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High variety impacts on Bill of Materials Structure: Carmakers case study

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Abstract: The great variety of offerings from companies engaged in mass customization such as in the automotive sector, implies millions of end products. As in the case of carmakers, this variety proceeds from the combination of dozens of optional or alternative components. A number of technical or commercial constraints prevent most combinations of alternative components (ACs). In these conditions, the creation and updating of the full set of the Bills of Materials corresponding to each end-product is extremely complex. Additionally, customers may not define their product requirements by specifying a list of alternative components because of the number of alternative components (including some entirely unknown to them) and their interdependence. In the past 25 years, scant research has been dedicated to Bills of Materials representation problems in this context. The most exciting ones use predicates to formalize combinatorial constraints between ACs and introduce a 'generic Bill of Materials' concept to avoid an exhaustive description of all end products. Additionally, product description for customer purposes was streamlined through a further concept – the set of alternative services (SAS). This approach, implemented by several carmakers in the last fifteen years, superseded the traditional approach to bills of materials, though it never gave rise to the theoretical exercise described here that involves an analysis of its impact on bills of materials and on operational and tactical decisions. It describes the product based on its market features, before moving on to the actual ACs combinations based on predicates for alternative services (ASs). We show how some carmakers successfully use the AS concept to support sales at configurator level and address operational production issues.

Keywords: mass customization, Planning Bill of Materials, generic Bill of Materials, alternative services, automotive industry

1. INTRODUCTION

Over five decades, many organizations have switched from mass production to mass customization in order to better meet customer expectations. This has resulted in an explosion of potential offering variety that far outstrips actual annual production volume (Pil & Holweg, 2004). This variety of end products is taken for granted for purposes of this paper.

The automotive industry is a perfect example of this context because a car is the result of the assembly of hundreds of components and few industries have pushed the envelope further in implementing mass customization (Anderson & Pine, 1997). Accordingly, all the examples referred to in our paper are drawn from a simplified but real automotive case study, the data of which is used to illustrate some approaches set forth in the literature (§2) as well as that adopted by several carmakers (§3).

From a production point of view, variety is obtained on an assembly line through the combination of alternative components and a few physical postponement operations (such as painting...). We assume that an alternative component (AC) is a variant chosen from a set of alternative components (SAC) that may be used in the same assembly line station. Such variants can differ in terms of technology (engine...), shape (wheels...) or functionality (radio / radio with CD player...). Obviously, end products assembled on a given line share many components but those components that are systematically included do not impact the end-product variety. A variety analysis of a Renault final assembly line shows that vehicle production involves around 700 systematic components and as

many SACs. The 700 SACs account for a total of more than 1900 ACs.

Through the commercial information at their disposal, customers cannot be aware of the underlying variety of the cars they consider purchasing. Indeed, a lot of SACs such as wires or alternators cannot be selected directly by the customer; such hidden components are indirectly linked to customer choices such as electrical equipment (air conditioning, heated seats, foldable mirrors, electric sunroof...). Therefore, neither can the customers define the vehicle they wish to acquire nor the sales departments the vehicles they offer on sale on the basis of a list of ACs. This observation determines the substantial difference there is between the approach we describe here and the literature on the subject.

All products that can be assembled are traditionally described with reference to a Bill of Materials. The Bill of Materials describes unambiguously a product's composition and is shared by all departments within the organization (production, design and manufacturing engineering, sales, management control, after-sales...) (Garwood, 1995). Each separate product therefore, has a specific reference number in the Bill of Materials. The Bill of Materials used in production establishes the list and quantity of all components used by an assembly line to obtain a given end product. For some specific needs (commercial, after sales...), companies may amend Bills of Materials but they are all derived from Bills of Materials used for production.

Both the large variety of products and the existence of constraints between ACs generate two practical questions: i) how to create the exhaustive list of Bills of Materials for all

products potentially assembled (and does it make sense to do so?)? and ii) how to link a customer's order (during its definition or during its production) to a unique Bill of Materials? To answer these questions one needs to analyze Bill of Materials structure in the information system in the context of mass customization. The aim of this paper is to answer these questions through a new diversity model representation already used by some carmakers that conciliates both commercial and industrial issues.

In the literature review (section 2) we shall first describe the traditional way of building combinatorial diversity into Bills of Materials; this solution presents problems that some researchers tackled by introducing the concept of generic Bill of Materials. But due to the current scale of diversity, this solution is no longer adequate. Under section 3, we develop an additional step observed in some current practices based on introduction of a different end-product description that reflects customer added-value. This we call "services" using a functional approach, rather than an organic approach directly based on components. This approach, which does not explain the BOMs, is used by several carmakers (e.g., PSA, Renault, Nissan, Daimler) but appears never to have been theorized so far. Because in the production phase, the organic approach is the only valid one, we also described the solutions required to derive the list of ACs needed for a vehicle from the description of the services it delivers. In this paper we show that this approach satisfies both commercial operational requirements satisfactorily and, in a separate communication made to this congress, that, subject to certain conditions, it additionally meets tactical requirements (MPS) better than the traditional approaches in view of the forecasting process employed by sales departments.

2. LITERATURE REVIEW

Our analysis of extent literature focused on papers dealing with the representation of diversity in BOMs. We broke it up into two parts showing how BOMs developed over time.

2.1. The traditional representation of combinatorial diversity in bills of materials

The representation of combinatorial diversity is traditionally based on planning Bills of Materials, also known as modular Bills of Materials (Stonebraker, 1986). The principle is simple: the Bill of Materials of an end product is a list of component references systematically included in the product and a list of dummy component references corresponding to the SACs used on the assembly line. For both real and dummy components, a Bill of Materials coefficient is used. In this system, every dummy component must point to the ACs of the relevant SAC.

To precisely define a specific car to be built, in each SAC, a single AC has to be selected.

In this context, describing an end product in a relational database (Date, 2012) is quite straightforward. The SACs correspond to entity types, the ACs making up the SACs. Systematic components can be grouped in a kit representing a specific entity type made up of a single entity. In this approach, the Bill of Materials may be described through an association of all entity types of the model whose key is a concatenation of the keys of ACs belonging to different SACs. Note that the combinatory constraints between ACs comprising different SACs introduce additional complexity in representing diversity.

Those constraints are technical and/or commercial. Technical constraints result either from physical interaction between components (constraints regarding interface, volume or performance) or from optimization measures in the purchasing strategy. Commercial constraints result from segmentation to establish consistent offerings and avoid cannibalization between ranges. Both types of constraints may reflect a pack rationale (compulsory association of services) or an exclusion rationale. Chart 1 taken from our case study illustrates the respective roles of both the technical and commercial types of constraints.

In order to describe the problem created by the restrictions, let's use a virtual car model whose diversity results from four engines (E₁, E₂, E₃ and E₄), two radiators (R₁ and R₂), three alternators (A₁, A₂ and A₃), three heating ventilation and air conditioning systems (HVAC) (H₁, H₂ and H₃) and three air conditioning interface panels (I₁, I₂ and I₃). Excluding the systematic components and the other SACs, free of combinatory restrictions, this diversity of components yields $4 \times 2 \times 3 \times 3 \times 3 = 216$ different end-products. Chart 2 reads from bottom to top. It shows how the combinatory restrictions between ACs are taken into account step by step. Level 1 associations correspond to physical constraints, level 2 and 3 associations represent physical and commercial constraints. We note a legacy barred combinations of level *n* (mapped with 'X') with level *n+1* (mapped with a blank cell in grey). As a result, the actual number of end products drops from 216 to 10 (marked with an "O" representing the allowed combinations at level 2) that can be summed up with the following Bills of Materials: E₁R₁H₁A₁I₁, E₂R₁H₁A₁I₁, E₃R₁H₁A₂I₁, E₂R₁H₂A₁I₂, E₂R₂H₂A₂I₂, E₃R₁H₂A₂I₂, E₃R₂H₂A₃I₂, E₃R₁H₃A₃I₃, E₃R₂H₃A₃I₃, E₄R₂H₃A₃I₃.

Chart 2 illustrates the need to use the 5th normal form of relational databases to describe the existing Bills of Materials.

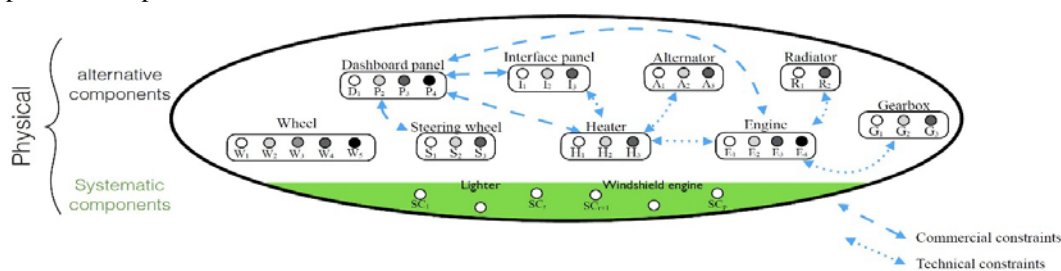


Chart 1 : Commercial and technical constraints between SACs

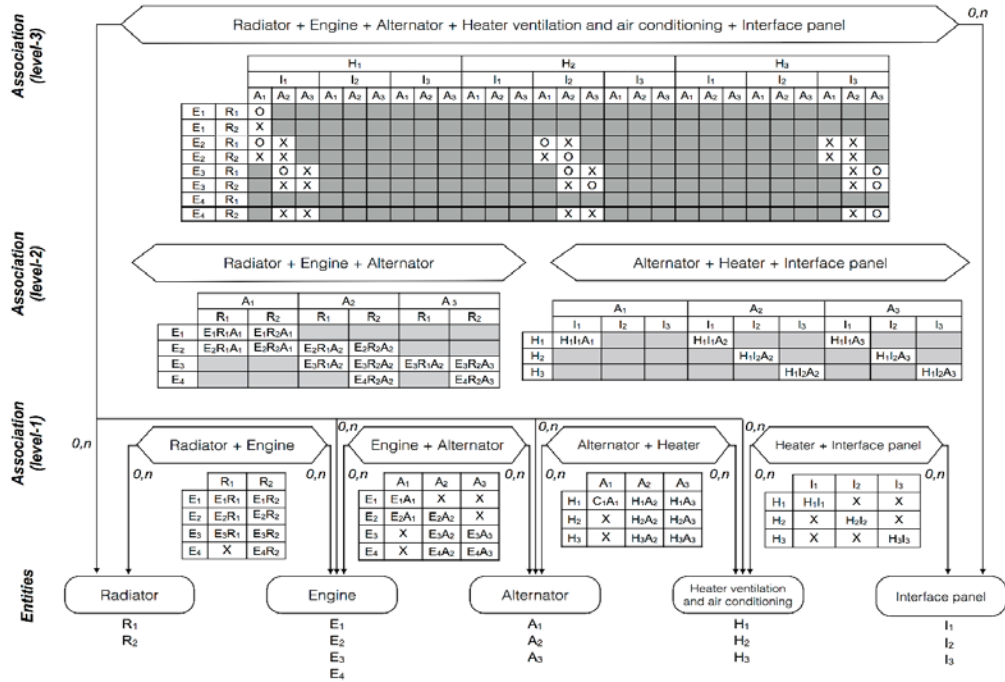


Chart 2 : Example of formal representation using the relational database model

It highlights the difficulties of taking into account the database integrity issues in connection with the combinatory restrictions between CAs in the description of a vehicle in the database. When the variety of end-products is low, as it is for Desktop computers, this approach seems valid.

Where variety results from the combination of dozens of SACs, however, this approach poses both the problem of defining hundreds of thousands of Bills of Materials describing product variety and the problem of its use in the definition of the customer's choices. In practice it is unrealistic to have a customer specify his product by choosing dozens of ACs (there are too many of them and customers are not even aware of some): another approach is required.

2.2. Recourse to generic bills of materials

Hegges and Wortmann (1991) first devised the solution of generic Bills of Materials, and attempted a summary representation of the set of Bills of Materials comprising an end product family. The generic BOM is based on a graph combining the systematic components and selected ACs from SACs. The SACs are labeled primary generic products, and the ACs are selected from parametered values. The solution cuts information redundancy but requires a prior explanation of the valid combinations between ACs. Van Venn and Wortmann (1992) complemented this approach by a translation of the constraints into predicates that reduce the number of ACs combinations. These predicates build on Romanos' suggested approach (1989). Olsen et al. (1997) then proposed recourse to programming language to describe the Bill of Materials of model variants thus making Bill of Materials more legible when restrictions are complex.

Before further analyzing the literature on generic Bills of Materials, let us discuss the use of predicates. A predicate is a logical expression combining a set of propositions that are

either "true" or "false". The combination can be a conjunction, AND (noted \vee) or a disjunction, OR (noted \wedge) and its result is also either "true" or "false". This logical sentence serves as a shorthand description of the constraints connecting use of an AC ("true" proposition) to the presence in the vehicle of ACs belonging to other SACs. Let AC_i^{-1} be the predicate "true" where the AC_i alternative component may be mounted on a vehicle and whose presence depends on that of a set of other AC_j alternative components, chosen from several possible sets. One shall also write $AC_j (=true)$ if component AC_j is mounted on the vehicle. One can then write the three following predicates matching the conditions of use of the three alternators out of fifteen possible parts (each having a predicate) in the example taken in Chart 2:

$$A_1^{-1} = E_1 \wedge R_1 \wedge ((H_1 \wedge I_1) \vee (H_2 \wedge I_2))$$

$$A_2^{-1} = (E_3 \wedge R_1 \wedge ((H_1 \wedge I_1) \vee (H_2 \wedge I_2))) \vee (E_2 \wedge R_2 \wedge H_2 \wedge I_2)$$

$$A_3^{-1} = (E_3 \wedge R_2 \wedge ((H_2 \wedge I_2) \vee (H_3 \wedge I_3))) \vee (H_3 \wedge I_3 \wedge ((E_3 \wedge R_1) \vee (E_4 \wedge R_2)))$$

In an article that aims to integrate data management of Bills of Materials and routings, Jiao et al. (2000) extended the Hegges and Wortmann's (1991) approach of generic Bill of Materials. They proposed a graph made up of nodes representing physical or abstract entities and lines between nodes to map conjunction constraints ("AND") and disjunction constraints ("XOR"). The abstract entity called a 'generic item', represents a set of variants (physical items) of the same type as ACs of a SAC. The graph is also made up of nodes between generic and physical items in which variety parameters are defined to select "XOR" the appropriate line. Configuration restrictions precluding free combination of variants are described separately by a set of logical restrictions (predicates) because mapping them in the graph proved too difficult.

The same year, Bertrand et al. (2000) used a generic Bill of Materials concept called ‘pseudo-item’ to describe the relevant AC combinations based on given criteria. They proposed structuring the generic Bills of Materials on the basis of pseudo-items corresponding to a predetermined sequence of customer choices. Each customer choice is a specific value of the criteria related to the pseudo-items. The outcome is a graph describing the valid combinations of ACs but it seems only practicable in straightforward cases. Finally they suggested defining the MPS at pseudo-item level, which, again, is only feasible if there are not too many of them.

Lamothe et al. (2006) have reengineered the generic Bill of Materials concept based on another set of abstract entities, called *logical items*. These reduce the variety based on explicit economic considerations. These *logical items* serve mainly to describe market segments defined by a set of needs and demand volume. Each need is translated into a hierarchy of service levels. A service level is matched by a unique indicator for a functional definition of the product that summarizes a set of criteria and serves to rank them. A market segment requiring at least one variant is characterized by the list {demand volume, minimum service level}. Each service level can be satisfied by one or more variants of the end-product. Authors proposed an economic model allowing to determine production variants meeting all market segment demand at the lowest cost.

Our review of the literature led us to the conclusion that academics who addressed the representation of diversity always did so with reference to the physical nature of components. Indeed, all of them seem to rely on a tree-like description of BOMs even though some of them introduce virtual levels. As a matter of fact, they implicitly share the assumption that a customer (just like the sales department when drawing up forecasts) defines an AC in each SAC. As already noted in the introduction, this approach does not address the operational and tactical issues of such sectors as the automotive sector due to the great diversity of its offering.

3. BILL OF MATERIALS STRUCTURE BASED ON SETS OF ALTERNATIVE SERVICES

Lamothe et al. (2006) explicitly introduced the commercial point of view in the definition of valid combinations. Their structuring approach is similar to that of commercial offering since a customer can view it through a configurator.

A configurator (Helo et al. 2010, Haug et al. 2012, Trentin et al., 2014) is a web-based interactive application available to potential customers to make a step by step definition of a customized end-product. The choices made at different stages can be restricted by previous choices. The configurator reflects the diversity that an average customer may be aware of. While one could design a configurator enabling customers to customize a product by choosing all the components, this solution nowadays is impracticable because too tedious and because many components require in-depth technical knowledge (more than 700 SACs used for a single car model). The solution chosen by most configurators is implicitly based on the concept of alternative services (ASs). The ASs are grouped into sets (SASs) from which customers can only choose one AS. The SASs correspond to the logical items used by Lamothe et al. (2006). ASs describe product functionalities open to customization options in a language customers can readily understand. For many years Renault, like most carmakers, opted for this approach based on commercial language (which customers can understand) rather than using an approach based on GBOM. Very early on, Renault has developed a detailed structure for this break up of BOMs into SASs (Astesana et al. 1995).

The French web configurator for *Renault Twingo* usually works this way, but there is no set sequence such as ‘equipment level’, then ‘motorization and transmission’ to end with the various options (e.g., color, alloy wheels, air conditioning and parking sensors). The motorization is a SAS comprising all the main engine features (described in sales literature for example). It is coupled with a lot of other alternative

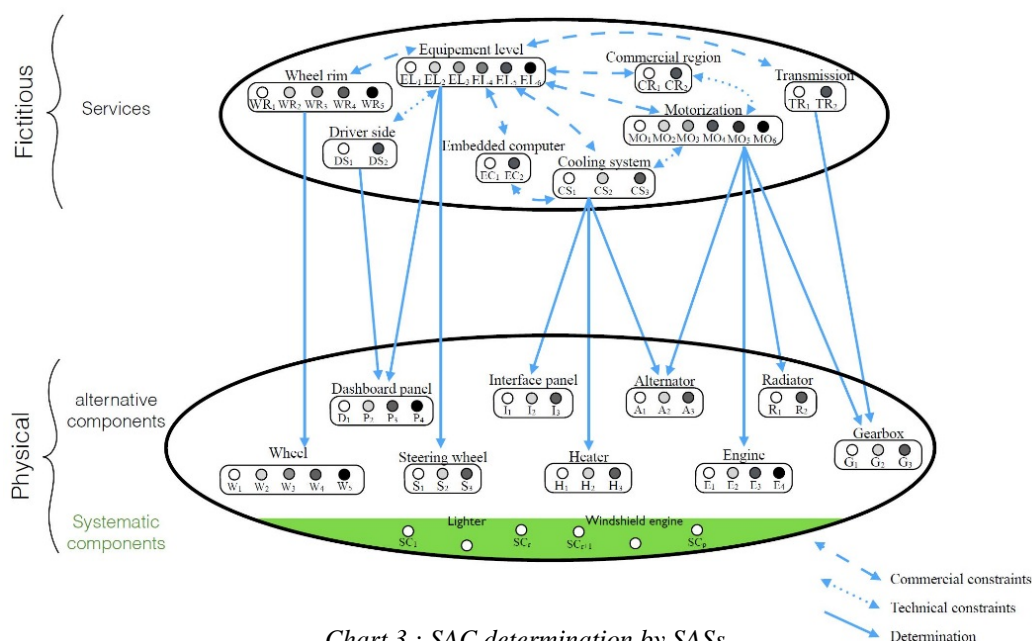


Chart 3 : SAC determination by SASs

Table 1 : Example of alternator AC determination based on 2 SASs

		SAS Motorization (MO)					
		MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆
SAC : Alternator (A)	A ₁	O	O	X	X	X	X
	A ₂	X	O	O	O	O	X
	A ₃	X	X	X	O	O	O

		SAS : Cooling System (CS)		
		CS ₁	CS ₂	CS ₃
SAC : Alternator (A)	A ₁	O	O	X
	A ₂	O	O	O
	A ₃	X	O	O

CS₁ : without cooling system ; CS₂ : manual cooling system ;
CS₃ : automatic cooling system

SAS Motorization (MO)		MO ₁			MO ₂			MO ₃			MO ₄			MO ₅			MO ₆		
		CS ₁	CS ₂	CS ₃	CS ₁	CS ₂	CS ₃	CS ₁	CS ₂	CS ₃	CS ₁	CS ₂	CS ₃	CS ₁	CS ₂	CS ₃	CS ₁	CS ₂	CS ₃
SAC : Alternator (A)	A ₁	O	O		O	X													
	A ₂				X	O	X	O	O	X	X	O	O	X	O	X			
	A ₃										X	X		X	O			O	O

O : possible X : forbidden

components (engine, turbo, filters, sensors, alternator...). The choice of motorization by a customer does not give access to those component variants as these depend on other parameters. This approach helps closely match customer expectations in terms of services leaving out actual product architecture and technical definition.

SASs are related to technical or commercial constraints similar to those between SACs in Chart 1. These commercial constraints have the same origin as those applying to SACs. Technical restrictions between SASs flow from the technical constraints between SACs. This legacy results from the fact that the choice of AS determines the choice of one or more AC(s) as shown in Chart 3 which is based on our real case study. Obviously, all these restrictions constraints between SASs can also be described by predicates, as further discussed below. Despite these restrictions, the diversity of customer offerings remains huge, for example, in France Renault offers millions of different Twingos.

Before describing the impact of AS choice on the determination of the ACs to be used in vehicle production, it is important to highlight the differences with the example of Chart 1 which illustrates the restrictions applying to alternative components. Chart 4 shows that the choice of AC is determined by the choice of one or more alternative services in as many SASs. We will use the term “*determination*” to refer to the causal relationship that links the choice of an AS within an SAS to the choice of one or more ACs. In this approach, it is important to remember that each SAC is determined by the choice of at least one SAS.

The determination relation, symbolized by arrows on Chart 3, should be explained. When just a few SASs determine the choice of an AC, it is possible to use tables to deliver an exhaustive description of the determination relationship. For example, the three tables (using our simplified real case) above illustrate the combinatory determination of the Alternator (which is an AC) from two SASs, i.e. motorization and cooling system. In the last table, the dashes stand for the exclusions inherited from the first two tables and the stars stand for additional exclusions flowing from the combination of two SASs in determining the SAC. In contrast with Chart 1, the choice of alternator is not based on physical SACs (Engine and Heating system) but rather on virtual commercial SASs: Motorization and Cooling system. The configurator integrates the restrictions between SASs by dynamically restricting the set of possible variants for the SASs to the subset of variants compatible with previously selected ASs. In fact, a vehicle ordered by a customer is completely defined by the choice of

a single AS from each SAS. The full list of ASs chosen cannot be seen as a vehicle Bill of Materials because there is not normally one-to-one relation between services and components. But the list explicitly and easily determines the set of level 1 components to use on the assembly line. To do so one may adjust the predicates discussed above to determine components.

So let now AC_i^{-1} be the predicate ‘true’ if AC_i component is used to assemble a vehicle defined by a set of alternative services AS_j (phrase also used to define the need ($AS_j=true$) for these services in this car). In these conditions, the three predicates previously used to define the choice of alternators versus other ACs may be replaced by the following predicates that relate component use to the choice of some alternative services:

$$A_1^{-1} = (MO_1 \wedge (CS_1 \vee CS_2)) \vee (MO_2 \wedge CS_1)$$

$$A_2^{-1} = (CS_1 \wedge MO_3) \vee (CS_2 \wedge (MO_2 \vee MO_3 \vee MO_4 \vee MO_6)) \vee (MO_4 \wedge CS_3)$$

$$A_3^{-1} = (CS_2 \wedge MO_6) \vee (CS_3 \wedge (MO_5 \vee MO_6))$$

To assemble a vehicle, the assembly line uses alternator i where $AC_i^{-1}= true$ in the relevant SAC. This principle applied to all SACs serves to evaluate as many predicates as there are ACs in each SAC, where a single AC can be true because ACs of a given SAC are mutually exclusive. This exploration is not a problem in practice. The predicates referred to under section 3 describe valid combinations of ACs but, unlike those used here, they do not serve to define the AC to be assembled without referring to the entire Bill of Materials for this particular vehicle. Note that the alternator is one of those components customers are not aware of, although they are keenly interested in the motorization and the cooling system option. Thus, the ability to determine the alternator to be used simply by combining two obvious customer choices is a real benefit of this product description approach combining alternative services.

4. CONCLUSION

In the context of strongly diversified mass production characterized by multiple combinatory restrictions required by this diversity as regards possible alternative components, Bill of Materials construction and use pose daunting methodological problems. We argue that detailed Bills of Materials of all potentially manufactured products makes little sense due to the issue of finding the exact reference of an end product without the list of the relevant alternative components.

Additionally, it is not feasible for customers to fulfill this condition when expressing their needs, due to the technical knowledge required and the multiplicity of alternative components of which they are unaware. Accordingly, describing an end-product using a combination of alternative services is the only viable alternative to the traditional Bill of Materials approach. This service-based product description, used by several automakers, involves multiple operational consequences.

- Based on services, the configurator walks the potential customer through the choice of SACs on offer. In these circumstances, the guaranty that the customized vehicle will be able to be built ('ready to buy') is obtained by the fact that upstream choices are guided by downstream choices through the dynamic cross referencing of restrictions between SASs. This approach therefore dispenses with the traditional Bills of Materials both at configurator and sales department levels.

- Describing a car through a set of built in alternative services serves to establish the ACs it is made of, through a number of predicates. This solution satisfies short-term practical needs that no longer require the set of all Bills of Materials one may produce.

- The transcription of the constraints by predicates based on alternative services instead of components simplifies their definition and updating since there are more commercial constraints than technical ones.

This new representation of end products well addresses some BOM problems in mass customization context, but it has also a huge impact on the way MPSs can be drawn up beyond the frozen horizon. This particular point needs to be highlighted in a dedicated second INCOM paper (Chatras *et al.*, 2015). Indeed, increased diversity results from marketing department pressure which assume that diversity, coupled with pricing differentiation is attractive for customers and profitable for business. This strategic vision of diversity combined with global alternative components procurement to lower costs has long been shared by large automotive companies worldwide. But in the aftermath of the 2008 crisis, one notes a paradigm shift in favor of streamlined offerings based on packages (no automatic air conditioning without CD player) or upgrading strategies (standard fitment of electrical rear window, embedded computer ...). The introduction of packages serves to generalize the determination of a SAC through a single SAP, which streamlines the forecasting of demand for particular ACs. The *low-cost* rationale has also flourished in recent years and involves lowering service levels to customers, this strategy also enables the production of less diversified vehicles. This approach as used in the automotive industry appears perfectly valid for other industries that face similar diversity in their finished product offering, obtained with heavy combinatorial constraints between ACs, due to technical and commercial constraints

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