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# PRODUCT WITH LARGE DIVERSITY: AN APPROACH TOWARDS SIMULTANEOUS DESIGN OF PRODUCT FAMILY AND SUPPLY CHAIN

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## Abstract

The objective of this paper is to provide an approach that allows designer and manufacturer to define simultaneously a product family and a supply chain. The first step deals with the product preliminary design process and proposes aided design tools that rely on configuration generic models and constraints satisfaction approach. The result of this step is a set of product solutions. The second step deals with the design of supply chains and presents an approach allowing to select a product solution and to specify the supply chain layout thanks to a mixed integer linear programming model. This permits to optimise the operating cost of the supply chain. This work is relevant to an industrial problem of automotive wiring harness design.

*Keywords: product family design, supply chain design, constraint satisfaction problem, mixed integer linear programming*

## 1 Introduction

Nowadays, the growing demand for customisable products involves an increasing number of product variants and a growing complexity of products. Consequently, a consistent approach is necessary to quickly define a product family and its supply chain, in order to guarantee the customer satisfaction and to minimise the global operating cost of the supply chain.

This paper proposes a design approach for defining simultaneously a product family and its supply chain while facing a demand with large diversity. Between product design and supply chain management, our simultaneous approach is closely related to the field of Concurrent Engineering [1]; more accurately in a "Design for X" approach, where X is the supply chain [2]. It is depicted as an interactive process between two steps: the product design and the supply chain design.

We will firstly describe the product preliminary design process and the proposed tools. The result of this first step is a set of design solutions. Then, the second step deals with the design of supply chains. The presented approach allows to select a design solution and to specify the supply chain layout.

Our approach will be depicted and illustrated by an industrial case dealing with the design of a wiring harness from automotive industry and its relevant supply network.

## 2 Interactive approach

In the context of large diversity, the choice of the product family to launch on the market is delicate for both the designer and manufacturer. In such case, three strategies exist:

1. the first consists in designing of one single variant of the product. This variant matches the highest functional requirements and needs of all customers,
2. the second strategy, that we call tailored product approach, proposes a specific product variant for each individual customer demand,
3. the third, which is an intermediate strategy, suggests a family with a limited number of variants or “packs”, where each pack matches a segment of the total customer demand.

The first strategy maximises over equipment cost but minimises references management cost while the second provides the opposite result. The pack strategy allows finding some compromise between the two kinds of costs.

Our approach targets the “pack family” strategy. Each product variant can be defined as a set of sub-assemblies. Each sub-assembly corresponds with a customer requirement. Each customer requirement can be characterised by a level of service that matches a variant of the relevant sub-assembly.

Therefore each couple (customer requirement, service level) can correspond with a couple (ref_sub-assembly, ref_variant). Our problem is to define a family of products P, where P = {(ref_sub-assembly, ref_variant)}, that can match any demand D, where D = {(customer requirement, service level)}. We define the various service levels according to an order relation meaning that a variant corresponding to a given service level fulfils the requirements of all lower service levels.

Our approach consists in the identification of the products that should be effectively manufactured, while taking into account supply chain aspects: (i) final assembly, sub-assembly manufacturing and inventory facilities are world-wide distributed (ii) demand can also come from any country, (iii) production, inventory and shipping costs are taken into account.

In this paper, we propose two interactive processes. The first process should be able to define easily and quickly errors free bill-of-material for each identified pack, given various demand segments or customer requirements. A second process would optimise the compromise "over equipment cost / references management cost", through the simultaneous definition of (i) the supply chain (where to manufacture, to assemble and to store) and (ii) the pack family (what are the packs provided by the first process that should be effectively produced). The product design process is considered only at the preliminary steps, while the second process concerns the supply chain strategic planning. The interactivity aspect between these two processes comes from the "try and evaluate" or iterative design approach that can be handled by our simultaneous approach, illustrated by the figure 1. For example, the first process can be achieved for some packs then the second process would provide a first result, then other packs can be proposed and optimised to improve the cost compromise in an iterative way.

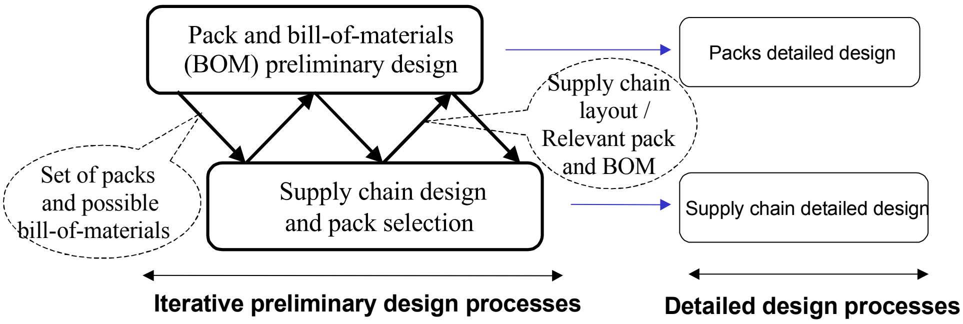

Figure 1. Interactive design process of products and supply chain

# 3 Pack family design process

## 3.1 Process description

We can summarise the first process as follows: given (i) various customer requirements and needs (including service level) expressed in a functional and descriptive ways; and some conditions restraining the possible combinations of these requirements, (ii) a set of predefined components that can be assembled to constitute a bill-of-material, and restrictions of the possible combinations of these components, (iii) a generic model enabling to identify the suitable bill-of-material of the product for any combination of customer requirements,

For each identified pack, the first process enables to find one or several bills-of-material that fulfil the requirements and the service levels.

The growing diversity and complexity of products require the design activity to be assisted with tools that can: (i) manage the combinatory explosion of possibilities (number of possible variants) with a good level of confidence and, (ii) speed up the generation of solutions.

Basically, design is the process of giving a product a description that satisfies a set of constraints and the customer requirements [3]. The objectives of configuration are alike. We propose to focus on a configuration approach in order to assist the design process because configuration improves both previous objectives. Given a generic model of the product representing a product family with all possible variants and options, configuration process enables, according to the customer requirements provided as input, to derive relevant bill-of-material. Generally speaking, configuration generates a component list, whereas all the components are standard or completely defined by parameter values during configuration.

## 3.2 Constraint based configuration model and processing

Constraint Satisfaction Problems (CSP) [4] are adapted to configuration problem: a solution to a CSP is an instantiation of all variables so that all constraints can be satisfied simultaneously. For our problem, in order to take into account the existence of variables depending on other variable value or existence, we use the Dynamic extension of CSP [5]. With Dynamic CSP framework, we will define a generic model of a pack that supports the diversity.

Our generic pack model uses two groups of variables (V1 and V2) and three groups of constraints (C1, C2 and C1-2). Variables V1 allow representing all the customer requirements with various service levels and specific characteristics allowing to capture any kind of demand segment requirements. Most of the time, these variables represent the product functional characteristics interesting the customers. Variables V2 permit to model all the sub-assemblies and their relevant variants (bill-of-material) and represent the possible technical solutions interesting the designers. Compatibility and activity constraints express specific restrictions on demand diversity or on functional requirements (group C1 between variables of V1), technical composition constraint between sub-assemblies (group C2 between variables of V2), and association between functional requirements and sub-assemblies (group C1-2 between variables of V1 and V2).

Any kind of demand is inputted with variables of V1 and then a constraint propagation mechanism [6] provides values to variables of V2. These values correspond with the description of the bill-of-material for a specific pack.

In the case of automotive industry, the carmaker targets to supply cars at low prices by defining a pack car family from a vast amount of functions and components. In that task electrical function identification, supported by the wiring harness, is a very important issue. The main goals of automotive wiring harness supplier are to speed up the time required for designing wiring harness pack family and to reduce design errors. The main interests for a configuration approach is that during specifications with the carmaker, configuration allows to quickly investigate many different solutions.

The configuration generic model of the wiring harness describes all the possibilities of functional requirements and technical solutions. An example of such model is shown in figure 2 for a car's front door window lifters system.

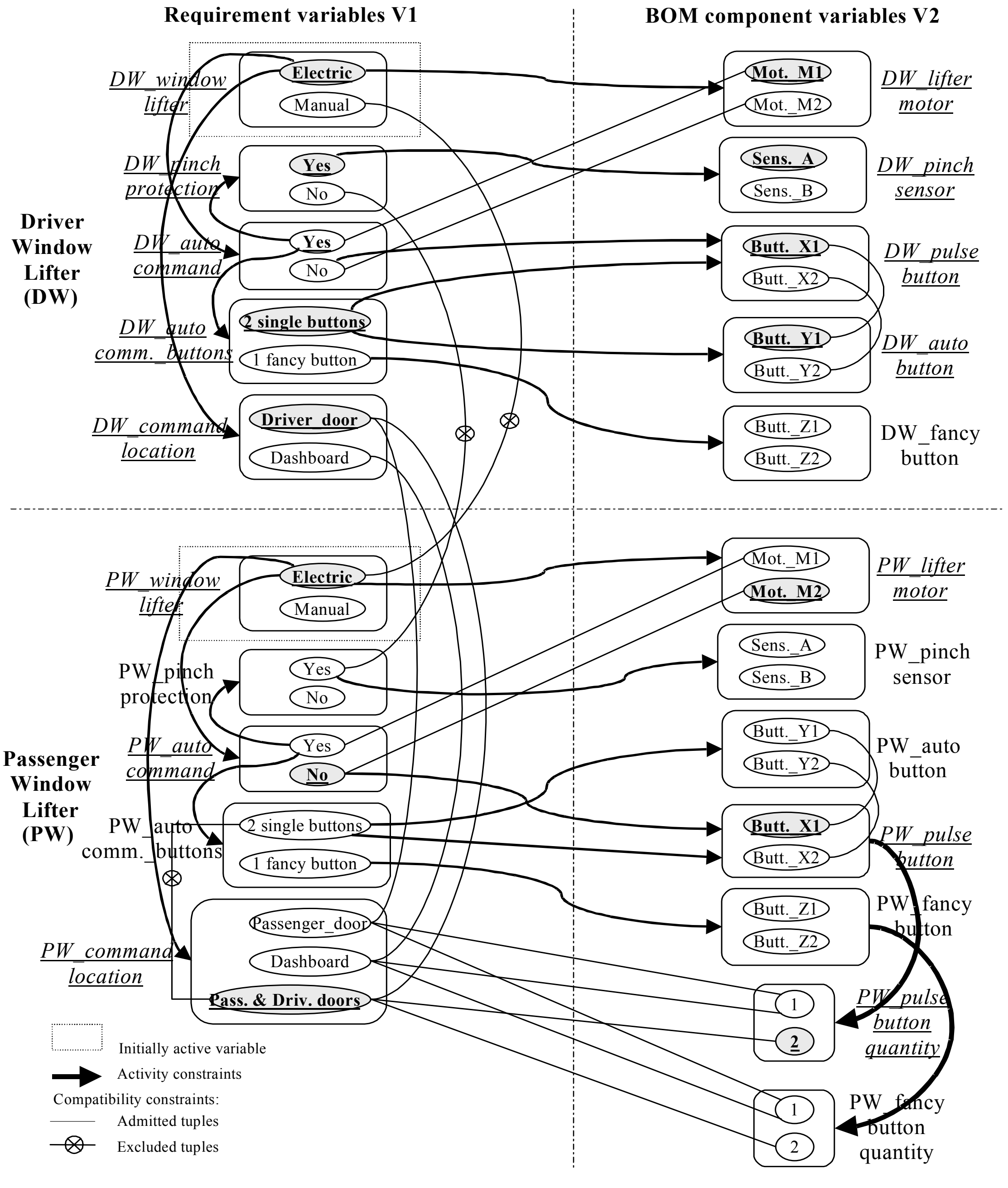

Figure 2. Configuration generic model example

The requirements variables V1 and BOM component variables V2 corresponding with the driver's window lifter are in the upper part of figure 2, while those concerning passenger's window lifter are in the lower part of figure 2. Underlined variables and values in bold characters represent an example of solution. V1 variables represent the functional or ergonomic requirements and allow capturing the wiring harness pack description. They are usually organised in a tree structure (functions/sub-functions) [4] and are located in the left part of the model of figure 2. These variables are subject to compatibility and activity constraints representing what can be gathered. In our example, these variables represent various possibilities of button type (pulse, auto and fancy), button position (driver's door, passenger's door, dashboard), sensor existence (pinch protection) or sub-function existence (electrical window lifter). V2 variables express the components that can be used to support the required function/sub-function. They are organised with respect to the function/sub-function tree and gather wiring harness captors and activators. They are located in the right part of the model of figure 2. Compatibility and activity constraints can exist between them.

# 4 Cost optimisation through pack family and supply chain design

## 4.1 Process description

Among the works dealing with supply chain design, strategic planning is interested in optimising the layout of a complete supply chain [7]. Basically, the strategic design of a supply chain requires to determine the location and capacity of facilities to open, the shipping channels to use and the product flows. Many models have been formulated for this problem, called GSCM (Global Supply Chain Model) [8]. All these models consider product bill-of-material (BOM) as a hierarchical tree of physical articles with only "AND" nodes. Therefore, given a set of packs with relevant bills-of-material (one for each pack) and an extended demand volume per pack, the GSCM permit, thanks to Mixed Integer Programming, to optimise the relevant supply chain layout for this specific set of packs.

As we also want to optimise the pack family, we propose to gather the set of all possible packs in a single generic hierarchical tree and call it G-BOM for "Generic Bill-Of-Material". In order to match this extension, we introduce the notions of "logical article" versus "physical article" and "exclusive OR" bill-of-material nodes versus "AND" nodes (figure 3).

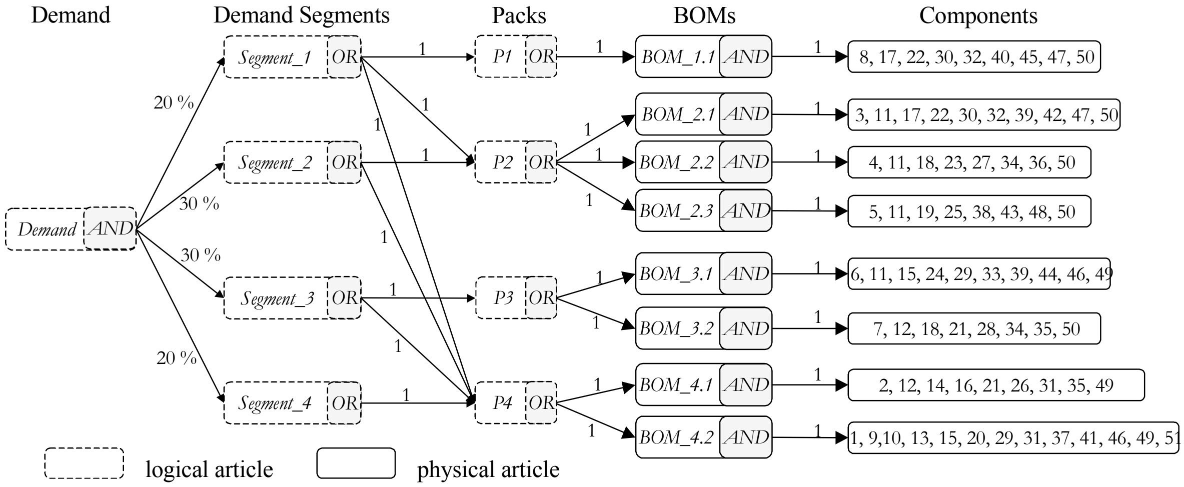

Figure 3. Generic bill-of-material example

- a logical article can neither be manufactured, stored nor shipped. In our case, a logical article represents *Demand*, *Segments* and *Pack*. It allows to identify a required quantity. A physical article corresponds either to bills-of-material "*BOM*" or Components,
- an "exclusive OR" node is introduced to show that one and only one article must be selected among all its lower level articles. Consequently, it allows representing the choice of existence of an article. For example, to define the logical article *P3*, we must select either *BOM_3.1* or *BOM_3.2*.

For the wiring harness design problem of figure 3, the G-BOM enables to represent the potential existence of allowed combination of packs. In our case, (*P1*, *P2*, *P3*, *P4*), the allowed combinations are: {*P4*}, {*P1*, *P4*}, {*P2*, *P4*}, {*P3*, *P4*}, {*P1*, *P2*, *P4*}, {*P1*, *P3*, *P4*}, {*P2*, *P3*, *P4*} and {*P1*, *P2*, *P3*, *P4*}.

The G-BOM of the figure 3 contains 68 articles, split up into five levels: (1) "*Demand*" (1 logical article) "AND" → (2) "*Segments*" (4 logical articles) "OR" → (3) "*Packs*" (4 logical articles) "OR" → (4) "*BOM*" (8 physical articles) "AND" → (5) "*Components*" (51 physical components defining the leaves of the G-BOM).

## 4.2 Optimisation model proposed and processing

In this section, we define a MIP (Mixed Integer Programming) model that optimises the supply chain design, processes the G-BOM and therefore identifies the optimal pack family.

Basically, the supply chain design models [7] [8] are defined with:

- continuous variables: one for each occurrence of (product, time period, facility, quantity) with three kinds of facilities: manufacturing, inventory and shipping (transportation),
- integer variables: one for each facility describing if the facility is used or not,
- classical strategic planning linear constraints between theses variables,

and permit to minimise a cost function gathering variable costs (manufacturing, inventory and shipping) and fixed costs (article references management and facility operating cost).

We propose to add for representing the generic bill-of-material:

- binary variables: one for each article of the G-BOM describing if the article exist or not, one for each G-BOM link parent → child (arising only with the "OR" nodes) describing if the parent article requires the child article,
- constraints between these binary variables.

Now, we will describe the proposed MIP model. The resolution of the MIP provides (i) the pack family definition or the list of packs that should be produced, (ii) the list of facilities that should be used and (iii) the optimal supply chain operating cost. We present the MIP model as an extension of classical models and we assume that: (i) any facility has an infinite resource capacity, (ii) a single shipping channel is available between two facilities, (iii) the time period is much larger than the total production and shipping times.

*Sets, costs and parameters notations*

- $P = \Phi \cup \overline{\Phi}$ : set of articles (physical $\Phi$ /logical $\overline{\Phi}$ ), with $P_c \subset P$ is the sub-set of articles with external demand relevant to customer *c*,
- $BOM_p$ : set of child articles of an article *p* (with "AND" or "OR" node), and $BOM_p^{-1}$ is the set of parent articles of an article *p*,
- $P^{\wedge}$ (resp. $P^{\vee}$ ): set of articles with node "AND" (resp. with node "OR"),
- *C*: set of customers, *T*: set of time periods, *U*: set of production/inventory facilities,
- $ECF_p$ : fixed cost of physical article existence, $UCFO_u$ : fixed cost of facility opening,
- $MCF_{uv}$ : fixed cost of shipping channel existence between two facilities $u \in U$ and $v \in U \cup C$,
- $UCV_{pu}$ (resp. $SCV_{pu}$ ): variable cost to manufacture (resp. to store) one unit of a physical article *p* at facility *u*, and $MCV_{puv}$ is the variable cost to ship one unit of a physical article *p* on the channel between two facilities *u* and *v*,

- $Dem_{pct}$ : external demand from customer facility *c* for article *p* during period *t*,
- $\alpha_{pq}$ : units of child article *p* required to make one unit of parent article *q*,
- $M_{\infty}$ : maximum number of articles to manufacture, to store or to ship (close to $\infty$),

*Binary/continuous decision variables*

- $\lambda_p$ = 1 if article *p* exists, otherwise 0, and $X_u$ = 1 if facility *u* is opened, otherwise 0,
- $\lambda_{pq}$ = 1 if article $q \in P^{\vee}$ requires article *p* as a child, otherwise 0. This binary variable allows to select a bill-of-material link for article *q* with an "OR" node,
- $Z_{uv}$ = 1 if the shipping channel between two facilities *u* and *v* exists, otherwise 0,
- $X_{put}$ : amount of net requirement associated to an article *p* on facility *u* during time period *t*. For physical article, this requirement is equivalent to the manufactured quantity,
- $X_{pqut}$ : amount of net requirement associated to a parent article *q* with node "OR" using a child article *p* at facility *u* during period *t*, if the link *q*→*p* exists ($\lambda_{pq} = 1$),
- $Y_{put}$ : amount of physical article *p* stored at facility *u* at the end of period *t*,
- $Z_{puvt}$ : amount of article *p* shipped between two facilities *u* and *v* during period *t*,

Using these notations and decision variables, a mathematical programming model can be formulated to solve the optimisation problem studied in this paper.

*Mathematical formulation*

**Minimise total cost** = Fixed cost relevant to article existence, facility existence and shipping channel existence (1) + Variable manufacturing, inventory and shipping costs (2).

$$\sum_{p}^{P} ECF_p.\lambda_p + \sum_{u}^{U} UCFO_u.X_u + \sum_{u}^{U} \sum_{v}^{U \cup C} MCF_{uv}.Z_{uv} \tag{1}$$

$$\sum_{p}^{\Phi} \sum_{u}^{U} \sum_{t}^{T} UCV_{pu}.X_{put} + \sum_{p}^{\Phi} \sum_{u}^{U} \sum_{t}^{T} SCV_{pu}.Y_{put} + \sum_{p}^{\Phi} \sum_{u}^{U} \sum_{v \neq u}^{U \cup C} \sum_{t}^{T} MCV_{puv}.Z_{puvt} \tag{2}$$

**Subject to various constraints:**

1. Generic Bill-Of-Material constraints

The G-BOM constraints are introduced to model the existence of articles and bill-of-material links. According to the type of the G-BOM node ("AND" or "OR"), we express differently the constraints restricting the binary variables $\lambda_p$. We note that variables $\lambda_{pq}$ are of interest only when dealing with "OR" nodes.

- For all kind of nodes

A net requirement is associated to an article *p* on facility *u* if and only if this article exists and the relevant facility is opened (3):

$$X_{put} \leq M_{\infty}.\lambda_p \text{ and } X_{put} \leq M_{\infty}.X_u \qquad \forall p \in P, u \in U \cup C, t \in T \tag{3}$$

Constraints (4) express that when an article *p* (without external demand) is selected, either one of its parent articles with an "AND" node exists, or a link relevant to an "OR" node exists.

$$\lambda_p \leq \sum_{q}^{BOM_p^{-1} \cap P^{\wedge}} \lambda_q + \sum_{q}^{BOM_p^{-1} \cap P^{\vee}} \lambda_{pq} \qquad \forall p \in P - P_c \tag{4}$$

- For "OR" nodes

Constraints (5, 6, 7, 8) are given only for an article *q* with "OR" node.

$$\lambda_{pq} \leq \lambda_q \text{ and } \lambda_{pq} \leq \lambda_p \qquad \forall q \in P^{\vee}, p \in BOM_q \tag{5}$$

$$\sum_{p}^{BOM_q} \lambda_{pq} = \lambda_q \qquad \forall q \in P^{\vee} \tag{6}$$

$$\sum_{p}^{BOM_q} X_{pqut} = X_{qut} \qquad \forall q \in P^{\vee}, u \in U, t \in T \tag{7}$$

$$X_{pqut} \leq M_{\infty} . \lambda_{pq} \qquad \forall q \in P^{\vee}, p \in BOM_q, u \in U, t \in T \tag{8}$$

Constraints (5) ensure that a link relevant to an "OR" node exists if and only if both parent and child articles exist. Constraints (6) stand that if an article $q \in P^{\vee}$ exists, one and only one bill-of-material link must be selected in the G-BOM. Constraints (7) mean that the existing of a net requirement of an article *q* triggers a gross requirement of its child articles. Constraints (8) make sure that if a link $q \to p$ exists, the net requirement associated to the article *q* requires the child article $p$. Constraints (5, 6, 7, 8) together, imply that:

$X_{pqut} = X_{qut} \Leftrightarrow \lambda_{pq} = 1$ $(\forall q \in P^{\vee}, p \in BOM_q, u \in U, t \in T)$.

- For "AND" nodes

Constraints (9) ensure that the existence of a parent article $q \in P^{\wedge}$ implies the existence of all child articles.

$$\lambda_p \geq \lambda_q \qquad \forall q \in P^{\wedge}, p \in BOM_q \tag{9}$$

2. Article flow conservation constraints

Flow conservation constraints specify that for each facility *u* and during each time period *t*, the inventory variation of each article *p* must be equal to the sum of quantities generated in the facility (*X*) and coming from other facilities (*Z*) minus the sum of quantities shipped to other facilities (*Z* and *Dem*) and consumed in the facility to satisfy the requirements associated to the parent articles (*X*).

According to our G-BOM definition: (i) a logical article can neither be manufactured, stored nor shipped, but it can generate a gross requirement in any facility, (ii) a physical article can neither be manufactured nor stored in a customer facility, but it can be shipped to it.

Therefore, according to the type of facility (production or customer) and the type of article (physical or logical) flow conservation constraints are formulated as follow (figure 4):

- Constraints (10): physical articles in production facility, $\forall p \in \Phi, u \in U, t \in T$

$$Y_{put} - Y_{put-1} = X_{put} + \sum_{v \neq u}^{U} Z_{pvut} - \sum_{v \neq u}^{U \cup C} Z_{puvt} - \sum_{q}^{P^{\vee} \cap BOM_p^{-1}} \alpha_{pq}.X_{pqut} - \sum_{q}^{P^{\wedge} \cap BOM_p^{-1}} \alpha_{pq}.X_{qut} \qquad (10)$$

- Constraints (11): logical articles in production facility, $\forall p \in \overline{\Phi}, u \in U, t \in T$

$$0 = X_{put} - \sum_{q}^{\left(P^{\vee} \cap BOM_p^{-1}\right)} \alpha_{pq}.X_{pqut} - \sum_{q}^{\left(P^{\wedge} \cap BOM_p^{-1}\right)} \alpha_{pq}.X_{qut} \qquad (11)$$

- Constraints (12): physical articles in customer facility, $\forall p \in \Phi, c \in C, t \in T$

$$Dem_{pct} = \sum_{v}^{U} Z_{pvct} - \sum_{q}^{P^{\vee} \cap BOM_p^{-1}} \alpha_{pq}.X_{pqct} - \sum_{q}^{P^{\wedge} \cap BOM_p^{-1}} \alpha_{pq}.X_{qct} \qquad (12)$$

- Constraints (13): logical articles in customer facility, $\forall p \in \overline{\Phi}, c \in C, t \in T$

$$Dem_{pct} = X_{pct} - \sum_{q}^{P^{\vee} \cap BOM_p^{-1}} \alpha_{pq}.X_{pqct} - \sum_{q}^{P^{\wedge} \cap BOM_p^{-1}} \alpha_{pq}.X_{qct} \qquad (13)$$

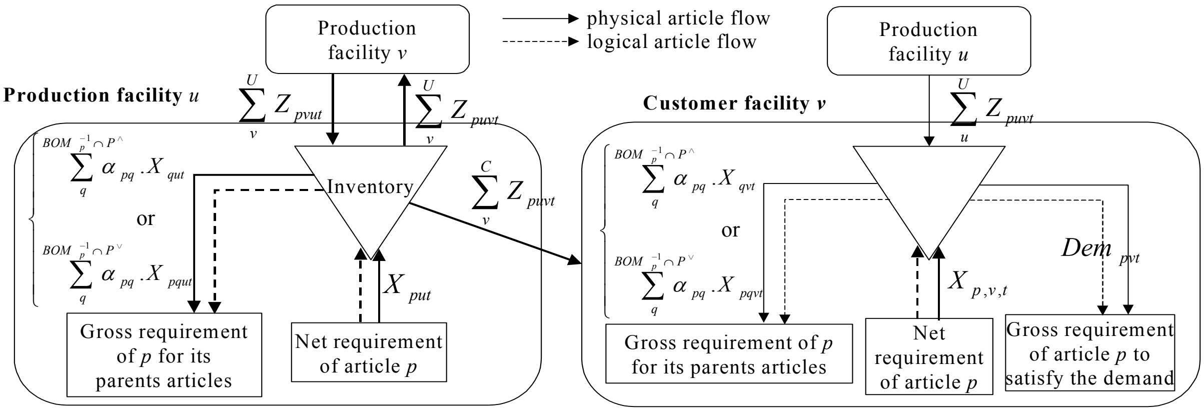

Figure 4. Physical/logical articles flows throughout production/customer facilities

3. Shipping constraints

Constraints (14, 15) together, mean that shipping quantities depend on the existence of facilities, shipping channels and articles.

$$Z_{uv} \leq X_u \text{ and } Z_{uv} \leq X_v \qquad \forall u \in U, v \in U - \{u\} \cup C \qquad (14)$$

$$0 \leq Z_{puvt} \leq M_{\infty}.Z_{uv} \text{ and } Z_{puvt} \leq M_{\infty}.\lambda_p \qquad \forall p \in \Phi, u \in U, v \in U - \{u\} \cup C, t \in T \qquad (15)$$

4. Inventory constraints

Constraints (16) show that the inventory depends on existence of articles and facilities. With constraints (17), we assume that the minimum inventory level at each period is equal to 0.

$$Y_{put} \leq M_{\infty}.X_u \text{ and } Y_{put} \leq M_{\infty}.\lambda_p \qquad \forall p \in \Phi, u \in U, t \in T \qquad (16)$$

$$Y_{put} \geq 0 \qquad \forall p \in \Phi, u \in U, t \in T \qquad (17)$$

5. Binary variables constraints

$$X_u, Z_{uv}, \lambda_p \in \{0,1\} \quad (\forall u \in U, v \in U \cup C, \forall p \in P) \text{ and } \lambda_{pq} \in \{0,1\} \quad \forall q \in P^{\vee}, p \in BOM_q \quad (18)$$

## 4.3 Experimental evaluation

This MIP model has been tested with a problem of a realistic size. For: (i) a supply chain with 11 production facilities and 4 customer facilities, (ii) a generic bill-of-material with 68 articles (figure 3) and (iii) an extended demand on 8 periods; our model contains 20 073 continuous variables, 559 binary variables and 30 849 constraints. This resulting large-scale model is solved in 744 seconds using a commercial solver CPLEX 6.5 on a SUN station with a 143MHz processor.

# 5 Conclusion

The presented approach allows to define a product family (set of packs) that matches a demand presenting a large diversity and the relevant supply chain while minimising the cost compromise "over equipment cost / references management cost".

The approach and relevant models fit the first steps of new products design when supply chain aspects are important and must be taken into account and when the demand diversity is high. This problematic is very common for example in automotive industry, electrical-appliance or PC industry. This result can be considered as a step towards the Holy Grail of integrating product design and logistic in a concurrent engineering context.

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