prescriptive research surveyed.

- That of the school of research focusing on postponed differentiation. Here, the set of SACs and their ACs is known and the question is to find the optimal level of AM diversity (where AMs are seen as groups of components) to be managed (Swaminathan and Tayur, 1998; Agard and Tollenaere, 2002; Rai and Allada, 2003; Agard and Penz, 2009; Baud-Lavigne et al., 2012; Agard and Bassetto, 2013). These papers address quality and assembly time rather than cost reduction issues. In this case, the make-up of SACs used to build the modules is predetermined and not open to amendment through introduction of new ACs. This approach therefore appears to be quite remote from the multi-level standardization approach we chose.
- In the second school of research, that founded by Renard (1877), the starting point is a set of needs and of a set of components suitable to meet them. Here, the onus is on determining the corresponding diversity at the lowest cost for this set to be used and therefore produced (Rutenberg, 1971; Dupont and Cormier, 2001; Fisher et al., 1999; Lamothe et al., 2006; Giard, 1999, 2001, Chatras & Giard 2014). This question can be posed at any phase of the life cycle of a product or set of products. Here, the aim is to find the best compromise between the cost of excessively diverse solutions tuned to a wide variety of needs and the cost of a single, over-performing solution, capable of meeting all needs. The definition of a SAC is sometimes implicit in the literature (Rutenberg, 1971; Dupont and Cormier, 2001; Lamothe et al., 2006) as it is not linked to the definition of any function used to define needs and components. Where the SAC is explicit, it is defined either through a single function (Renard, 1877; Fisher et al., 1999) or

through several fuctions (Giard, 1999,2001). From an operational standpoint it is clear that defining components through multiple functions is both more efficient for analytical purposes and for the purposes of defining the input data for the optimization model.

Some authors on standardization as it is defined in our introduction have attempted to standardize several interdependent SACs simultaneously (Rutenberg, 1971; Dupont and Cormier, 2001; Lamothe et al., 2006). But they did not propose to introduce “junction components” to lift some of the coupling restrictions and so further streamline costs. Moreover, none of these articles include a simultaneous analysis of standardization at two levels of the BOM to deal with the overall diversity of a SAM and of its component SACs as the first step of an approach that can have several levels. The approach that we develop aims to fill the gap through a model readily useable by business actors to directly and easily integrate all of the technical constraints and junction components capable of lifting some of them.

The determination of demand through ACs is a major stake for the model as it is crucial to the solution (Fisher et al., 1999; Baud-Lavigne et al., 2012). Approaches that fail to take demand into account in the target function thus appear not to be entirely relevant from an economic standpoint (Renard, 1877; Agard and Tollenaere, 2002; Agard and Penz, 2009). All of the other approaches rely on volume or percentage by type of need. Our model improves the definition of demand used for economic analysis in three important respects: first by lending consistency to the demand to be satisfied by the AMs and the ACs without reference to any predetermined BOM. Here the BOM actually stems from the optimization exercise. Second, recourse to modules uses an aggregate level of forecasting similar to that produced by sales departments. Third but not least, not only does it take into account demand but also demand change and life cycle dynamics as well as the emergence of new future needs.

Additionally, the fact that the model is capable of integrating the time horizon, an essential feature of strategic choices, enables it to account for both existing and future needs (Fisher et al., 1999). Our recommendation diverges slightly from that by Lamothe et al. (2006) (only paper to have explicitly taken time into account in the target function). To conclude this literature review, we note that our approach is in line with part of the body of research and introduces a number of substantial improvements.

3 Formulation of the standardization problem

Our description of the problem is a two-stage process. We begin by a quick analysis (Section2.1) of the models our approach actually extends. This will enable us to discuss a few important concepts as well as introduce our analytical approach. We go on (Section2.2) to fully develop our model against a general context. One can find a table of notations by using the link in section 4.

3.1 The Single SAC Standardization Model

Renard (1877) appears to be the first author to have streamlined the number of ACs required to meet multiple demands. A single functional characteristic f is used to specify the need to be satisfied by an AC and a single technical characteristic q of the AC is taken into account; in the case studied by Renard, q is the diameter of cable and f is the maximum traction the cable can sustain before breaking. Through an experimental study, f is described by a monotonous increasing function of q. Renard proposes to define the variety arbitrarily, by breaking up the possible values for f into a fixed number of ranges whose upper limits are subject to geometrical growth. One may criticize this approach in three respects, all of which are actual shortcomings of a number of current ISO standards: it uses a single functional characteristic of continuous nature; one has no reason to determine a priori the optimal number of ACs; the definition of the number of ranges and their boundaries is not based on any economic criteria since demand and costs are not part of the reasoning.

An explicit reference to several functional features and economic criteria is proposed by Giard (1999, 2002). The selected features may be quantitative (weight, torque…) or qualitative (reference to a standard…). Table R cross-referencing ACs $(c = 1..C)$ and functional features $(f = 1..F)$ of these ACs, either existing or under study can be drawn up, with item R_{fc} corresponding either to a numeric value or to a qualitative attribute (see tables below). The inclusion of ACs in the study phase refers to a perception of future needs, useful in substantiating the conclusions of the selection process. In order to harmonize the terminology used, we consider in this paragraph that an AS is directly satisfied by an AC, since we consider a single BOM level. To each AS s $(s = 1..S)$ is associated demand d_p , these ASs actually corresponding to the breakdown of demand. An AS is satisfied by a single AC, which is justified in the absence of production constraints, by the fact that we should use the most cost-efficient AC to satisfy an AS, with any mix leading to a cost increase. On the other hand, an AC can satisfy several ASs. The analysis of these ASs is based on the same functional AC features with quantitative features corresponding to value ranges and qualitative features to the list of acceptable attributes. Table S describes $(\rightarrow S_{sf})$ the conditions for AC eligibility. The combination of tables R and S information serves to draw up the table of Booleans A indicating whether the AC c meets $(A_{cs} = 1)$ or not $(A_{cs} = 0)$ the specifications of AS s. To optimize the selection of the ACs to be used, we introduce binary variable x_{cs} = 1 if AC c is used to satisfy service s; and of course, this variable is only relevant where $A_{cs} = 1$. The constraint $\sum_c x_{cs} = 1$ guarantees that each AS shall be satisfied by a single AC. Total AC c demand is written $\sum_s d_s \cdot x_{cs}$. The function of cost to be kept down refers to AC production costs. If one only uses direct variable costs w_c , the target function is $\sum_c w_c \cdot \sum_s d_s \cdot x_{cs}$ The cost function developed by Giard (1999, 2002) in this formulation of the problem is more complex: it is a monotonous increasing function, which is partly linear. This enables the inclusion of new AC study and investment fixed costs stemming from development of new CAs while in their pre-launch, study phase. It also enables the inclusion of any positive or negative synergy effects induced by production of several ACs at a particular site.

R_{fc}		Actual functional characteristic f: f=1 Power (hp DIN)	f=2 Climate 1:Temp- 2:Cold	f=3 CO_2 (g/km)	f=4 Wheight (in kg)	$f=F=5$ Euro.X
Alternative Component	c=1	75	1	90	160	5
	c=2	90	1	105	160	5
	c=3	90	1	90	160	6
	c=4	110	1	110	170	5
	c=5	110	2	110	170	5
	c=6	120	2	110	170	5
	c=7	130	1	120	200	5
	c=8	150	1	160	180	5
	c=9	130	2	140	200	5
	$c=C$ =10	130	2	120	170	6

S_{pf}		Required functional characteristic f: f=1 Power (hp DIN)	f=2 Climate 1:Temp- 2:Cold	f=3 CO_2 (g/km)	f=4 Wheight (in kg)	$f=F=5$ Euro.X	Demand (10^5)
Alternative Prestation (AP)	p=1	≥ 65	1	≤ 92	≤ 163	≥ 5	60
	p=2	≥ 80	1	≤ 107	≤ 160	≥ 4	40
	p=3	≥ 90	1	≤ 108	≤ 171	≥ 5	20
	p=4	≥ 90	1	≤ 93	≤ 160	≥ 6	20
	p=5	≥ 90	1	≤ 104	≤ 170	≥ 6	90
	p=6	≥ 105	1	≤ 115	≤ 175	≥ 5	52
	p=7	≥ 110	1	≤ 110	≤ 186	≥ 5	49
	p=8	≥ 110	2	≤ 135	≤ 200	≥ 4	8
	p=9	≥ 115	1	≤ 143	≤ 185	≥ 4	40
	p=10	≥ 115	1	≤ 125	≤ 205	≥ 5	12
	p=11	≥ 130	1	≤ 150	≤ 200	≥ 5	5
	p=12	≥ 150	1	≤ 160	≤ 180	≥ 4	92
	p=13	≥ 130	2	≤ 185	≤ 220	≥ 4	26
	$p=P$ =14	≥ 130	1	≤ 125	≤ 170	≥ 6	2

A_{cp}		Alternative Component: c=1	c=2	c=3	c=4	c=5	c=6	c=7	c=8	c=9	$c=C$ =10
Alternative Prestation (AP)	p=1	1		1							
	p=2		1	1							
	p=3		1	1							
	p=4			1							
	p=5			1							
	p=6				1	1	1				
	p=7				1	1	1				
	p=8					1	1				1
	p=9						1				1
	p=10						1	1			1
	p=11							1		1	1
	p=12								1		
	p=13									1	1
	$p=P$ =14										1

Table 1. example of functional definition of 10 ACs, 14 ASs and the Boolean matrix resulting from the cross-referencing of these definitions

This approach, however, present three important limitations that we address under Section 3.2: first the SACs are supposed to be independent but this is not realistic (Chatras & Giard, 2014); moreover, defining needs and, therefore, demand at component level is very difficult in practice; finally, these approaches largely ignore the spatial (logistical chain) and temporal aspects (demand change and possible launch of new components) in the cost function.

3.2 Formulation of joint standardization of a SAM and its component SACs

The originality of our extended model lies in the simultaneous selection of AMs and their component ACs to satisfy the requirements of a set of ASs. In our proposed model, Boolean variables are linked to these decisions (Section3.2.1). The way in which both the time horizon and spatial dimensions are factored into the coefficients of the target function is described under Section3.2.2. below.

3.2.1 The basic model

Our formulation uses four kinds of sets: ASs, ACs and SACs complemented by another set, discussed below, so as to include the junction components required to couple two ACs from two different sets in the absence of any suitable interface.

- The set of ***alternative services*** includes S ASs, subscripted by *s*. d_s is the Demand for service *s*.
- The set of ***alternative modules*** includes **M** AMs, subscripted by *m*. Some AMs may not meet the needs of some ASs. The Boolean parameter a_{sm} takes a value of 1 where AM *m* is suitable to meet demand for AS *s*, and the value 0, if it does not. An AM may satisfy several ASs. Since the needs for an AS are met by a single AM, the number of AMs selected in the solution cannot exceed S. The fixed cost f_m corresponding to the development and investment expenditure for the selected AM *m* is then added to the formula as well as its direct variable production cost, g_m .
- One distinguishes **K** sets of ***alternative components*** (SACs), subscripted by $k\ (k=1..K)$. SAC *k* includes C_k alternative components ($c_k=1..\mathrm{C}_k$). The choice of AC c_k from SAC *k is* associated to a fixed cost w_{ck}^k , corresponding to development and investment expenditure, plus direct variable production cost v_{ck}^k . Where one has to factor in two SACs simultaneously, subscripts k_1 and k_2 are used. An AM always includes an AC drawn from each SAC. The same AC can be mounted in multiple AMs and some ACs cannot be mounted on certain AMs. The Boolean parameter b_{mck}^k takes a value of 1 where AM *m* can comprise AC c_k from the SAC, and 0, if it does not.

Let x_{sm} be a *decision variable* that corresponds to the demand for the AM *m* selected for the purpose of the AS *s*. This variable is only utilized if AS *s* can be provided through module *m* $(\rightarrow \mathrm{a}_{sm}=1)$. Service *s* is met by an AM, as enforced by constraint (1).

$$\sum_{m=1}^{m=\mathrm{M}} x_{sm}=d_s, \forall s=1..S \tag{1}$$

The demand for module *m*, possibly null, is $\sum_{s=1}^{s=S} x_{sm}$. It is then useful to create *auxiliary variable* $y_m=1$ if AM *m* is chosen. This binary variable is related to the decision variables x_{sm} by constraint (2) in which constant Ω is a big value (for example $\Omega=\sum_{s=1}^{s=S} d_s$). Constraint (2) is sufficient because the cost function to be minimized integrates variable y_m , weighted by fixed cost g_m .

$$\sum_{s=1}^{s=S} x_{sm} \le \Omega \cdot y_m, \forall m=1..\mathrm{M} \tag{2}$$

Let u_{mck}^k be a *decision variable* that corresponds to the demand for AC c_k from SAC *k* used to produce the AM *m*. This variable is only utilized if AC c_k can be assembled in module *m* $(\rightarrow b_{mck}^k=1)$. The total demand for AC c_k from SAC k, possibly null, is noted $\sum_{m=1}^{m=M} u_{mck}^k$. The relation (3) enforces that module *m* is composed of one AC from each SAC and that demand for each AC from AM *m* is equal to the total demand for *m*.

$$\sum_{ck=1}^{ck=Ck} u_{mck}^k=\sum_{s=1}^{s=S} x_{sm}, \forall m=1..\mathrm{M}, \forall k=1..K \tag{3}$$

One must create *auxiliary variable* $v^k_{mc_k}$ =1 if AC c_k from SAC *k* is chosen for module *m*. This binary variable is related to the decision variables $u^k_{mc_k}$ by constraint (4). The constraint [5] enforces that the AM *m* uses only one AC from each SAC.

$$u^k_{mc_k} \le \Omega \cdot v^k_{mc_k}, \forall m = 1..\mathrm{M}, \forall k = 1..K, \forall c_k = 1..C_k \tag{4}$$

$$\sum_{c_k=1}^{c_k=C_k} v^k_{mc_k} = y_m, \forall m = 1..\mathrm{M}, \forall k = 1..K \tag{5}$$

One must introduce a second *auxiliary variable* $s^k_{c_k}$ =1 if AC c_k from SAC *k* is chosen for one or several modules. This binary variable is related to the decision variables $u^k_{mc_k}$ by constraint (6). This constraint is sufficient because the cost function to be minimized integrates variable $s^k_{c_k}$, weighted by fixed cost $\mathrm{w}^k_{c_k}$.

$$\sum_{m=1}^{m=\mathrm{M}} u^k_{mc_k} \le \Omega \cdot s^k_{c_k}, \forall k = 1..\mathrm{K}, \forall c_k = 1..\mathrm{C}_k \tag{6}$$

The above formulation rests on the implicit assumption that there is no constraint on possible combinations of ACs assembled in a module. It is, however, possible that ACs c_{k1} and c_{k2} belonging to SACs k_1 and k_2 cannot be assembled in the same module, in particular for reasons of interfacing. In this case, the Boolean parameter $\lambda^{k1\wedge k2}_{c_{k1}c_{k2}} = 1$ is used to represent this coupling restriction; alternatively it will be = 0. This leads to creation of the Boolean matrix $\Lambda_{k1\wedge k2}$ for each couple of SACs whose ACs can be interfaced. This restriction results in the introduction of constraint (7) to deal with cases of incompatibility.

$$u^{k1}_{mc_{k1}} + u^{k2}_{mc_{k2}} \le \sum_{s=1}^{s=S} x_{sm} \\ \forall m = 1..\mathrm{M}, \forall k_1 = 1..\mathrm{K}, \forall k_2 = 1..\mathrm{K} / k_2 \ne k_1 \wedge \lambda^{k1\wedge k2}_{c_{k1}c_{k2}} = 1, \forall c_{k1} = 1..C_{k1}, \forall c_{k2} = 1..C_{k2} \tag{7}$$

In some cases, impossibility of coupling ACs c_{k1} and c_{k2} belonging to SACs k_1 and k_2 may be lifted through a junction component whose impact in the target function is fixed cost $\theta^{k1\wedge k2}_{c_{k1}c_{k2}}$ and direct variable production cost $\eta^{k1\wedge k2}_{c_{k1}c_{k2}}$. This situation is expressed by the Boolean parameter $\gamma^{k1\wedge k2}_{c_{k1}c_{k2}} = 1$, or 0 in the absence of a junction component coupling ACs c_{k1} and c_{k2} . This leads to the use of Boolean matrices $\Gamma_{k1\wedge k2}$ in addition to matrices $\Lambda_{k1\wedge k2}$. These matrices are such as $\gamma^{k1\wedge k2}_{c_{k1}c_{k2}} \le \lambda^{k1\wedge k2}_{c_{k1}c_{k2}}$, the junction components lifting the coupling prohibition. One then introduces *decision variable* $\pi^{k1\wedge k2}_{mc_{k1}c_{k2}}$ standing for the demand for junction component to lift the coupling prohibition of ACs c_{k1} and c_{k2} belonging to SACs k_1 and k_2 for the purposes of module *m*. This variable is used only where $\gamma^{k1\wedge k2}_{c_{k1}c_{k2}} = 1$. In order to force $\pi^{k1\wedge k2}_{mc_{k1}c_{k2}}$ to be equal to the demand for module *m* if ACs c_{k1} and c_{k2} are selected, we introduce constraint (8), dedicated to coupling incompatibilities. The total demand of this junction component is noted $\sum_{m=1}^{m=M} \pi^{k1\wedge k2}_{mc_{k1}c_{k2}}$. And constraints (7) is to be replaced by constraint (9).

$$u^{k1}_{mc_{k1}} + u^{k2}_{mc_{k2}} \le \sum_{s=1}^{s=S} x_{sm} + \pi^{k1\wedge k2}_{mc_{k1}c_{k2}} \\ \forall m = 1..\mathrm{M}, \forall k_1 = 1..\mathrm{K}, \forall k_2 = 1..\mathrm{K}, \forall c_{k1} = 1..C_{k1}, \forall c_{k2} = 1..C_{k2} / k_2 \ne k_1 \wedge \gamma^{k1\wedge k2}_{c_{k1}c_{k2}} = 1 \tag{8}$$

$$u^{k1}_{mc_{k1}} + u^{k2}_{mc_{k2}} \le \sum_{s=1}^{s=S} x_{sm} \\ \forall m = 1..\mathrm{M}, \forall k_1 = 1..\mathrm{K}, \forall k_2 = 1..\mathrm{K}, \forall c_{k1} = 1..C_{k1}, \forall c_{k2} = 1..C_{k2} / k_2 \ne k_1 \wedge \lambda^{k1\wedge k2}_{c_{k1}c_{k2}} + \gamma^{k1\wedge k2}_{c_{k1}c_{k2}} = 1 \tag{9}$$

One must introduce a second *auxiliary variable* $\rho^{k1\wedge k2}_{c_{k1}c_{k2}}$ =1 if the solution needs a junction components for coupling ACs c_{k1} and c_{k2} from SACs belonging to SACs k_1 and k_2 used for one or several modules. This binary variable is related to the decision variables $\pi_{mc_{k1}c_{k2}}^{k1\wedge k2}$ by constraint (10). This constraint is sufficient because the cost function to be minimized integrates the variable $\rho_{c_{k1}c_{k2}}^{k1\wedge k2}$, weighted by fixed cost $\theta_{c_{k1}c_{k2}}^{k1\wedge k2}$.

$$\sum_{m=1}^{m=M} \pi_{mc_{k1}c_{k2}}^{k1\wedge k2} \leq \Omega \cdot \rho_{c_{k1}c_{k2}}^{k1\wedge k2} \quad \forall k_1 = 1..\mathrm{K}, \forall k_2 = 1..\mathrm{K}, \forall c_{k_1} = 1..C_{k_1}, \forall c_{k_2} = 1..C_{k_2} \,/\, k_2 \neq k_1 \wedge \gamma_{c_{k1}c_{k2}}^{k1\wedge k2} = 1 \tag{10}$$

The ***objective function*** to be minimized is the weighted sum of binary variables corresponding to the sum of fixed costs and variable costs, proportional to the quantities to be produced. The three fixed costs are those induced by the selected AMs, $\sum_{m=1}^{m=\mathrm{M}} \mathrm{f}_m \cdot y_m$, the selected ACs, $\sum_{k=1}^{k=\mathrm{K}} \sum_{c_k=1}^{c_k=\mathrm{C}_k} \mathrm{w}_{c_k}^k \cdot s_{c_k}^k$ and by the junction components $\sum_{k1=1}^{k1=\mathrm{K}1} \sum_{k2=1,k1\neq k2}^{k2=\mathrm{K}2} \sum_{c_{k1}=1}^{c_{k1}=\mathrm{C}_{k1}} \sum_{c_{k2}=1}^{c_{k2}=\mathrm{C}_{k2}} \theta_{c_{k1}c_{k2}}^{k1\wedge k2} \cdot \rho_{c_{k1}c_{k2}}^{k1\wedge k2}$. Three variable costs, proportional to the quantities to be produced, have to be distinguished.

- Total demand for AM *m*, $\sum_{s=1}^{s=S} x_{sm}$, is to be weighted by its direct variable cost g_m, inducing partial cost $\sum_{m=1}^{m=M} \mathrm{g}_m \cdot \sum_{s=1}^{s=S} x_{sm}$.
- Total demand for AC c_k from SAC *k*, $\sum_{m=1}^{m=M} u_{mc_k}^k$, is to be weighted by its direct variable cost $\mathrm{v}_{c_k}^k$, inducing partial cost $\sum_{k=1}^{k=\mathrm{K}} \sum_{c_k=1}^{c_k=\mathrm{C}_k} \mathrm{v}_{c_k}^k \cdot \sum_{m=1}^{m=\mathrm{M}} u_{mc_k}^k$.
- Finally, total demand for the junction component linking ACs c_{k_1} and c_{k_2} belonging to SACs k_1 and k_2, $\sum_{m=1}^{m=\mathrm{M}} \pi_{mc_{k1}c_{k2}}^{k1\wedge k2}$, is to be weighted by its direct variable cost $\eta_{c_{k1}c_{k2}}^{k1\wedge k2}$, inducing partial cost $\sum_{k1=1}^{k1=\mathrm{K}1} \sum_{k2=1,k1\neq k2}^{k2=\mathrm{K}2} \sum_{c_{k1}=1}^{c_{k1}=\mathrm{C}_{k1}} \sum_{c_{k2}=1}^{c_{k2}=\mathrm{C}_{k2}} \eta_{c_{k1}c_{k2}}^{k1\wedge k2} \cdot \sum_{m=1}^{m=\mathrm{M}} \pi_{mc_{k1}c_{k2}}^{k1\wedge k2}$.

This cost function is an affine function that combines, for every selected item (AC or AM), an expenditure that depends on production volume equal to demand to be met, plus a fixed cost independent of volume. It is possible, as in Giard (1999, 2002), to formulate the problem in a more complex cost function, being "monotonically non-decreasing and piecewise linear" and to integrate the cost synergy (positive or negative) resulting from simultaneous production of several ACs at the same plant. This transformation of the problem, easy to operate but not selected here, substantially increases the number of variables.

3.2.2. Temporal and spatial dimensions included in the objective function

Though seemingly static, this model is flexible enough to efficiently integrate change in demand, which only impacts direct variable costs. It can also easily be customized to take new AC launch dates into account.

AS demand induces AM demand and, consequently, AC demand. Taking into account the change of demand over time involves replacing d_s by d_{st}, and thus $u_{mc_k}^k$ by $u_{mc_kt}^k$, for periods *t* belonging to a common economic horizon, and to discount production costs using an appropriate periodic discount rate α. In the absence of change in direct variable costs, assuming their real value is constant, the discounted partial cost of AC c_k, chosen for illustration, is $\mathrm{v}_{c_k}^k \cdot \sum_{t=1}^{t=\mathrm{T}} \sum_{m=1}^{m=\mathrm{M}} u_{mc_kt}^k \cdot (1+\alpha)^{-t}$. Function $u_{mc_k}^k = \sum_{t=1}^{t=\mathrm{T}} u_{mc_kt}^k \cdot (1+\alpha)^{-t}$ restores the initial formulation which is to apply instantly to all the direct variable costs of the target function. Three additional remarks may be made.

- By factoring in demand change over time through discounted demand one can address demand beyond the first year simply by changing the lower limit of summation. This device is valuable where new services are coming up or where certain services are slated to replace current services.

- Where some ACs (or AMs) are in the pre-development study phase, the fixed costs associated with the selection of such products is a discounted value of their development cost and, if necessary, investment. Certain constraints must then be included in the formulation of the problem since an AC which is in the study phase cannot be mounted on an AM selected to satisfy immediate demand for one or more ASs. This can result in dividing certain services into two: demand for existing products being defined prior to launch of new ACs while demand for forthcoming products will be defined subsequently. The related data consistency issue is to be dealt with upstream of optimization process.
- Defining the relevant economic horizon (H) presents methodological difficulties common to all economic analyses in connection with product launches; it will therefore not be addressed here.

Coefficients for the target function implicitly include a ***spatial dimension***: the location of AC and AM production plants determines manufacturing costs. If one supposes the location of final assembly lines to be predetermined along with their assigned production, the shipping costs to final delivery are hardly impacted by any decisions. The choice of AM produced in a given plant only impacts assembly cost, which is integrated in direct variable cost. If an AM is produced at multiple plants, this reasoning is valid only if the economic impact is similar. The choice of location of a production plant for new ACs impacts direct variable cost, which includes manufacturing costs as well as delivery costs of the ACs to the AM plants. The choice is relatively straightforward in the absence of impact from decisions concerning other ACs which ought to be manufactured at the same site to achieve synergies. To take such synergies into account, one should adjust the formulation of the problem by integrating supply chain design considerations. This aspect is left aside here.

4 Numerical Example

We have implemented this model on a real case of an automotive company. We take as an example the engine cooling system of cars. Our example that rests on functional definition for linking parts to services, takes into account 178 AMs that need 3 SACs: radiator (RAD), charged air cooler (CAC) and fan. Those three SACs have respectively 71, 40 and 61 ACs. Some CAs from two different SACs cannot be combined freely. The AMs aim at meeting a list of 390 ASs. Matrices a_{sm} and b_{mck}^{k} are around 96% null. With this set of data the number of variables created is 11989 and the number of constraints is 10499. Xpress-IVE solved it with an optimal solution in 3.5s as it is linear. For more information (table of notations, data and results) see Example.

The solution permits to reduce drastically the diversity of the two BOM levels. The number of AMs goes from 178 to 82, the number of RAD goes from 71 to 24, the number of CAC goes from 40 to 15 and the number of FAN goes from 61 to 23. The optimal solution found uses junction components for 8 (RAD, FAN) 2 (RAD, CAC) and 12 (CAC,FAN).

5. Conclusion

The multi-level standardization approach we propose delivers several advantages compared to previous approaches. It relies on a multi-functional standpoint readily implemented by business players and engineers to define the needs (ASs), the AMs and the ACs. It supports simultaneous standardization of AMs and of all the SACs they comprise while taking into account any interfacing incompatibilities and allowing for introduction of junction components. The BOM then stems from this optimization process. The sets may integrate existing components (or modules) as well as others that are still in the design stage. The definition of ASs can be made at a sufficient level of aggregation, which is that used by many configurators, such that demand forecasts are relevant. Finally, the economic model factors the temporal and spatial dimensions both of which are crucial for business.

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