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a case study from the automotive industry

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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 whereby thousands or even millions of end products can be obtained. 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. For the purposes of our paper, such variety is taken for granted and our focus is the associated impact on Bills of Materials. 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). The idea of this new approach developed in this paper, is to describe the product based on its market features, before moving on to the actual AC 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. Because ASs are also useful for sales forecasting purposes, the concept facilitates Master Production Schedule (MPS) preparation. Nevertheless, daunting methodological problems remain to be tackled in connection with drawing up MPSs beyond the frozen horizon: first, owing to forecasting problems in connection with combinations of interdependent ASs and also because of longer lead times resulting from globalization.

Keywords: mass customization, planning Bill of Materials, generic Bill of Materials, alternative services, master production schedule

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 which is taken for granted for purposes of this paper, results from the combination of alternative variants of components. In the case of sophisticated products, this means that thousands of different components are potentially used on the assembly line. Standard practice is to group end products comprising a majority of common components into product families, also called 'models'. Even when using a modular architecture, offering a huge diversity of sophisticated products implies managing a large number of alternative components, many of which cannot be combined freely.

Our paper describes the methodological problems arising in the context of huge variety in order to define, store and retrieve the Bills of Materials required for operational and tactical decision-making purposes. It reviews a number of solutions that are either used or available to solve these problems. 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). Therefore, our paper builds on a real life case to describe both the methodological issues and potential solutions pertaining situations of high product variety. Accordingly we combine the automotive sector's technical terminology and that relevant to the concepts we draw upon in order to fully describe the problems and actual or potential solutions.

For reasons of efficiency, a conventional treatment of this article, starting with a review of literature, was set aside to better focus on the complex issues addressed. Understanding product variety on an assembly line for a given product family is a prerequisite to analyzing its consequences for setting up Bills of Materials in the information systems used for operational and tactical decision making (Section 1). One will then turn to the conventional Bills of Materials and show (in Section 2) that they are not tailored to an exhaustive description of the population of millions of different finished products proposed by highly customized mass production industries, by means of a set of equivalent Bill of Materials references. The arduousness of the task has led researchers to devise solutions that do away with this need for exhaustiveness. Nevertheless they did not solve all of the commercial and operational problems one is confronted with. Some carmakers have worked around the problem through a solution hinging on a functional product description. This enables customers to choose the vehicle they are looking for while enabling the operational players (in assembly line procurement and production scheduling...), to retrieve the list of ACs

required for each vehicle. At tactical decision level, however, the solutions available to describe a vehicle are not fully satisfactory and researchers don't seem to have paid much attention to this (Section 3): on the one hand, building Master Production Schedules (MPS) involves relying on Bills of Materials to procure the required components for assembly lines, and on the other hand, the sales departments can only base their forecasts on the functional vehicle features. And translating forecasts based on virtual objects into forecasts applicable to physical objects to be procured, poses daunting methodological problems. Two valid paths may be explored to solve them, though none can claim to be a comprehensive solution to the problems.

1. Variety analysis in a mass customization context

From a production point of view, variety is obtained on an assembly line through the combination of optional and 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...). An optional component (roof bars, parking sensors...) can be said to be a particular AC of a SAC describing the presence or absence of the component where the implicit and virtual alternative can be a physical object (bumper without sensor...) or nothing (absence of roof bars...). In the following pages we only use the general terms of AC and SAC since they cover both the optional and alternative components. 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. Thus, we distinguish two types of components as shown in Chart 1 representing a sub-set of the SACs. Since the section of the Bill of Materials that describes the shared components poses no difficulty, we shall only deal with the ACs, which define the identity of the product chosen by the customer.

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...).

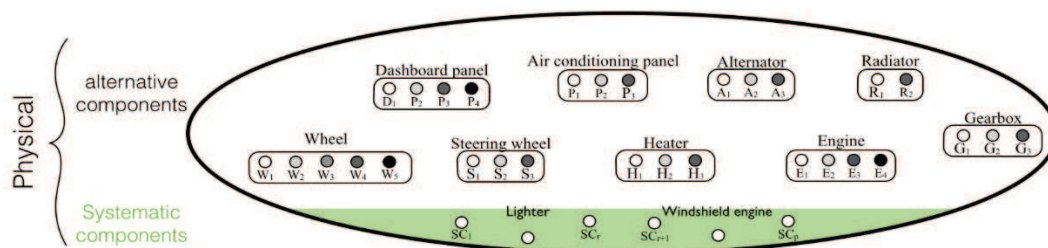


Chart 1: Typology of Components used in Mass Customization

An assembly line variety is sometimes difficult to define because it is closely linked to the definition of a specific scope including geographic and time dimensions as well as production organization. Those three dimensions further complicate the definition, updating and use of Bills of Materials. Note that those factors are usually discarded in papers dealing with variety measurement. So let us address the impact of those three dimensions:

- The commercial offering for a given car model varies from one commercial region to another. A commercial region (market) can be a country (Germany, UK...) or group of countries (eg: France/Belgium/Luxembourg/Switzerland). Many products are common to different commercial offerings but some ACs can be exclusive to a commercial region in order to address special local needs or comply with local regulations. For example, in the UK the steering wheel is on the right, in Germany pollution standards are stricter than in France and for the models used in our study, the canvas roof option is only available in Germany and the smoker pack only available in the UK. Generally, an assembly line produces vehicles for different markets. Therefore each SAC includes all the ACs of all the markets supplied by the relevant assembly line. For example, the "roof" SAC of the Renault Twingo must include the "sheet metal roof", "sun roof" and "canvas roof" ACs resulting from the consolidation of the German and French varieties. In practice, therefore, two assembly lines producing the same model for different markets have a different product variety, but at corporate level, they are merged into a single set.
- Production organization also matters in defining Bills of Material as readily observed when two production plants assemble the same product family. Indeed, to put in MRP language, a car produced on a line has a level-0 reference resulting from the assembly of systematic and alternative level-1 components. The ACs of a SAC are identified by a Bill of Materials reference; that may be a virtual Bill of Materials if the ACs are produced at an assembly line that is commanded by another that it feeds into, and where no intermediate stock is required at the station where the ACs are assembled. This convention enables the diversity of a family produced by multiple lines to exist independently of the industrial organization option (synchronous production, synchronous procurement). Then there is the case where two assembly lines dedicated to the same product family adopt different postponement strategies. For example, a plant may assemble an AC

made up of an engine coupled to a gearbox while another plant building the same product may receive and mount the engine and the gearbox separately on two different stations. In this case, one needs to establish the link between the Bills of Materials and the plants. These organizational aspects are also left aside in the sections below.

- The features of product offering change over time for three reasons. First, range renewal can involve changing some ACs. Additionally, AC combinatory limitations may change in line with commercial strategy. For example, an optional air conditioning system may become standard at a certain point and for a given equipment level. Finally, for cost or quality reasons some components may be replaced without customers being aware of this. Therefore the diversity offered by a market is always time-specific and valid only until further notice. Time-driven change is identified in the literature by the concept of dynamic diversity (Pil & Holweg, [7]). These temporal aspects are left aside in the sections below.

With these considerations in mind, let us now turn to the impact of production diversity. A variety analysis of a Renault 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. Additionally, note that 50% of the SACs are made up of ASs worth less than €4s. Because of their relatively low cost, one can dispense with MPSs for most of them. The fact that this number of SACs is greater than the number of stations on the assembly line shows that each station assembles ACs belonging to multiple SACs. To further illustrate this point, let's take the example of the station mounting wheels on the car body: that station will use different nuts depending on the wheel type. Similarly, for the above reasons, and to further evaluate the volumes involved, note that several dozen Bill of Materials references for an assembly line dedicated to a model are updated monthly. Finally, two plants that produce the same model use around 80% of common parts.

Along with the boom of product variety, supply chain globalization driven by global competition has increased lead times. This dual development has created two new methodological problems that can be addressed by different solutions. The first is discussed under Section 2 and concerns the definition of Bills of Materials: this has become difficult due to both the large diversity of end products and the constraints on alternative components combinations. The second is discussed under Section 3 and flows both from the problem of Bill of Materials definition and longer lead time in the supply chain. It has to do with the definition of Master Production Schedules (MPSs) for the final assembly plants and also plants located upstream in the supply chain.

2. Bills of Materials, Mass Customization and Information Systems

All products that can be assembled are 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, 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 combination restrictions 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.

We shall first describe the traditional way of building combinatorial diversity into Bills of Materials (section 2.1). This solution presents problems that some researchers tackled by introducing the concept of generic Bill of Materials (section 2.2). But due to the current scale of diversity, this solution is no longer adequate. Under section 2.3, we recommend an additional step 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. 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.

2.1. The Traditional Representation of Combinatory Diversity in Bills of Materials

A solution to the MRP issue of using an AC chosen from a SAC has been available for years. It is 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. For example, a car always has four identical wheels: "4" is the coefficient for wheels and, because there are several wheels on option, the set of eligible wheels forms a SAC, represented by a dummy component in the Bill of Materials. 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. We shall see below under Section 3 how this structuring is used for planning beyond the frozen horizon. To isolate the provisional portion of the MPS, one may allocate to the different ACs of a set specific BOM coefficients standing for the provisional percentage of use of each AC within the relevant set. For the time being, we focus on

the fact that a vehicle BOM is defined from the BOMs of its systematic and alternative components, with a single AC being selected in each SAC, and that all SACs must be taken into account.

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 2 complements Chart 1 by illustrating the respective roles of both the technical and commercial types of constraints, through a simplified but real case.

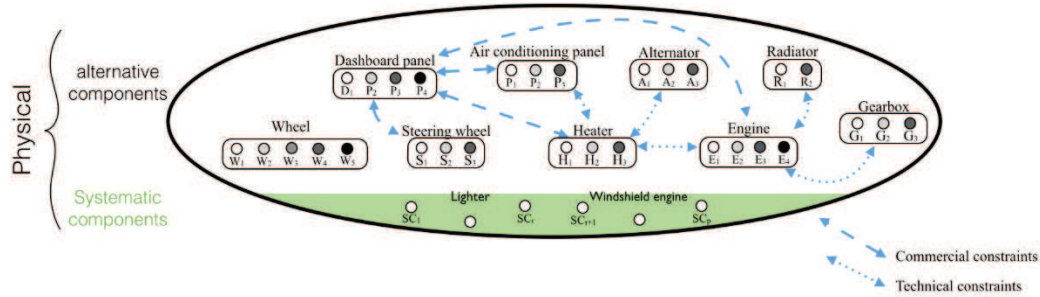


Chart 2: Commercial and technical constraints between SACs

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 et A₃), three heating ventilation and air conditioning systems (HVAC) (H₁, H₂ and H₃) and three heater 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 3 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. These restrictions are drawn from a simplified actual case. We note a legacy barred combinations of level *n* (mapped with '*') with level *n*+1 (mapped with '.'). As a result, the actual number of end products drops from 216 to 10 that can be summed up with the following Bills of Materials: E₁R₁H₁A₁I₁, E₂R₁H₁A₁I₁, E₃R₁H₁A₂I₁, E₂R₁H₂A₁I₂, E₂R₂H₂A₂I₂, E₃R₁H₂A₂I₂, E₃R₂H₃A₃I₃, E₃R₁H₃A₃I₃, E₃R₂H₃A₃I₃, E₄R₂H₃A₃I₃.

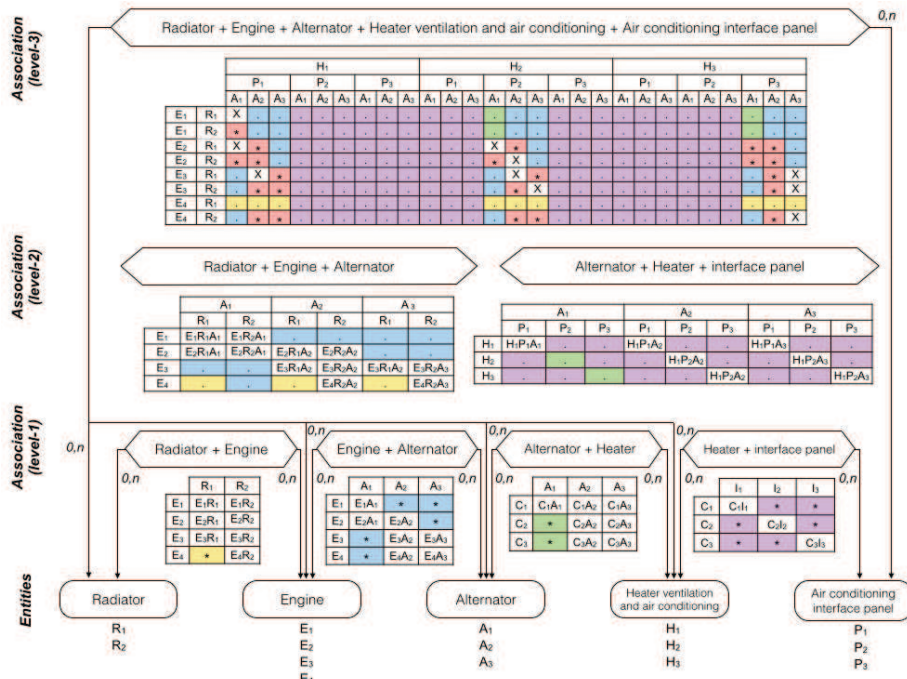


Chart 3: Example of formal representation using the relational database model

Chart 3 illustrates the need to use the 5th normal form of relational databases to describe the existing Bills of Materials. 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 $\wedge$) or a disjunction (OR, noted $\vee$) 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 3:

$$\begin{aligned} A_1^{-1} &= E_1 \wedge R_1 \wedge ((H_1 \wedge I_1) \vee (H_2 \wedge I_2)) \\ A_2^{-1} &= (E_3 \wedge R_1 \wedge ((H_1 \wedge I_1) \vee (H_2 \wedge I_2))) \vee (E_2 \wedge R_2 \wedge H_2 \wedge I_2) \\ A_2^{-1} &= (E_3 \wedge R_1 \wedge ((H_1 \wedge I_1) \vee (H_2 \wedge I_2))) \vee (E_2 \wedge R_2 \wedge H_2 \wedge I_2) \end{aligned}$$

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. The cost function includes supply chain costs whose configuration is driven by the choice of production variants. This model resembles that proposed by Giard (2000) though the economic functions differ, and does not take explicitly take ACs combination restrictions into account.

2.3. 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. 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.

The French 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, cooling system 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 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. The equipment level indicates the comfort features and motorization services for a market segment and is based on services and prices. Furthermore, equipment level automatically defines some components (interior plastics, seat shape and fabric, etc.) whose variety is not displayed. The diversity featured in the model configurator feeds into a commercial offering comprising eight equipment levels, six engines, eleven colors, fifteen wheel rims and over twenty-five options. This approach helps closely match customer expectations in terms of services leaving out actual product architecture and technical definition.

As shown in Chart 4 (drawn from a simplified actual case), SASs are related to technical or commercial constraints similar to those between SACs in Chart 2. 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 5. 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.

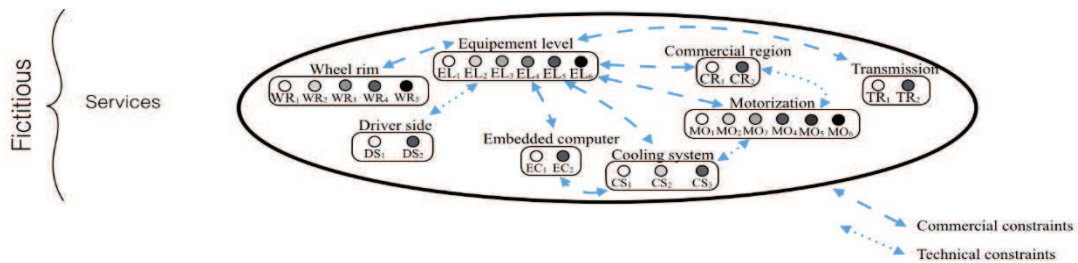


Chart 4: Representation of set of alternative services (SASs) and their alternative services

This restriction of allowed combinations can be illustrated by a table as table 1 which is based on the real configurator information.

SAS Motorization (MO)	SAS : Transmission (TR)	SAS : Equipement Level (EL)							
		EL ₁	EL ₂	EL ₃	EL ₄	EL ₅	EL ₆	EL ₇	EL ₈
MO ₁	TR ₁	X	X	X	.	.	X	.	.
MO ₂	TR ₂	.	.	.	X	.	X	.	.
MO ₃	TR ₁	.	.	.	.	X	.	.	.
MO ₄	TR ₁	.	.	.	.	.	.	X	X
MO ₅	TR ₁	.	X	X	X	.	.	.	.
MO ₆	TR ₁	.	.	.	.	X	.	.	.

TR₁ : manual transmission ; TR₂ : automatic transmission

Table 1: Real-life Example of combinatory restriction between ASs of three SASs: Motorization, Transmission and Equipment Level

At this stage, we can draw two conclusions about this configurator:

- The choice of a market (commercial region) is implicit when the customer chooses his country on the web site before actually customizing the product. The market, therefore can be assimilated to a SAS since it is chosen by the customer. Note that this choice impacts a number of alternative components that usually don't attract customer interest such as the depollution filter (not standard component as it is very expensive).
- The car model can also be seen as a SAS because the customer chooses it on the website. Note that carmakers usually use historical model segmentation to breakdown the large amount of data required to be stored (for configurator purposes for example). Accordingly models are chosen after the country because all models are not available everywhere, and customers cannot switch countries without losing all prior customization settings.

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 5 shows on a real example 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.

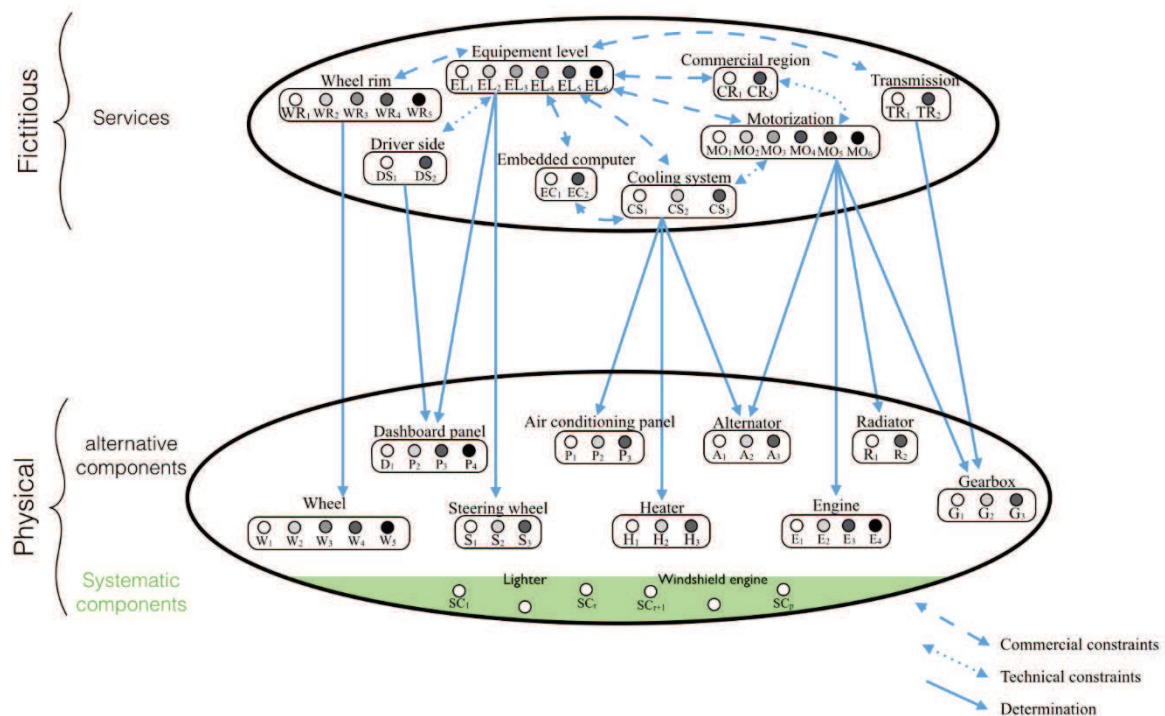


Chart 5: SAC determination by SASs

The determination relation, symbolized by arrows on Chart 5, 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 below illustrate the combinatory determination of the Alternator (which is an AC) from two SASs : 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 3, the choice of alternator is not based on physical SACs (Engine and Heating system) but rather on virtual commercial SASs: motorization and cooling system.

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

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

CS₁ : without cooling system ; CL₂ : manual cooling system ; CL₃ : automatic cooling system

SAS Motorization (MO)		MO ₁			MO ₂			MO ₃			MO ₄			MO ₅			MO ₆		
SAS Cooling System (CS)		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	X	X	.	X	*	.	.	.	.	.	.	.	.	.	.	.	.	.
	A ₂	.	.	.	*	X	*	X	X	*	*	X	X	*	X	*	.	.	.
	A ₃	.	.	.	.	.	.	.	.	.	.	*	*	.	*	X	.	X	X

Tables 2: Example of alternator AC determination based on SAS (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 normally no 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_i (phrase also used to define the need ($AS_i = true$) 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:

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

$$A_2^{-1} = (CS_1 \wedge MO_3) \vee (CS_2 \wedge (MO_2 \vee MO_3 \vee MO_4 \vee MO_5)) \vee (MO_4 \wedge CS_3)$$

$$A_3^{-1} = (CS_2 \wedge MO_5) \vee (CS_3 \wedge (MO_5 \wedge CS_6))$$

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 2.2 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.

This service-based product description involves multiple operational consequences. The first two consequences address the problems set forth in the introduction of this section 2.

- 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 approach to describing end-products based on SASs and predicates satisfies all practical needs. It seems difficult to manage the tactical decisions in any other way since, beyond the frozen horizon, production planning is based on sales forecasts that are defined at SAS level. The problems arise from the fact that MPS have to be defined at SAC level. This gap is the origin of the major methodological problems that we now turn to.

3. Production planning in a mass customization context

Drawing up master production schedules (MPSs) for final assembly plants is based on product Bills of Materials. During the frozen period, the needs of level-1 components are easily deducted from the BOM of the vehicle ordered. It is interesting to highlight that many carmakers arbitrarily delineate the frozen period without taking into account the volume of overall backlog that might be important for certain product models. Beyond the frozen horizon, the definition of the MPS for final assembly plants is more complex. The same is true for MPSs of plants lying upstream in the supply chain whose orders result from the application of MRP principles based on MPSs of final assembly plants whose lead times are beyond the frozen horizon.

Therefore, the consistency of production decisions made in the upstream part of the supply chain (final assembly line) is closely dependent on both the reliability of the MPSs for those lines beyond the frozen horizon and the stability of this information through the MPS rolling updates. Usually, when the end products variety is relatively low, MPSs are defined for level-0 items of the BOM, that is to say at end product level. However, beyond a certain level of variety, it seems easier to define AC MPSs at level-1 of the BOM, as they are fewer. In both cases, the combinatorial constraints between ASs is an issue in defining the MPSs (Section 3.1). If MPSs are defined for level-1 components, each AC should be dealt with separately to limit the problem by taking into account only the relevant constraints (Section 3.2). If the MPSs are defined for end products, then all the constraints must be taken into account and translated at AC level (Section 3.3).

3.1. Description of the MPS definition problem in the context of mass customization

In a mass customization context, defining assembly line MPSs requires a prior definition of overall production volume for each unit of the planning period. Because this type of assembly line is characterized by fixed cycle time, production volume is directly deducted from overall production time derived from the number of shifts for the period. In order to manage teams and also part supplies, this information must be forecasted over the planning period, so we will suppose this to be known for purposes of this paper.

The large number of end products makes difficult to define the MPSs at that level because of the huge combinatorial between the ACs relevant to them. This difficulty can be lifted as it is not mandatory to use the finest level of combination for procurement planning. Indeed, the diversity induced by some SACs such as stickers, can easily be ignored in the planning process provided those ACs are relatively cheap and easy to procure. The remaining end product diversity is still huge in the car industry, but some automakers use an MPS definition device at this level; this solution is discussed under Section 3.3. The difficulties of such a device also include some of the difficulties of level 1 MPS definition for components determined by several SASs.

The definition of systematic level-1 component MPSs is easy as the information (BOM coefficients and total production volume per period) used for those components is reliable. For the alternative level-1 components, the planning Bill of Materials presented under Section 2.1 and production volume are key to MPS definition beyond the frozen horizon. Note that a planning BOM is defined for each SAC for a given period: a BOM coefficient is associated to each AC of the SAC, corresponding to the percentage of occurrence of this AC in the SAC during a certain period. Assuming that the BOM coefficients are reliably defined – important assumption discussed in the next paragraph – two MPS calculation approaches beyond the frozen horizon are available; the first one for MPSs of both end products and level-1 components.

- Note also that the first solution was proposed for the introduction of the planning BOM in the MRP. The requirements for a period beyond the frozen horizon are also calculated as the total production volume for the period multiplied by the AC BOM coefficients. This calculation is implicitly based on the assumption of certain production. With this assumption, calculated demand beyond the frozen horizon cannot be changed during the rolling planning. This strong assumption is not realistic. In order to limit the cascading spread of disruptions in the upstream part of the supply chain of the assembly line due to MPS rolling changes, it is important to dispose of safety stocks for those ACs. Their definition is often tentative, a drawback the second solution does not have.
- The second solution is based on probabilistic AC demand beyond the frozen horizon. The planning BOM coefficients for a SAC are used as a vector of a Multinomial distribution in which the number of trials is the total number of cars produced for the period (Camisulis and Giard, 2010; Sali and Giard, 2012, 2014). AC demand in a given period beyond the frozen horizon can be seen as a random variable following a binomial distribution and the safety stock calculation can be done by defining a replenishment level coupled with a predetermined shortage risk. In this context, it can be shown that the gross requirements for a level-1 component triggered by stochastic MPS requirements beyond the frozen horizon, are random variables defined as the weighted sum of those random variables (Sali and Giard, 2010, 2014).

The relevance of those two approaches is based on the quality of the planning BOM coefficients' forecasts. When the number of SACs is low and there is no constraint between ACs (as it is for desktop computers production), we can easily define planning BOM coefficients' forecasts from their demand records. The exponential smoothing technique can be used when structural change is slow and the lead time relatively short; such forecasts must be corrected in order to reflect the predictable market trend disruption arising from any new model launches or

commercial campaigns by the firm or its competition. If there are constraints between ACs, the use of these approaches is only possible if the structural characteristics of demand are stable.

The problem is particularly acute in the mass customization context because of product variety and the multiple combinatory constraints between ACs. In Section 2.3 it was noted that, due to the commercial offering structure coupled with the impossibility for customers to define demand AC level, it is best to replace the classical BOM listing ACs for a given vehicle by a list of alternative services. The operational equivalence of those two descriptions is guaranteed by the determination of each AC using a predicate combining a subset of ASs which describe a product. This solution fully meets operational production requirements. Let us now turn to a description of AS use to define MPS for ACs beyond the frozen horizon.

One can easily transpose the SAC planning BOM method for SASs and use the above SAC forecast methods for SASs. In fact, those methods are more adapted to SASs since they are fewer than SACs and have been defined to address customer and sales needs whereas SACs correspond to a physical view. Three scenarios illustrated in Chart 3 should be distinguished:

- If AC procurement lead time is within the frozen period, no MPS needs be drawn up beyond the frozen horizon. Accordingly, the definition of systematic MPS component is purposeless since it uses known information ie: production volume and planning BOM coefficient.
- If AC procurement lead time is beyond the frozen horizon, an MPS beyond the frozen horizon is required. Two scenarios are then possible:
 - o AC is determined by a single SAS. Here the forecast is straightforward based on the ASs of the SAS.
 - o AC is determined by multiple SASs. Here, planning BOM definition of AC coefficient is a difficult problem, even where all AS planning BOM coefficients have been forecasted. Indeed, the existence in the AC predicate of AS combinations that belong to different SASs is an issue we will address below.

Lead time		Systematic components	Number of SASs that determine the SAC	
			1	≥ 2
	$\vee$	Synchronized supply or production possible but not mandatory	Synchronized supply or production preferred	Synchronized supply or production preferred
	$\wedge$	Easy supply based only on the forecasts of production volume	Supply based on the planning BOM of the unique SAS	Supply based on a complex replenishment policy that has to be defined

Table 3: Typology of problems for defining level-1 component MPSs

Let us illustrate the forecast definition problems for ACs determined by a predicate using several SASs. Table 4 takes the information of table 2 and serves to highlight how each alternator is defined by a combination of the motorization services and cooling system services. The three definition predicates for the three ACs of the "alternator" SAC are shown above the table.

		SAS Motorization (MO)					
		MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆
SAS Cooling System (CS)	CS ₁	A ₁	A ₁	A ₂	-	-	-
	CS ₂	A ₁	A ₂	A ₂	A ₂	A ₂	A ₃
	CS ₃	-	-	-	A ₂	A ₃	A ₃

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

$$A_2^{-1} = (MO_2 \wedge CS_2) \vee (MO_3 \wedge (CS_1 \vee CS_2)) \vee (MO_4 \wedge (CS_2 \vee CS_3)) \vee (MO_5 \wedge CS_2)$$

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

Table 4: Determination of alternators via the motorization and cooling system services

If one uses standard probability notation to describe planning BOM coefficients for the ACs and the ASs, one can draw up table 5 describing alternator calculation coefficients, based on motorization and the cooling system services; these calculations are shown above the table and use the twelve variables of the table (other than void and excluding marginal distributions parameters as they are given).

		SAS Motorization (MO)						
		MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆	MO _{Set}
SAS Cooling System (CS)	CS ₁	$P(MO_1 \wedge CS_1)$	$P(MO_2 \wedge CS_1)$	$P(MO_3 \wedge CS_1)$	-	-	-	$P(CS_1)$
	CS ₂	$P(MO_1 \wedge CS_2)$	$P(MO_2 \wedge CS_2)$	$P(MO_3 \wedge CS_2)$	$P(MO_4 \wedge CS_2)$	$P(MO_5 \wedge CS_2)$	$P(MO_6 \wedge CS_2)$	$P(CS_2)$
	CS ₃	-	-	-	$P(MO_4 \wedge CS_3)$	$P(MO_5 \wedge CS_3)$	$P(MO_6 \wedge CS_3)$	$P(CS_3)$
	CS _{Set}	$P(MO_1)$	$P(MO_2)$	$P(MO_3)$	$P(MO_4)$	$P(MO_5)$	$P(MO_6)$	100%

$$P(A_1) = P(MO_1 \wedge CS_1) + P(MO_1 \wedge CS_2) + P(MO_2 \wedge CS_1)$$

$$P(A_2) = P(MO_2 \wedge CS_2) + P(MO_3 \wedge CS_1) + P(MO_3 \wedge CS_2) + P(MO_4 \wedge CS_2) + P(MO_4 \wedge CS_3) + P(MO_5 \wedge CS_2)$$

$$P(A_3) = P(MO_5 \wedge CS_3) + P(MO_6 \wedge CS_2) + P(MO_6 \wedge CS_3)$$

Table 5: planning BOM coefficient definition for alternators based on motorization and cooling system services

As 6 $P(MO_i)$ and 3 $P(CS_j)$ are assumed to be known, defining planning BOM coefficients is actually finding a solution of the following system with 9 equations and 12 variables.

$$P(CS_1) = P(MO_1 \wedge CS_1) + P(MO_1 \wedge CS_2) + P(MO_3 \wedge CS_1)$$

$$P(CS_2) = P(MO_2 \wedge CS_2) + P(MO_3 \wedge CS_2) + P(MO_4 \wedge CS_2) + P(MO_5 \wedge CS_2) + P(MO_6 \wedge CS_2)$$

$$P(CS_3) = P(MO_4 \wedge CS_3) + P(MO_5 \wedge CS_3) + P(MO_6 \wedge CS_3)$$

$$P(MO_1) = P(MO_1 \wedge CS_1) + P(MO_1 \wedge CS_2)$$

$$P(MO_2) = P(MO_2 \wedge CS_1) + P(MO_2 \wedge CS_2)$$

$$P(MO_3) = P(MO_3 \wedge CS_1) + P(MO_3 \wedge CS_2)$$

$$P(MO_4) = P(MO_4 \wedge CS_2) + P(MO_4 \wedge CS_3)$$

$$P(MO_5) = P(MO_5 \wedge CS_2) + P(MO_5 \wedge CS_3)$$

$$P(MO_6) = P(MO_6 \wedge CS_2) + P(MO_6 \wedge CS_3)$$

We are therefore faced with an underdetermined system that accepts an infinity of solutions, not sufficient to define the alternator planning BOM coefficients. This under determination is systematic when a SAC is determined by two or more SASs, except in the rare scenario where each AC of a SAC is determined by a single AS per SAS that determines this SAC. In order to find a solution to define the alternator MPSs beyond the frozen horizon, we need to add three additional constraints or add an optimization function. The second possibility is illustrated by table 6. Both solutions imply a measure of arbitrary decision to solve the problem.

As mentioned above, in a mass customization context, the MPS could be defined for level-1 components (Section 3.2) or for end products (Section 3.3). We identified two possible uses of planning BOM coefficients to define an MPS: a determinist approach and a stochastic one. In the MPS definition for level-1 components, we use a stochastic approach beyond the frozen horizon. In the end product MPS definition, which is the method used by some carmakers, we use a deterministic approach.

3.2. Defining MPSs for level 1 of the Bill of Materials

Table 3 makes serves to narrow the level-1 MPS component definition problem down by eliminating the systematic components and those whose lead time does not exceed the frozen period. Thus the problem arises for the ACs not included in these categories. In this paragraph, it is supposed that these ACs are determined by one or more SASs.

When one disposes of SAC BOM coefficient forecasts, one may use the probabilistic approach of MPS definition beyond the frozen horizon (see Section 3.1). To use this solution, one needs SAC BOM estimated coefficients values. Three cases can be distinguished

- Case 1. SAC BOM coefficients are calculated from the SASs which determine it.
- Case 2. SAC BOM coefficients are calculated without reference to SASs, on the basis of their time series. In this case, it is useless to make forecasts for SASs that determine these SACs.
- Case 3. The supply of a SAC's ACs cannot be monitored by the MRP but by a system not based on forecasts but, for example, on an "order point – fixed ordered quantity" policy. This solution is used to manage the components whose management is excluded from the MPS, as indicated in the beginning of Section 3.1.

Case 1 – SAC BOM coefficients calculated from SAS coefficients

The first case implies knowledge of BOM coefficients for the SASs that determine the relevant SACs, via the predicates. Thus, one has the estimated SAS BOM coefficient values required for forecasting SAC BOM coefficients taken into account in the MPS. One should then distinguish between two possibilities:

- AC is determined by a single SAS. The BOM coefficient forecast for this AC is determined by those of the concerned SAS. One may then to use the probabilistic approach referred to under Section 3.1, using an arbitrarily weak risk of stockout, to determine component production launches, required to fully or partly cover random requirements. This approach was used in about ten benchmarks with real cases drawn from an automaker (Sali and Giard 2014, Giard and Sali 2012), by comparing the results obtained with those obtained through the end product MPS solution described under Section 3.3. The random approach yielded clearly better results.

- AC is determined by several SAS. The BOM coefficient forecast problem more complex as showed at the end of Section 3.1. One can attempt to solve the under-determination problem highlighted at the end of Section 3.1 through a function to be optimized. Using again the example of table 4, one can attempt to recourse to estimated values of $P_0(CS_i \wedge MO_j)$ to minimize an indicator of difference between these forecasts and the last values $P_1(CS_i \wedge MO_j)$ historically recorded. This method is illustrated by tables 6

Initial coefficients $P_0(CS_i \wedge MO_j)$									Forecasted coefficients $P_1(CS_i \wedge MO_j)$							Forecasted structure of cooling system
		SAS Motorization (MO)							SAS Motorization (MO)							
		MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆	MO _{Set}	MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆	MO _{Set}	
SAS Cooling System (CS)	CS ₁	0,020	0,080	0,110				0,210	0,02667	0,06667	0,10667				0,200	
	CS ₂	0,070	0,120	0,060	0,050	0,110	0,080	0,490	0,07333	0,10333	0,05333	0,04333	0,09334	0,08333	0,450	
	CS ₃				0,110	0,100	0,090	0,300				0,12667	0,10666	0,11667	0,350	
	CS _{Set}	0,090	0,200	0,170	0,160	0,210	0,170	1,000	0,100	0,170	0,160	0,170	0,200	0,200	1,000	
P(A ₁)=0,17 : P(A ₂)=0,56 : P(A ₃)=0,26									Forecasted structure of motorization							
P(A ₁)=0.1667 : P(A ₂)=0.5267 : P(A ₃)=0.3067																

Tables 6: alternator BOM coefficients example of determination based on motorization and cooling system services with minimization criterion

Let us look at a SAC determined by several SASs. The case of a SAC determined by a single SAS having implicitly been treated in case 1. The solution used consists in performing direct SAC BOM coefficients forecasts. Rather than to take the last actual BOM coefficients values for a given SAS, one may use a simple exponential smoothing technique yielding forecasts $\hat{P}_{t'>t}(AS_i) = \alpha \cdot P_t(AS_i) + (1-\alpha) \cdot \hat{P}_{t'-1}(AS_i)$ for these coefficients, for the periods beyond t . In these calculations, the $\sum_i \hat{P}_{t'>t}(AS_i) = 1$ constraint must be respected. This is guaranteed at the initialization of the calculation process of the exponential smoothing which uses coefficients which sum must be equal to 1; this condition is obtained because this SAC coefficient forecasts use the same smoothing coefficient. This exponential smoothing technique implies that structure changes are slow and that procurement lead times are relatively short, failing which, the sales department should conduct an explicit forecast. Two complementary remarks can be made. The value of the smoothing coefficient used in the SAS BOM coefficients forecasts can be adjusted periodically, for example based on a minimization criterion of the sum of the squares of the forecast error. In addition, use of a linear filter always generates oscillations known as the Slutsky-Yule effect, which induce a skew in the forecasts. This skew can be easily neutralized by increasing forecasts by the quantity corresponding to the standard deviation of forecast errors. This avoids undervaluation if the forecast is on the high part of an oscillation (which can be known only latter), at the cost of building excess safety stock in the contrary case.

3.3. Defining MPSs for level 0 of the Bill of Materials

At each step of the enrichment process, the resolution of the equation system consists in choosing a particular solution among the infinite number of possible solutions. To select a particular solution, one needs to define a selection criterion that may be for example, as proposed in § 3.2, the minimization of a difference between the forecasts (decision variables) and the last observed values. To pursue the logic of calculating the coefficients at a higher level of AS combination (eg. combination involving three SASs), $MO_i \wedge CL_j$ combinations such as $P(MO_i \wedge CL_j) > 0$ are considered as ASs that pertain to a set that can be qualified as a Meta-SAS. This iterative

process therefore aims to gradually expand, at each period of the planning horizon, the sales forecasts expressed at the SASs. The tables below illustrate how a calculation of coefficients associated with combinations of ASs from the SASs Motorization, Cooling system and Commercial Region (prohibited combinations $MO_i \wedge CL_j$ are not included in the Meta-SAS combining the SASs Motorization and Cooling system).

		Initial coefficients												
		Meta-SAS (Motorization, Cooling System)												
		CS ₁	CS ₁	CS ₁	CS ₂	CS ₂	CS ₂	CS ₂	CS ₂	CS ₂	CS ₃	CS ₃	CS ₃	CS/AMQ _{Set}
		MO ₁	MO ₂	MO ₃	MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆	MO ₄	MO ₅	MO ₆	
		P(CS1/AMO1)	P(CS1/AMO2)	P(CS1/AMO3)	P(CS2/AMO1)	P(CS2/AMO2)	P(CS2/AMO3)	P(CS2/AMO4)	P(CS2/AMO5)	P(CS2/AMO6)	P(CS3/AMO4)	P(CS3/AMO5)	P(CS3/AMO6)	
Commercial Region	CR ₁	0,020	0,050	0,070	0,090	0,080	0,060	0,010	0,015	0,060	0,070	0,005	0,070	
	CR ₂		0,050	0,050		0,040	0,020	0,040	0,080	0,025	0,010	0,080	0,005	0,400
	CR _{Set}	0,020	0,100	0,120	0,090	0,120	0,080	0,050	0,095	0,085	0,080	0,085	0,075	1,000

		Forecasted coefficients												
		Meta-SAS (Motorization, Cooling System)												
		CS ₁	CS ₁	CS ₁	CS ₂	CS ₂	CS ₂	CS ₂	CS ₂	CS ₂	CS ₃	CS ₃	CS ₃	CS/AMQ _{Set}
		MO ₁	MO ₂	MO ₃	MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆	MO ₄	MO ₅	MO ₆	
		P(CS1/AMO1)	P(CS1/AMO2)	P(CS1/AMO3)	P(CS2/AMO1)	P(CS2/AMO2)	P(CS2/AMO3)	P(CS2/AMO4)	P(CS2/AMO5)	P(CS2/AMO6)	P(CS3/AMO4)	P(CS3/AMO5)	P(CS3/AMO6)	
Commercial Region	CR ₁	0,027	0,000	0,000	0,073	0,000	0,000	0,000	0,017	0,083	0,127	0,107	0,117	
	CR ₂		0,067	0,107		0,103	0,053	0,043	0,077	0,000	0,000	0,000	0,000	0,450
	CR _{Set}	0,027	0,067	0,107	0,073	0,103	0,053	0,043	0,093	0,083	0,127	0,107	0,117	1,000
		Forecasted structure of (Climatisation, Motorization)*												
		Forecasted structure of Commercial Region												

*Forecast coefficients obtained at the last iteration (Cf. Tables 6)

Tables 7: Example of BOM coefficient determination for a combination of three ASs belonging respectively to the Motorization, Cooling System and Commercial Region SASs

The existence of alternative components determined by a large number of SASs involves multiple steps in the enrichment process. The extreme case is that of an AC determined by all the SASs. In practice, this method leads to forecasts expressed at finished vehicle level, ie level 0 of the Bill of Materials, excluding any systematic or postponed components. If it were not improved, the described enrichment process would be difficult to implement in practice. Indeed, at the last stage of enrichment, the number of decision variables reaches the diversity of finished products. To work around this problem, ASs are combined into groups of strongly dependent SASs. The notion of dependency between SASs refers to the existence of technical and/or commercial constraints between ASs belonging to these sets (cf Chart 4). Meta-SASs formed from interdependent SASs include combinations of ASs whose coefficients are calculated using the previously illustrated optimization method. By grouping SASs into Meta-SASs, which by construction have more limited dependency between them, it becomes possible to calculate coefficients by combining two by two the elements of the Meta-SASs. The coefficients obtained are then used to generate, for each period of the planning horizon, CDVs that are characterized over all of the ASs. The total number of the CDVs per period is equal to the total periodic production of the assembly line. We will return to the device used to switch from coefficients associated with combinations of ASs to a population of CDVs for each period of the planning horizon.

In accordance with the time-driven technical and commercial constraints, a CDV is one of the possible AS combinations representative of all SASs. A CDV has no physical existence, but is a reflection of what could be a real finished product produced at a given time. It may be considered as a virtual product. By construction, a CDV respects the commercial and the technical constraints. This property gives the CDV the same consistency as marketable products. The ACs making up a CDV can thus be easily identified from predicates.

To illustrate how this approach works, take the example of a vehicle that is configurable from the SASs specified in Chart 5 (Commercial Region, Motorization, Equipment level, Transmission, Driver Side, Wheel rim, Cooling System, Embedded Computer). To simplify matters, let's assume a stable commercial offering over the planning period and a production line dedicated to the assembly of the relevant vehicle model.

In the approach described in this section, the sales department expresses its demand in the form of forecasts for each AS of all the SASs. These forecasts are expressed as a percentage of total production per period. The sales forecast enrichment process can then be described in four steps.

The first step in the enrichment process is the construction of several Meta-SASs as shown below. It may be noted that in this arbitrary construction, SASs belonging to a Meta-SAS are interdependent and that the Meta-SASs, taken in pairs, are independent except where one of them is that formed from the SASs: Equipment Level, Commercial Region and Motorization. This particular Meta-SAS, called “principal” and highlighted in blue in Chart 6, constitutes a base from which sales forecasts will be enriched by combining its elements with those of the secondary Meta-SASs highlighted in yellow in Chart 6.

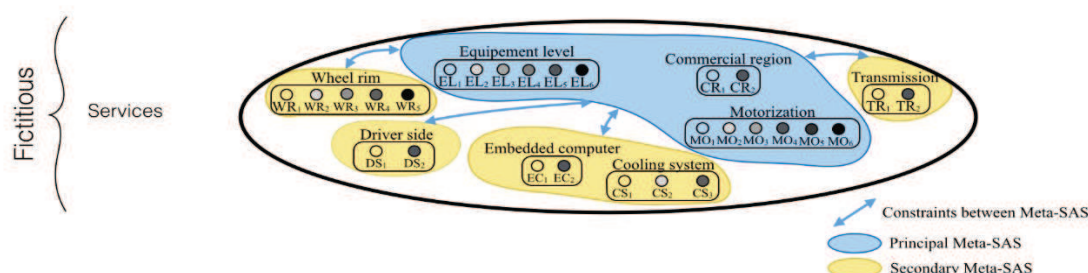


Chart 6: Meta-SAS definition

The second stage of the enrichment process consists in applying the optimization method referred to above to each Meta-SAS in order to calculate coefficients for ASs combinations. This yields marginal coefficients related to new synthetic ASs resulting from the combination of ASs.

The third step also uses the above optimization method (see beginning of the section) to calculate the coefficients associated with the combination of two ASs, one which belongs to the principal Meta-SAS. For each planning period the exercise consists in filling Tables 8 below one by one, and in any order where the marginal coefficients are yielded by the second step of the enrichment process. In Tables 8 the marginal coefficients are materialized by their respective formula in red.

		AS of the principal Meta-SAS (Commercial Region, Equipment Level and Motorization)																							
		CR ₁	CR ₂	CR ₃	CR ₄	CR ₅	CR ₆	CR ₇	...	CR ₈	...	CR ₉	CR ₁₀	CR ₁₁	CR ₁₂	CR ₁₃	CR ₁₄	CR ₁₅	CR ₁₆	CR ₁₇	CR ₁₈	CR ₁₉	CR ₂₀	CR ₂₁	CR ₂₂
		EL ₁	EL ₂	EL ₃	EL ₄	EL ₅	EL ₆	EL ₇	...	EL ₈	...	EL ₉	EL ₁₀	EL ₁₁	EL ₁₂	EL ₁₃	EL ₁₄	EL ₁₅	EL ₁₆	EL ₁₇	EL ₁₈	EL ₁₉	EL ₂₀	EL ₂₁	EL ₂₂
		MO ₁	MO ₂	MO ₃	MO ₄	MO ₅	MO ₆	MO ₇	...	MO ₈	...	MO ₉	MO ₁₀	MO ₁₁	MO ₁₂	MO ₁₃	MO ₁₄	MO ₁₅	MO ₁₆	MO ₁₇	MO ₁₈	MO ₁₉	MO ₂₀	MO ₂₁	MO ₂₂
		PCR1 AEL1AM01	PCR2 AEL1AM02	PCR3 AEL1AM03	PCR4 AEL1AM04	PCR5 AEL1AM05	PCR6 AEL1AM06	PCR7 AEL2AM01	...	PCR8 AEL2AM06	...	PCR9 AEL3AM06	PCR10 AEL5AM01	PCR11 AEL5AM02	PCR12 AEL5AM03	PCR13 AEL5AM04	PCR14 AEL5AM05	PCR15 AEL5AM06	PCR16 AEL6AM01	PCR17 AEL6AM02	PCR18 AEL6AM03	PCR19 AEL6AM04	PCR20 AEL6AM05	PCR21 AEL6AM06	PCR22 AEL6AM06
AS of the secondary Meta-SAS (Embedded Computer, Cooling System)	EC ₁ CS ₁	P(EC1 ACS1)																							
	EC ₁ CS ₂	P(EC1 ACS2)																							
	EC ₁ CS ₃	P(EC1 ACS3)																							
	EC ₂ CS ₁	P(EC2 ACS1)																							
	EC ₂ CS ₂	P(EC2 ACS2)																							
	EC ₂ CS ₃	P(EC2 ACS3)																							
AS of the secondary Meta-SAS (Wheel rim)	WR ₁	P(WR1)																							
	WR ₂	P(WR2)																							
	WR ₃	P(WR3)																							
	WR ₄	P(WR4)																							
	WR ₅	P(WR5)																							
AS of the secondary Meta-SAS (Driver Side)	DS ₁	P(DS1)																							
	DS ₂	P(DS2)																							
AS of the secondary Meta-SAS (Transmission)	TR ₁	P(TR1)																							
	TR ₂	P(TR2)																							

Tables 8: Calculation tables for the BOM coefficients associated with AS combinations of the principal Meta-SAS and ASs of the secondary Meta-SASs

In the fourth and final step of the enrichment process a set of CDVs that correspond to assembly line total production for the period is generated, using the coefficients calculated in the third step. To this end, the coefficients calculated in the third step are transformed into conditional probabilities (probability of having a CDV with an AS of a secondary Meta-SAS knowing that this CDV is characterized by an AS of the principal Meta-SAS). These conditional probabilities are used to generate a random integer number of different CDVs. The total number of generated CDVs must be equal to total assembly line production for the period. The independence of the secondary Meta-SASs serves to characterize independently a CDV for each one of them. The conditional probabilities are updated after each draw (draw without replacement) to reflect the changes in the properties of the population. The products generated and characterized for all SASs correspond to the MPS at level 0 of the BOM. The quantities generated for the MPS are considered as reliable over the non-frozen period. One is then able to calculate AC requirements from these quantities through their predicates.

Because they match the physical features of CDVs, MPSs defined at BOM 0 level are comfortable for supply chain practitioners. Indeed, their use for medium-term planning is treated as a mere extension of the short-term schedule. By construction, the use of finished product level guarantees consistent component requisitions in terms of technical and commercial constraints. While finished product level production scheduling is mandatory for the short-term, conducting this exercise beyond the frozen horizon produces the impression one disposes of reliable information for the medium-term.

But in practice, the quest for strict consistency through compliance with the technical and commercial constraints, through finished product level MPSs has substantial consequences on the performance of the upstream supply chain. The rules inherent in the enrichment process can generate serious disturbances that propagate along the upstream supply chain, generating bullwhip effect (Childerhouse et al., 2008, Niranjana et al., 2011).

The detailed analysis of the enrichment process used by a French automaker, briefly summarized in this section, revealed the existence of this effect (Sali 2012). From SAS level planning BOMs provided by the sales department, the solution selected by the automaker to generate MPSs at finished product level uses mathematical programming techniques to solve a series of cascading optimization problems for each period of the planning horizon. By propagating errors in each iteration, this solution ultimately produced unreliable forecasts leading to shortages and costly emergency supplies, or overstock that impacted cash flow.

4. Conclusion

In the context of mass customization 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 that correspond to readily grasped functional features for both customers and sales departments, is the only viable alternative to the traditional Bill of Materials approach. With this new approach, the list of alternative components for an end product is easily derived from predicates based on the alternative services selected when defining the end product. This solution meets all business operational requirements. One must rely on SASs to prepare MPSs beyond the frozen horizon since sales department forecasts are based on service offering forecasts. Switching from AS- to AC-based forecasts is however not straightforward when ACs are determined by several SASs. Two MPS formulation options are available and described in our paper: one, used by several carmakers, boils down to defining MPSs at “level 0” of the Bill of Materials, the other is based on “level 1”. Both solutions have pros and cons, which calls for further analysis of their respective performance.

Whatever the preferred solution, both increasing diversity and longer lead times in the supply chain severely impact forecasting reliability beyond the frozen horizon. This induces unwarranted supply chain costs resulting from stockout and associated remedial measures. From a strategic standpoint one should focus on the root cause of these orientations both implemented to increase margin often without proper evaluation of their potential impact on supply chain management cost. Indeed, increased diversity results from marketing department pressure which assume that diversity, coupled with pricing differentiation is attractive for customers and profitable for business. On the other hand, the increase in lead times is due to control department pressure on purchasing costs.

This strategic vision of diversity combined with global alternative components procurement to lower costs has long been shared by automakers worldwide. But in the aftermath of the 2008 crisis, one notes a paradigm shift in favor of streamlined offerings based on packages (no automatic cooling system without CD player) or upgrading strategies (standard fitment of electrical rear window, embedded computer ...). In Europe these trends seem driven by Asian carmakers especially Korean ones. 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.

Though all three above trends tend to reduce the diversity of end product offerings, they don't threaten the mass customized production model. In fact in the last few years, automakers have been reluctant to cut commercial offering diversity and have launched different alternative component (AC) streamlining measures while maintaining the commercial offering. Building modular products is clearly the most successful strategy. By standardizing

component interfaces, modularity can substantially lower the number of technical constraints that generate many of the issues. Also, generalizing assembly line sharing of several models accelerates the delivery of multi-model platforms that facilitate component sharing. Of all carmakers, the one that seems to have gone furthest in this standardization rationale is Volkswagen group, which is becoming world no1 carmaker.

To sum up, in order to improve their planning process sustainably in a context of strong diversity, carmakers dispose of strategic levers on product and upstream supply chain design. Streamlining diversity to limit the cases of determination involving a multiplicity of steps requires standardization and modularization measures at the product design stage including ACs. To address technical unfeasibility of perfect modularity involving fully standardized interfaces, the supply chain design lever may be relied on to switch back to local procurement to cut lead times beyond the frozen horizon for the ACs determined by more than one SAS.

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