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# A Model to design a Product and its Extended Supply Chain integrating PLM (Product Lifecycle Management) Solution

Oulfa Labbi, Latifa Ouzizi, Mohammed Douimi, Youssef Aoura

**Abstract**— The aim of this study is to propose a new model of the extended supply chain where design of new products is integrated into the process of designing the supply chain. The paper deals with a recent approach that tackles the product and the supply chain design issues at the same time and proposes a methodology of an optimal design of the product and its extended supply chain. We also propose UML conceptual models of the digital mock up where new product design specificities and constraints of old supply chain partners are both integrated.

Assuming that several product design alternatives are possible using PLM solutions, the design of the extended supply chain is achieved by levels corresponding to the product's bill of material. For this purpose, a mathematical model is proposed for optimizing costs for each level in relation to adjacent ones. By this consideration, the model became simpler to solve. Time periods in the mathematical model are considered to be product life cycle phases to show the evolution of the supply chain at each phase. Finally a numerical example is given to illustrate the application of the model.

**Index Terms**— Extended supply chain (ESC) design, Product Design, Product Lifecycle Management (PLM), Integration, Unified Modeling Language (UML), Optimization, Mixed integer linear programming.



## 1 INTRODUCTION

For many years, companies, independent of one another, focus on enhancing their own activities functions and processes to meet their customers' needs. New forms of organizations have emerged, such as the extended enterprises in which partners must demonstrate strong co-ordination and commitment capabilities to achieve the desired goals.Today, because of increasing competition and advances in information technology, reaching the best customer value at the lowest cost is no longer a matter of managing its own business process but a matter of the whole supply chain (Barratt et al., 2011).That's why companies should exploit the benefits associated with supply chain integration and information sharing to improve their supply chain performance (Zhu et al., 2010).

Research studies showed that 85% of logistics costs are driven by product design choices (Laurentie et al., 2006)and over 70% of product cost is determined by decisions during development phase (H'mida and Martin, 2007).Most benefits of collaboration among supply chain partners lie in the design phase of the product lifecycle. In fact, the cost of design changes increases as the design phase of the product lifecycle ends and the manufacturing phase starts (Gokhan, 2007).

Novak and Eppinger (2001) have explored by an empirical study, the link between product architectures and vertical integration decisions of supply chains. Their analysis showed that the companies optimizing the requirements of their product architectures as well as the capacities of their supply chains will outperform the firms focusing only on supply chain structures or product characteristics.

Therefore, it is important to integrate product architecture and supply chain decisions during the early stages of the product development (Tang et al, 2004, Nepal et al., 2012; Chiu and Okudan,2012).This integration requires strong cooperation and coordination between supply chain upstream and downstream partners. Indeed, different activities, with technological character, of different partners produce massive technical data that need to be exchanged, managed and stored in a coherent and standardized way. This has led to the emergence of methods and systems to manage data, information and knowledge throughout the whole product lifecycle, namely, product lifecycle management (PLM).

PLM enables comparison, evaluation and optimization of the different product requirements, linking production information (specifications, models, results of performance, best practices, and reviews) to design thanks to knowledge management it provides (Trotta and Di Torina, 2010).

It integrates and makes available all data collected during all phases of the product lifecycle for all the stakeholders across the extended enterprise (Sudersan et al., 2005).In general, the product goes through different states during its lifecycle. It starts by being an idea or a project at the level of requirements definition, it is called a digital mock up (DMU) at the design phase, a prototype at the testing level, a product

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at the production phase and a finished product when the distribution operation begins.

Data to be managed are generally classified into three main categories namely, product data, production data and operational support data (Vezzetti et al., 2011).Product data describe how the product is designed, manufactured, operated or used, serviced and then retired. Production data focus on all activities associated with the production and the distribution of the product. Operational support data deal with the enterprise's core resources, such as people, finances and other resources required for supporting the enterprise. In this paper, we will address the product and supply chain design problem at the product development phase, especially when realizing the DMU.

The aim of this paper is to propose a supply chain model where the product design phase integrates the process of designing the SC in order to achieve an optimal supply chain, which we will call Extended Supply Chain (ESC). In fact, the product design joins the functions of the supply chain that are supply, production, distribution, transportation and sale. Each decision on one function affects the others, for example sales fluctuation influences production decisions, storage decisions and so on. Hence, a change in the product design will influence all supply chain functions' decisions .This imply a constant change at the organization of the whole supply chain.The extended supply chain may include new participants and new channels. Therefore, product constraints must be integrated in the supply chain design and all partners' constraints are taken into account in the product design as well.

This work has broadened the traditional way of building the digital mock up that consists on integrating product's constraints in this latter by integrating also logistical constraints. This means that both of product and all supply chain members' constraints are incorporated at the DMU. As a result, data volume to be handled is very important. To overcome this complexity, we propose a conceptual model of the DMU which will be integrated with PLM. Another complexity lies in the fact that the extended network considers more complex supply chain nodes and flows between them, which make the optimization problem more difficult. Hence, we will address this issue by considering the supply chain as a set of levels corresponding to product's bill of materials .Then, a MILP formulation is proposed to design the optimal extended supply chain.

The rest of this paper will be organized as follows: In Section 2, we give a literature review regarding different approaches adopted for product and supply chain design, PLM for management of product data and support of design process and extended supply chain design. In section 3, we propose our methodology based on PLM to design the product and its extended supply chain simultaneously. Section 4 presents the optimization mathematical models. Section 5 gives a numerical example to show the application of our model. Finally, a conclusion with perspectives is presented at the end of the paper.

## 2 LITERATURE REVIEW

### 2.1 Product and Supply chain design

In the literature, the most studied problems of designing a product and its supply chain follow three approaches (Baud-Lavigne et al., 2010).

A first approach consists on integrating product design constraints in supply chain design by taking into account the bill of material (BOM) of the product (assembly constraints).Works following this approach assume that product's bill of material is well defined and already known ,so product design is finalized.

Cordeau et al (2006) and Paquet et al (2008) have proposed mixed linear programming models to design a multi-echelon supply chain and multi-product, considering assembly constraints and detailed bills of materials.

A second cross approach consists on integrating logistic constraints in the product design. The literature suggests some methods facilitating the integration between engineering and logistics actors like Design For Logistics (DFL) (Dowlatshahi, 1996) and Design for Supply Chain Management (DSCM) (Lee and Billington, 1992).These methods define rules to optimize logistics costs by taking into account the logistical constraints in product design. Works on DFL and DFSCM promote the use of concepts such as modular design, delayed differentiation and components standardization to lower costs related to diversity management, storage and transportation of products (Mather, H, 1992; Newlands and Steeple, 2000).In the same context, Nishigushi(1994) and Handfieldand Nichols (1999) have put their interest on supplier integration at the early phases of product design. Nevertheless, these works on logistical constraints integration assume that the supply chain already exists.

A third recent approach considers the design of a product and its related supply chain simultaneously. Supply chain design must be in interaction with product design process. On one hand, supply chain constraints must be integrated into product design phase. On the other hand, product specificities should be considered while determining supply chain structure. Therefore, the supply chain must be flexible and responsive to eventual product redesigns.

Works on simultaneous design of a product and its supply chain are very recent. Baud-Lavigne et al (2012) used a mathematical model in mixed linear programming to optimize the supply chain simultaneously with products standardization. They illustrated impacts of product or component standardization on supply chain structure. El hadj khalaf et al. (2009) have proposed a model to choose simultaneously modules to be produced and their suppliers, under final assembly time constraint. El Maraghy and Mahmoudi (2009) have proposed a multi-period model that simultaneously optimizes the supply chain and product nomenclature. They defined several alternative BOMs, one being selected in the optimal solution. This approach needs a complete enumeration of all product configurations. Kumar and Chatterjee (2013) have developed mixed integer linear programming (MILP) models to simultaneously optimize product line decisions and supply chain configuration.

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However, only rather simple network topology of supply chains is considered. Jafarian and Bashiri (2013) have proposed a model of supply chain network configuration considering new product development. In their model dynamic supply chain configuration is optimized while new product introduction time and supplier's engagement and involvement time are determined simultaneously. Another approach formulating joint optimization for coordinated configuration of product families and supply chains as a leader-follower game, such that a bi-level decision structure performs to model Product family configuration as a leader and Supply chain configuration as a follower was adopted by yang et al. (2015).They developed a bi-level nested genetic algorithm with constraint-reasoning to derive optimal or near-optimal product family and supply chain configuration solutions.

The simultaneous optimization of product and supply chain design is a difficult problem. Due to the complexity of the induced models, very few models address the integrated problems. Moreover, the design problem would be more complex if we consider more complex supply chain nodes and complex logic flows between them such as transportation and storage problems. This is the case of the extended supply chain model proposed.

## 2.2 Product design via PLM and Extended Supply chain

Browsing literature sources, several definitions of PLM are available. CIMdata, a research firm focused on PLM, proposes a very comprehensive definition: "PLM is a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise, and spanning from product concept to end of life-integrating people, processes, business systems, and information. PLM forms the product information backbone for a company and its extended enterprise (CIMdata, 2002). Several other authors have joined this definition as Garetti and Terzi (2003), (Angelo et al, 2013)…

At the technical software integration level, McKay et al. (2001) presented a data model that allows product specifications to be captured in a structured fashion. The specification data model proposed could be used to provide data for software that supports the earlier stages of design processes for the set up of product architectures reflecting the functional requirements of the product. Eynard et al. (2004) explored the advantages of using the oriented object approach to model and implement PDM (Product Data Management) systems using UML diagrams to specify the product structure and workflows. Aziz et al. (2005) have added to a PLM and an open alternative source, an ontological knowledge management methodology utilizing the semantic web initiative data formats to support collaboration in product development for small and medium enterprises.

Several authors have studied the role of PLM solutions in improving effectiveness, efficiency and control of the new product design (NPD) process. It concerns the reduction of design mistakes, the anomaly detection in the first phases of NPD and the management of design changes with a lower impact on process (Saaksvuori and al., 2002; Bergsjo and al., 2008; Goanta and al., 2010). It regards also a better and deeper comprehension of product architecture and components features (Schuh and al., 2006), an improved management of design alternatives, a greater design diversification, the possibility of design alternative comparisons and the exploitation of past design information (Saaksvuori and al., 2002; Schuh and al., 2008; Chakrabarti and al., 2007). PLM permits also the reduction of time needed for information research and an improved management of complex tasks (Rahmani and al., 2011). Moreover, data integration, reduction of data redundancy, real-time updating and knowledge management (Stark and al., 2005; Jun and al., 2007), provided by PLM systems, contributes to an effective support for teamwork and cross-functional collaboration (Sharma and al., 2005; Ming and al., 2008).

Regarding the extended supply chain design, only few articles address this concept. McCormack and Katie Kasper (2000) have driven a statistical study to measure and investigate Internet usage and the impacts on specific supply chain management practices in the extended supply chain. Zhu and Geng (2013) gave a hierarchical analysis to examine whether drivers motivate Chinese manufacturers to implement ESC practices for energy savings and emission reduction goals, and whether barriers impede ESC practices. The problem of ESC design was raised by Fandel and Stammen (2004) that have suggested extending the perspective of traditional supply chain which consists on management of procurement, production, distribution and sales by also including the business processes of development and recycling. They have used a new perspective of a product life cycle; a linear optimization model is designed that considers development and recycling costs, capacities and process integration into an extended supply chain. The model presented in their work integrates strategic and operational decisions but its resolution is certainly very hard.

In most of the extended supply chain literature, the focus is on downstream supply chain functions such as reverse logistics (Huang, 2013; Chuang et al., 2014). In this paper, the interest is given to the very upstream functions by considering the product design as a function of the supply chain. This means that all supply chain members contributes to the product design.

Precisely, we assume that we are in the case of designing a new product starting from an existent old one. The extended supply chain configuration is done from the existing partners of the existent supply chain related to the old product and by introducing, of course, new ones necessary for the new product achievement. In other words, we prioritize supply chain partners that already exist and integrate their constraints at the product design phase. New partners that may be required for the new design are chosen according to new product specificities. We use the PLM solutions which integrate the whole technical data of the product and give multiple alternatives design. Different logistical constraints related to existent supply chain, will be integrated in the digital mock up's product. Multiple product-supply chain design solutions will be generated. Each solution corresponds

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to an extended supply chain configuration. Each ESC is designed as a set of levels corresponding to product's bill of material and its structure is obtained by the resolution of its related Mixed Integer Linear Programming models. The design of the product and its extended supply chain that will be chosen is that which provides the best cost and incorporates as many partners of the initial supply chain. Next section explains in details our proposed methodology to design the product and its corresponding extended supply chain. Figure 1 illustrates this new concept.

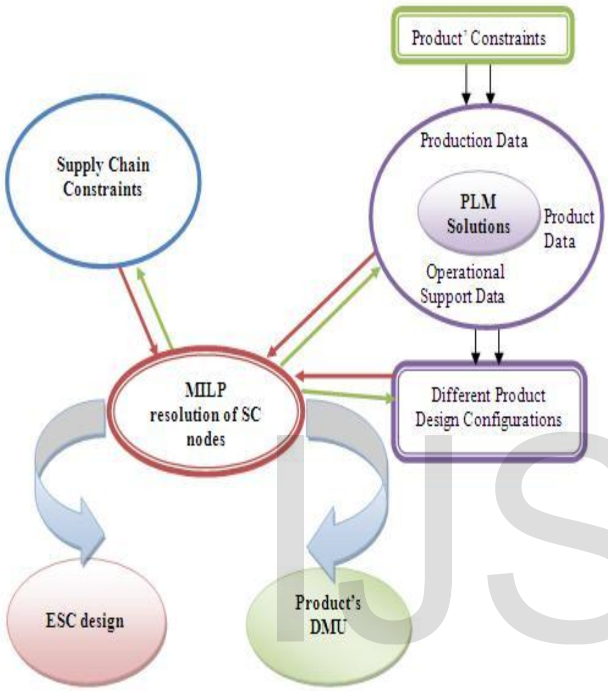


Fig.1.Extended supply chain integrating PLM.

## 3 Methodology of Designing the Product and its Extended Supply Chain

### 3.1 Methodology Description

The product and its extended supply chain design will be handled by combining the following:

- Integration of product constraints in the supply chain design, by considering different bill-of-materials, which means different components, different processes for manufacturing, different conditions of storage or transportation …
- Product Lifecycle Management (PLM) solutions to manage all technical data incorporated at the product design and generate different product design alternatives.
- Integration of supply chain constraints at the product design. For example, Constraints of means of transport or storage conditions are included. These constraints will be introduced in the digital mock up (DMU) model proposed.
- Optimization of the Extended Supply Chain (ESC) design favoring the existing supply chain partners using mathematical models minimizing costs and considering additional contracting costs for new participants introduced.

We assume that market research and marketing has been made. Product demand is assumed to be a priori known to the estimator. Its determination is out of the scope of this paper. The supply chain design problem is, mainly, a problem of suppliers and outsourcers' selection (location and allocation problem), allocation of production sites, implementation or removal of production facilities, storage and transportation.

We present in (Fig2) the flowchart of our methodology for designing a product and its extended supply chain.

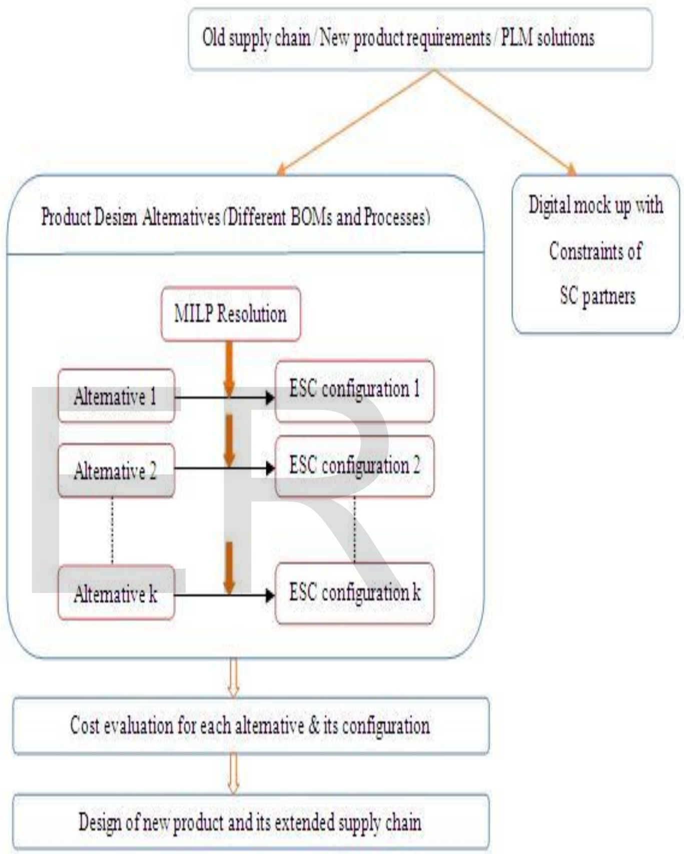


Fig.2.Flowchart of designing a product and its extended supply chain methodology.

### 3.2 Product Design alternatives

Several design scenarios or alternatives are generated thanks to PLM solutions (design and production process).In fact; the new product design (redesign) could affect either product components or the manufacturing process or both at once. The redesign may include the following three cases:

- Redesign configuration consists of only components which are common with the initial product having similar or different bill of material's coefficients. This implies that product's design change affects the manufacturing process.
- It is composed of new components that have never existed in the old nomenclature.
- It combines common components and new ones.

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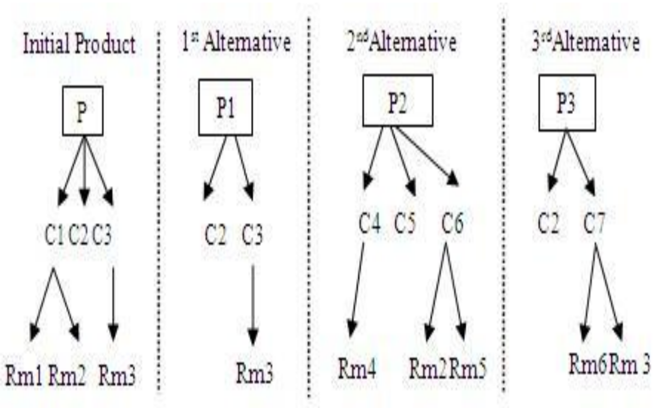


Fig.3. Illustrative example of redesign alternatives' nomenclature.

To assemble the product according to each redesign alternative, we could either keep the same existing assembling technology (machine) or implement new technologies or have a mixture between old and new technologies.

Figure 3 shows an illustrative example of the initial product P and that of three redesign alternatives proposed. We suppose that the initial product is composed by components C1, C2, and C3 and raw materials Rm1, Rm2 and Rm3. Components C4, C5, C6, and C7 are new ones.

To each product design alternative corresponds an extended supply chain that assures the realization of all operations related to its life cycle. We evaluate the cost of each ESC alternative. We propose a mixed integer linear programming (MILP) model to optimally choose the best suppliers, producers, transporters and storage areas. Section 5 shows in details the MILP building.

### 3.3 Description of the extended supply chain design process

#### 3.3.1 Architecture by levels of the extended supply chain

When studying a design alternative, the extended supply chain will be designed as a set of levels (Ouzizi et al, 2006), following the levels of bill of material of the product, starting from producers level. The optimization of the extended supply chain design consists on optimizing each level in relationship with a predecessor level (customer) and a successor level (supplier). Each partner of the extended supply chain is in relation with several customers and suppliers. It is assumed that each partner is only in relationship with its adjacent partners (No loop between partners allowed). Thus, each partner belongs to exactly one level. In the case of a relationship between two partners from two nonadjacent levels, fictitious nodes may be introduced into the model. These fictitious nodes ensure relationships between adjacent levels. We could identify two types of levels within the ESC, namely:

- Internal levels that are both customers and suppliers in the ESC.
- The level directly related to the customers of the ESC which is the first level of the ESC.

Figure 4 shows an example of an ESC comprising four levels.

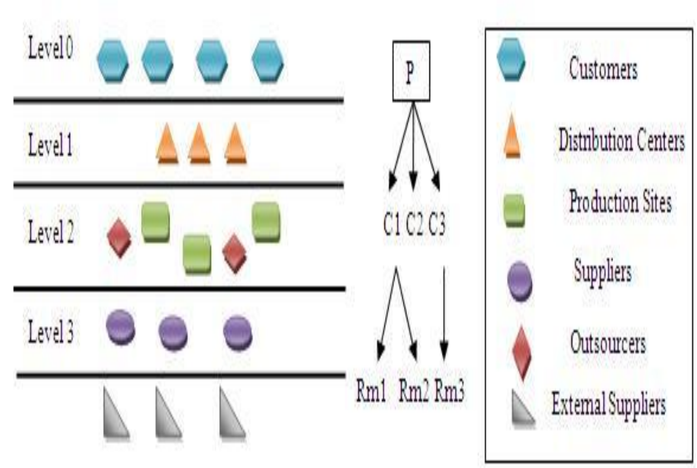


Fig.4. Architecture by levels of the extended supply chain corresponding to the product P.

We consider that the product P to be realized in each node of the ESC is defined by its components. For example, the finished products for suppliers' nodes are, in fact, the components of production sites' finished product whereas their components would be raw of materials, supplied from their successor suppliers and so on. The design of the extended supply chain is then achieved by levels corresponding to levels of bill of materials of the product. The optimization of the extended supply chain design will consist on optimizing each level in relation to adjacent ones starting from producers' level.

#### 3.3.2 Extended supply chain evolution

This model proposes a dynamic approach for the design of the extended supply chain by considering a multi periodic decision horizon. Time periods in the optimizing mathematical models (MILP) are taken as the product life cycle phases. In each period (life cycle phase), some strategic decisions have to be made: selecting suppliers and outsourcers, adding or closing production technologies, selecting distributers and so on .Therefore, there is an evolutionary configuration of the supply chain following the product lifecycle phases behaviors. In other words, the supply chain evolves through the decision horizon. For example, we could mention an increase of suppliers and investment on new machines at growth and maturity phases as the demand increases. Also, some suppliers, subcontractors and also machines will be removed at decline phase where the demand decreases.

### 3.4. Digital mock up development

DMU is the process of building a numerical (digital 3D) representation of a product to conduct tests that will predict product function and performance in the real world. While developing the DMU, we are reducing the need for physical product prototyping that is the most expensive aspect of the product development. The DMU also encourages more design

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alternatives, leading to increased product innovation.

The old supply chain, the new product specificities and PLM solutions are the key elements of our methodology. In fact, before starting the product's DMU development, the design team should carry out constraints of old supply chain partners, technical constraints of the manufacturers and customer specifications to list the new product requirements. The DMU is tightly integrated with PLM solutions to decrease product development time and costs and to improve product quality by allowing a greater number of design alternatives to be investigated before a final one is chosen. Indeed, the DMU integrated with PLM solutions will assure sharing product information and will allow design reviews to be quickly and easily conducted among multiple team members and across multiple companies and geographies.

Product design engineers, manufacturing engineers, support engineers and supply chain partners work as a team to create and manage the DMU. While building the product's DMU, the existing supply chain partners are favored by integrating their constraints at the design. Several design alternatives are provided using PLM solutions, which means different bill of materials and different production processes are proposed.

### 3.4.1 Conceptual model of the DMU

We use Unified Model Language (UML) to model the static aspect of the product and its extended supply chain design at DMU using a class diagram (Figure 5).

The **ESC Node** class represents each node belonging to the extended supply chain. It could be one of different partners (supplier, client, producer, subcontractor, distributor…). As explained before, each node of the ESC belongs to one level and it is related to nodes of its adjacent level. In fact, an ESC node is related to nodes of its predecessor level that could be either a client or a distribution center and also related to nodes of its successor level (suppliers). The ESC node could be related to nodes of its level if it is the case of a subcontractor node since it belongs to the same level of bill of materials.

Each ESC node could have many production processes (machines) to realize its finished Product .We consider the cardinality 0...* between ESC node class and process class to take into account the case where the ESC node is a distribution center (it doesn't have a production machine).

The **Product DMU** (Digital Mock Up) class is the numerical representation of the product. It allows the product description during its entire lifecycle. It provides technical data of the product such as bill of materials (BOM) or components. We mention that each ESC node could produce a product (finished product, manufactured product or raw material). In fact, if the ESC node is a production plant, the class product comprises data of the finished product and its related components. If the ESC Node is a supplier, the product class will provide data about a manufactured product. In this case, Components class will provide data about raw materials of the final product.

We represent also association classes that result from relationship between different classes such as: "supplying", "order", "production", "outsourcing" and "distribution" classes. In these association classes, we are informed about costs and quantities data.



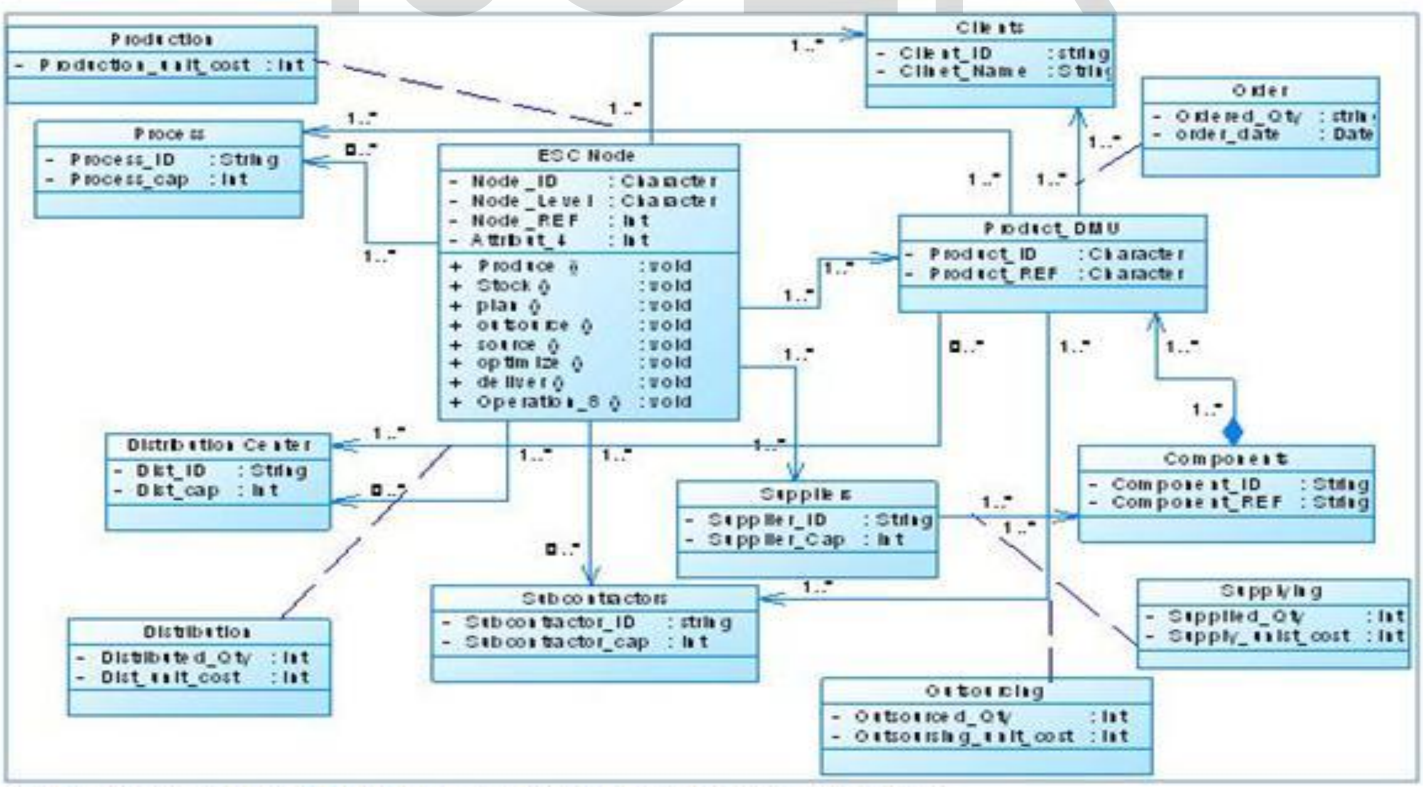


Fig.5. UML class diagram modelling the design of the product and its supply chain

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By this conceptual model, we showed that the product's DMU comprises not only data regarding product architecture and features of its components but also incorporates the logistical constraints of all SC participants.

### 3.4.2 Interaction diagram for the ESC design

The extended supply chain is considered as a set of levels mainly to reduce the complexity of optimization. The ESC optimization starts from the upstream level (producers' level) by solving the MILP model for each node belonging to. Each node will be optimized with its adjacent level.

Once the optimization of the first level is done, we move to the optimization of its successor level until sweeping the whole extended supply chain. MILP outputs for a predecessor level are taken as inputs for the resolution of the MILP model related to its successor level. For example, outputs of producers level as quantities of components to buy from each supplier will be taken as inputs (demand) for the suppliers level optimization.

To have a better insight of the design methodology adopted, figure 6 present an UML sequence diagram modelling the interactions between nodes of the ESC and illustrating the scenario of the product and its supply chain design.

Constraints of nodes belonging to different levels are taken in consideration in order to realize the DMU of the product. Once the DMU of the product is realized, the MILP consider its specificities and constraints .The predecessor node inform the node to be optimized about demanded quantities of the product. The MILP optimize costs of the node studied after introducing its input data. The resolution of the MILP provides optimal quantities of components to be ordered from successor nodes, quantities to be outsourced and produced at the same level and quantities to be transferred to predecessor level. Quantities to be ordered will be as demanded quantities (inputs) when optimizing the successor node. The optimization process is repeated for successor nodes till sweeping the whole supply chain. The MILP formulation is provided in details in next section.

Once the optimization process is finalized, we obtain the configuration of the extended supply chain related to the product design alternative studied. The same approach is applied to other alternatives. Finally, we choose the best product design and its extended supply chain configuration after cost evaluation.

## 4 Optimization mathematical Models

### 4.1 Problem assumptions

The assumptions considered are as follows:

- The demand for the product is a priori known.
- Each node of the ESC undertakes the transportation of required product for its predecessor level.
- Components transportation unit cost is in the range of minimum and maximum capacity of each supplier.
- Each component can have a different quality index, that's why a segmentation based on the desired quality index is done earlier. In other words, all suppliers selected for a component must deliver it with the same quality index to have homogeneous quantities.
- Each internal node specifies to its direct suppliers a minimum acceptable defect rate for each component.
- Internal nodes may call upon subcontractors to meet their product demand.



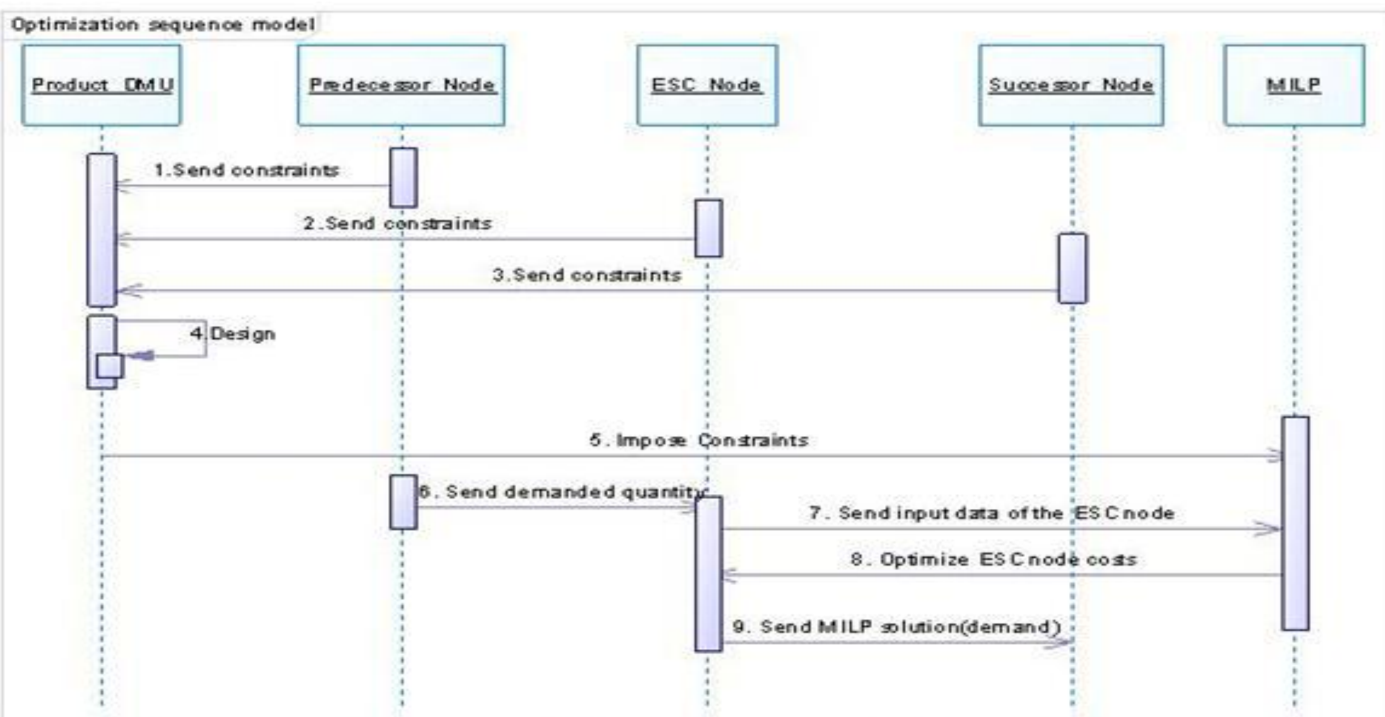


Fig.6. UML sequence diagram explaining the design methodology adopted.

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- Internal nodes pay a fixed cost including contract and partnership costs for suppliers and subcontractors newly introduced. This is for prioritizing suppliers and subcontractors that already exist at the starting supply chain.
- Each subcontractor must respect the product's quality level required by its predecessor.
- All assembling processes (machines) added or implanted must not exceed a maximum number in order to respect the plant capacity and the investment budget for this new product.
- Only one mode of transportation is considered.
- Distribution centers assure the storage, the treatment and the transport of finished products.
- All the customers are served through distribution centers and not directly from the plants.
- New distribution centers could be introduced in case of the lack of capacity of the existing ones or when the new product design requires special conditions of storage that existing warehouses couldn't assure.
- Plants' nodes pay a contracting cost to distributers newly introduced.

### 4.2 Problem sets and data

We propose the following definitions:

- A: the set of possible design alternatives indexed by a.
- $N^a$ : The set of design alternative nodes , indexed by i and j, such as:
- $N^a = (N^0 \cap N^a) \cup (N^a \setminus N^0)$ with $N^0$: the set of existing product's nodes.
- Similarly,
- $D^a$ : set of distribution centers corresponding to the alternative (a),indexed by d, such as :
- $D^a = (D^0 \cap D^a) \cup (D^a \setminus D^0)$ with $D^0$ the set of distribution centers employed to distribute the existing product.
- $K^a$ : set of ESC clients corresponding to the alternative (a),indexed by k, such as :
- $K^a = (K^0 \cap K^a) \cup (K^a \setminus K^0)$ with $K^0$ the set of clients of the existing product.
- $C^a$ : set of design alternatives' components, indexed by c, such as:
- $C^a = (C^0 \cap C^a) \cup (C^a \setminus C^0)$ with $C^0$: the set of components existing in the starting nomenclature
- $M^a$ : The set of machines required for the design alternative(a), indexed by m, such as:
- $M^a = (M^0 \cap M^a) \cup (M^a \setminus M^0)$ with $M^0$: the set of machines used to produce the existing product.
- T : the decision horizon indexed by t.
- $N_i^{a-}$ : set of nodes belonging to the predecessor level of a node i.
- $N_i^{a+}$ : set of nodes belonging to the successor level of a node i.
- $N_i^{a}$ : set of nodes belonging to the same level of a node i.

The model includes the following data regarding each node i:

$\mathbf{CA}_{c,j,t}^{(i)}$: Purchasing unit cost of the component **c** from the node **j** in period **t**.

$\mathbf{CS}_{j,t}^{(i)}$: Outsourcing unit cost related to the node **j** in period **t.**

$\mathbf{CT}_{j,t}^{(i)}$ : Transport unit cost of a product (finished product, manufactured or raw material) from node **i** to **j** in period **t**.

$\mathbf{CF}_{j,t}^{(i)}$ : Partnership and collaboration fixed cost paid for a node **j** in period **t.**

$\mathbf{CD}_{d,t}^{(i)}$ : Contracting cost paid by the plant **i** to the distributor **d** in period **t.**

$\mathbf{q}_{c,j,t}$ **:** Defect rate of the supplier node **j** for the component **c** in period **t**.

$\mathbf{qa}_{c,i,t}$ **:** Acceptable defect rate of the node **i** for the component **c** in period **t**.

$\mathbf{D}_{c,i,t}$ **:** Demand of the node **i** for the component **c** in period **t.**

$\mathbf{Capmax}_{j,c,t}$**:** Maximum capacity of the node **j** to deliver the component **c** in period **t.**

$\mathbf{Chp}_{m,t}^{(i)}$**:** Production hourly cost for a unit of the finished product in the machine **m** on node **i** in period **t.**

$\mathbf{CFA}_{m,t}^{(i)}$ **:** Fixed cost of machine **m** implementation at node **i** in period **t**.

$\mathbf{CFS}_{m,t}^{(i)}$ **:** Removal or jobless cost of the machine **m** at node **i** in period **t**.

$\mathbf{D}_{k,t}$**:** Demand of the client **k** for the final product in period **t**.

$\mathbf{Cmax\_p}_{m,t}^{(i)}$**:** Production maximum capacity of the machine **m** belonging to node **i** in period **t**.

$\mathbf{Cmax\_st}_{j,t}$: Production maximum capacity of the subcontractor node **j** in period **t**.

$\mathbf{MaxST}_{i,t}$: Maximum quantity allowed for outsourcing the finished product at the node **i** in period **t**.

$\mathbf{tpu}_m$ **:** Production unit time of the finished product in a machine **m** in period **t**.

$\mathbf{NEI}^0_{m,i}$ **:** Number of copies of a machine **m** originally existing at the node **i**.

$\mathbf{MaxNE}_{m,t}^{(i)}$**:** Maximum number allowed for the addition of a machine **m** at the node **i** in period **t**.

$\mathbf{CSD}_{d,t}$: Storage unit cost of the distribution center **d** in period **t**.

$\mathbf{CTK}_{d,k,t}$: Transportation cost of the finished product from distribution center **d** to client **k** in period **t.**

$v_p$: Volume occupied by the finished product **p**.

$\mathbf{V_d}$ : Volume capacity reserved to the finished product **p** at the distribution center **d**.

$\boldsymbol{\alpha}^{(i)}$ : Parameter equal to 1 if the node **i** in question is a plant and equal to 0 otherwise.

### 4.3 Decision variables

$Q_{c,j,t}^{(i)}$ **:** Quantity of component **c** ordered from supplier node **j** in period **t** for the node **i**.

$QP_t^{(i)}$**:** Produced quantity of the finished product at the node **i** in period **t.**

$QS_{j,t}^{(i)}$**:** Outsourced quantity of the finished product from the subcontractor node **j** in period **t** for the node **i**.

$NEA_{m,t}^{(i)}$ **:** Number of copies added of a machine **m** at the node **i** in period **t**.

$NES_{m,t}^{(i)}$ **:** Number of copies removed of a machine **m** the node **i** in period **t**.

$QT_{j,t}^{(i)}$ **:** Quantity of finished product related to node **i** transferred to node **j** in period **t.**

$QTK_{d,k,t}$: Quantity of the final product transferred from the distribution center **d** to client **k** in period **t.**

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$\boldsymbol{NSD_{d,t}}$ : Quantity of the final product held in distribution center **d** in period **t.**

$\boldsymbol{S^{(i)}_{j,t}}$ **:** Binary variable for the allocation of subcontracting nodes **j** to node **i** with $\boldsymbol{S^{(i)}_{j,t}}$= 1, if the subcontractor node j supplies the node i, and $\boldsymbol{S^{(i)}_{j,t}}$= 0 otherwise.

$\boldsymbol{Z^{(i)}_{c,j,t}}$: Binary variable for the allocation of components supplying nodes **j** to node **i** with $\boldsymbol{Z^{(i)}_{c,j,t}}$= 1, if the supplier node j supplies the node **i,** and $\boldsymbol{Z^{(i)}_{c,j,t}}$ =0 otherwise.

$\boldsymbol{D^{(i)}_{d,t}}$ **:** Binary variable for the allocation of distribution centers nodes **d** to plant node **i** with $\boldsymbol{D^{(i)}_{d,t}}$= 1, if the distribution center d is selected, and $\boldsymbol{D^{(i)}_{d,t}}$= 0 otherwise.

### 4.4 Objective function for internal levels

For each possible design alternative and for each node belonging to the same level, the objective function is to minimize supply, outsourcing, production, transportation, and adding or removing machines costs. Therefore, supply chain design problem is, mainly, a problem of suppliers and outsourcers' selection (location and allocation problem), selection of distribution centers, implementation or removal of production facilities, storage and transportation. Our objective function f (i) for internal levels could be written as follows:

### 4.5 Constraints

- Suppliers capacity

$$\boldsymbol{Q^{(i)}_{c,j,t} \leq Capmax_{j,c,t} * Z^{(i)}_{c,j,t}} \ \forall c, j, t \qquad (2)$$

Purchased quantity of the component **c** is limited by the production capacity of its supplier node **j** .This is valid for each component at any planning period. With this constraint, we can also check if $\mathbf{Z}^{(i)}_{c,j,t}$ = 0 (the supplier node j is not selected for the component c) then $\boldsymbol{Q^{(i)}_{c,j,t}} = 0$ .

$$f(i): \underset{a \in A}{Min} \ Min \ \sum_{t \in T} \sum_{c \in C^r} \sum_{j \in N^{a-}_i} CA^{(i)}_{c,j,t} * Q^{(i)}_{c,j,t} + \sum_{t \in T} \sum_{c \in C^r} \sum_{j \in N^{a-}_i} CF^{(i)}_{j,t} * Z^{(i)}_{c,j,t}$$
$$+ \sum_{t \in T} \sum_{j \in N^a_i} \left( CS^{(i)}_{j,t} * QS^{(i)}_{j,t} + CF^{(i)}_{j,t} * S^{(i)}_{j,t} \right)$$
$$+ \sum_{t \in T} \sum_{m \in M^a} \left( Chp^{(i)}_{m,t} * QP^{(i)}_{t} + CFA^{(i)}_{m,t} * NEA^{(i)}_{m,t} + CFS^{(i)}_{m,t} * NES^{(i)}_{m,t} \right)$$
$$+ \sum_{t \in T} \sum_{j \in N^{a+}_i} CT^{(i)}_{j,t} * QT^{(i)}_{j,t} + \left( \alpha * \sum_{t \in T} \sum_{d \in D^a} \left( CD^{(i)}_{d,t} * D^{(i)}_{d,t} \right) \right) \qquad (1)$$

- Component demand satisfaction

$$\sum_{j \in N^{a-}_i} \boldsymbol{(1 - q_{c,j,t}) \ Q^{(i)}_{c,j,t} \ \geq D_{c,i,t}} \ \ \forall \text{ c, t} \qquad (3)$$

This constraint shows that the sum of the acceptable amounts of a component received from all successor nodes in a period must meet the forecasted demand of this component in this period.

- Quality verification

$$\sum_{j \in N^{a-}_i} \mathbf{q_{c,j,t} * Q^{(i)}_{c,j,t} \leq qa_{c,i,t} * D_{c,i,t}} \ \forall \ \mathbf{j, t} \qquad (4)$$

Constraint (4) ensures that the expected defects for a component c must be lower than the permissible defect rate. This is valid for each component in each period.

- Finished product demand satisfaction

$$\sum_{j \in N^a_i} \mathbf{QS^{(i)}_{j,t}} + \ \mathbf{QP^{(i)}_{t}} \geq \ \sum_{j \in N^{a+}_i} \mathbf{QT^{(i)}_{j,t}} \ \ \forall \ \text{j, t} \qquad (5)$$

Constraint (5) require that quantities produced and outsourced of finished product related to node i is greater than or equal to its delivered quantities for each period.

- Subcontractors capacity

$$\mathbf{QS^{(i)}_{j,t} \leq Cmax\_st_{j,t} * S^{(i)}_{j,t}} \ \ \forall \ \mathbf{s, t} \qquad (6)$$

Outsourced quantity of the finished product, related to node i, is limited by the production capacity of its subcontractor node for each period.

- Outsourcing limitation

$$\sum_{j \in N^a_i} \mathbf{QS^{(i)}_{j,t} \leq \ MaxST_{i,t}} \ \forall \ \mathbf{t} \qquad (7)$$

The quantities outsourced of the finished product, related to node i, received from all subcontractors must not exceed the allowed quantity for the outsourcing in each period.

- Producing capacity

$$\mathbf{QP^{(i)}_{t}} * \mathbf{tpu_m} \leq \mathbf{Cmax\_p^{(i)}_{m,t}} * \left( \mathbf{NEI^0_{m,i} + NEA^{(i)}_{m,t} - NES^{(i)}_{m,t}} \right) \ \forall \ \mathbf{m, t} \qquad (8)$$

Constraint (8) ensures that the quantities produced of finished product respect production capacities of all available machines in each period.

- Producing machine implementation limitation

$$\mathbf{NEI^0_{m,i} + NEA^{(i)}_{m,t} - NES^{(i)}_{m,t_{m,t}} \leq MaxNE^{(i)}_{m,t}} \quad \forall \ \mathbf{m, t} \qquad (9)$$

Constraint (9) shows that all assembling technologies including machines that originally existed and those newly implanted must not exceed a maximum number in order to respect the node capacity and investment budget for each machine type and each period.

- Distribution center capacity constraint

$$\mathbf{v_p} \ * \ \sum_{t \in T} \mathbf{QT^{(i)}_{d,t} \leq V_d * D^{(i)}_{d,t}} \ \ \forall \ \mathbf{d, t} \qquad (10)$$

This constraint is valid only when the node i is a plant having a distributor center as a predecessor and shows that quantities of finished product transferred from a plant i to a distributor center d is limited by its capacity of storage dedicated to the product. With this constraint, we can also check if $D^{(i)}_{d,t}$ = 0 (the plant i doesn't select the distributer node d) then $QT^{(i)}_{d,t} = 0$ .

- Non negativity and binary constraints

$$\mathbf{Q^{(i)}_{c,j,t} \ ; QT^{(i)}_{j,t} \ ; \ QP^{(i)}_{t} ; QS^{(i)}_{j,t} \geq 0} \qquad (11)$$

$$\mathbf{Z^{(i)}_{c,j,t} ; S^{(i)}_{j,t} ; D^{(i)}_{d,t} \in \{0, 1\}} \qquad (12)$$

$$\mathbf{NEA^{(i)}_{m,t} \ ; NES^{(i)}_{m,t} \geq 0} \qquad (13)$$

### 4.6 Objective function for the level directly related to ESC clients

For this level directly related to the clients of the extended supply chain (distribution level), the objective function consist on minimizing storage and transportation of the final product for each node belonging to this level (distribution centres). Our objective function f (d) for this level could be written as:

$$\text{f (d) : } \underset{a \in A}{\text{Min}} \ \text{Min} \ \sum_{t \in T} \sum_{d \in D^a} \sum_{k \in N^{a+}_d} \boldsymbol{CTK_{d,k,t} * QTK_{d,k,t}} + \sum_{t \in T} \sum_{d \in D^a} \boldsymbol{CSD_{d,t} * NSD_{d,t}} \qquad (14)$$

### 4.7. Constraints

- Demand satisfaction

$$\sum_{t \in T} \sum_{d \in D^a} \boldsymbol{QTK_{d,k,t} \geq \ D_{k,t}} \qquad (15)$$

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Constraint (15) shows that quantities of finished product delivered from all distributer centers should meet the demand of the client **k**.

- Product flow conservation

$$\sum_{t\in T}\sum_{j\in N_d^{a-}} QT_{j,t}^{(d)} = \sum_{t\in T}\sum_{k\in N_d^{a+}} QTK_{d,k,t} \quad \forall\, d,t \qquad (16)$$

Constraint (16) shows that quantities of finished product that have been transferred to a distribution center d must equal the quantities that will be transferred from this distributor to clients.

- Distribution center capacity

$$v_p \; * \; \sum_{t\in T}\sum_{j\in N_d^{a-}} QT_{j,t}^{(d)} \le V_d \quad \forall\, d,t \qquad (17)$$

$$\mathbf{v_p} \; * \mathbf{NSD_{d,t}} \le \mathbf{V_d} \qquad \forall\, d,t \qquad (18)$$

Constraints (17) and (18) shows that quantities of finished product transferred to a distribution center and stored at it are limited by its capacity of storage dedicated to this product.

- Flow conservation at distribution centers

$$NSD_{d,t} = NSD_{d,t-1} + \sum_{j\in N_d^{a-}} QT_{j,t}^{(d)} - \sum_{k\in K^r} QTK_{d,k,t} \qquad (19)$$

This constraint is about flow conservation at distribution centers, they must receive enough finished product from plants in order to meet all the demands.

- Non negativity Constraint

$$QTK_{d,k,,t} \;;\; NSD_{d,t} \ge 0 \qquad (20)$$

## 5. Numerical example

To have a better insight of our model, a numerical example is presented in this part. As this model aims to optimize product and supply chain design at a strategic (long term) level, time periods are considered to be product life cycle phases. In this example we considered four periods corresponding to introduction, growth, maturity and decline phases. We consider that a producing company wants to redesign a product P. The design team proposes three alternatives P1, P2, P3 for the redesign of the initial product P. In the three redesigns, there was either a change in the components or in the process or both of them at once. We consider the nomenclature of initial product and that of the three alternatives proposed at the illustrative example showed previously in figure 3 .The initial product is composed by three components C1, C2, and C3. Components C4 C5, C6, and C7 are new ones. The structure by levels of the extended supply chain corresponding to the initial product is presented in figure 7. The chain comprises three clients (K1, K2, K3), two distribution centers (D1, D2), one plant and three subcontractors (S1, S2, S3), three component 'suppliers (F1, F2, F3) and three external suppliers (E1, E2, E3).In this numerical example we will consider a structure that comprises three levels. The supply chain design will concern the selection of distribution centers, subcontractors and suppliers with allocation of quantities to be delivered, produced and transferred and also adding or removal of producing technologies. For the achievement of design alternatives, we will need to add new suppliers (F4, F5), new subcontractors (S3, S4) and a new distribution center (D3).

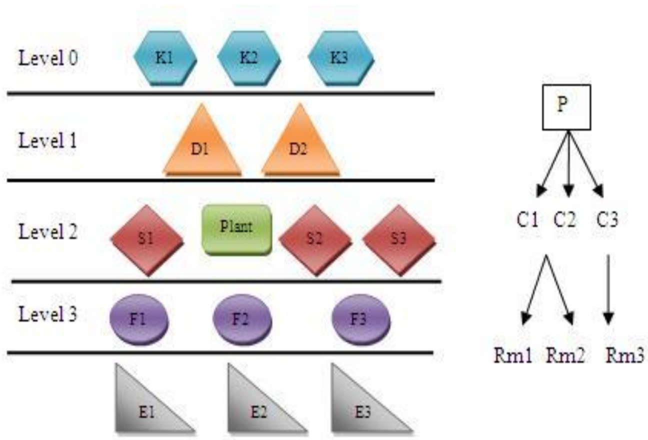


Fig 7. The initial product and its related ESC.

The set of suppliers for each component and raw material are as follows:

C1= {F1, F2, F3}; C2= {F2, F3}; C3= {F1, F2}; C4= {F1, F4}; C5= {F2, F5};
C6= {F4, F5}; C7= {F3, F4}.

It's assumed that the purchasing cost and the defect ratio for each supplier to each component are the same in each period. To assemble the redesigned product according to each alternative, we will need either the existing machines used to assemble the initial product or new ones or both of them at once. Fig 8 shows the necessary machines for producing the redesigned product according to each possible redesign. We supposed that the initial product needs three machines M1, M2, and M3 to be assembled. M4 and M5 are new machines to be implanted.

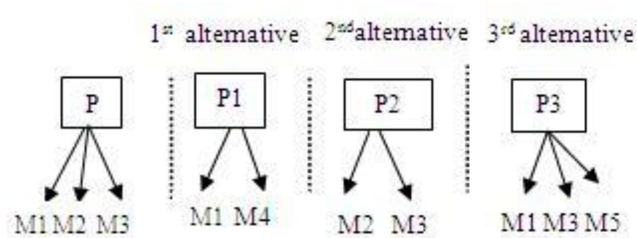


Fig 8. Production necessary machines

As outsourcing is concerned, it is assumed that the maximum capacity of each subcontractor at each period is the same .Regarding assembling machines; we assume that the production unit cost, the production capacity, the implementation and the removal costs are the same for each period.

Tables (1) to (13) in the appendix show data have been used for the numerical example. The mathematical models corresponding to each node were programmed and solved using the IBM Ilog Cplex 12.2. We started by the resolution of the MILP related to production level (plant).The outputs obtained will be then introduced as inputs for successor nodes (Suppliers). These steps were executed for each of the three

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alternatives. As a result, we will obtain three configurations of ESC. Table 14 illustrates the results obtained for the plant node at each design alternative.

TABLE 14. RESULTS OF MILP FOR THE PLANT NODE

| Redesign Alternative | Constraints | Variables | coefficients | Solution time(s) | MILP Objective |
|---|---|---|---|---|---|
| P1 | 132 | 117 | 336 | 448.43 | 1.6946e+004 |
| P2 | 184 | 165 | 424 | 824.51 | 1.9044e+004 |
| P3 | 140 | 125 | 340 | 595.31 | 1.4172e+004 |

We solve also the MILP related to distribution level to obtain the whole structure of the chain. Given that the MILP resolution of the plant node indicates the distributors to be selected and quantities to be transferred to each one of them, the MILP resolution of distribution level will give quantities to be stored and distributed to each client. Table 15 shows the results obtained for distribution level regarding the three alternatives.

TABLE 15. RESULTS OF MILP FOR DISTRIBUTION LEVEL

| Redesign alternative | Constraints | Variables | coefficients | Solution time(s) | MILP Objective |
|---|---|---|---|---|---|
| P1 | 132 | 117 | 336 | 246.71 | 1.6946e+004 |
| P2 | 184 | 165 | 424 | 243.37 | 1.9044e+004 |
| P3 | 140 | 125 | 340 | 365.93 | 1.4172e+004 |

From the resolution of the mathematical models, there is an ESC configuration related to each design alternative. Comparing the MILP objective of the three alternatives, we conclude that alternative three (P3) is the optimal one. The values of decision variables of design P3 are illustrated in table 16 of the appendix.

Figure 9 shows the ESC configuration related to the design alternative chosen “P3” and depicts its evolution through the design horizon (Product Lifecycle phases).Items colored with red show ESC nodes that must be active at each period.
Machines to be implemented or added in each period are also tagged in red color.

Results show that F2, F3 and F4 are the components’ suppliers that have been selected for all periods. Regarding outsourcing, S2 is the only subcontractor to be selected in introduction phase. At maturity phase, S3 and S4 were added to S2 to respond to the high product demand. In period 4, the company will not need to outsource its product since product demand decreases in decline phase. To assemble P3, the company needs to implant two new machines (type M5) at the introduction phase. To respond to the growing demand of maturity phase, one machine (type M1), one machine (type M3) and also three machines (type M5) must be added. Regarding the distribution, only distributor D2 was needed in the introduction phase, then distributor D1 and D3 were added in the third phase because of the demand growth.

This numerical example shows how the supply chain configuration could change when we are redesigning a product. Also, it shows the dynamic aspect of the model since the supply chain related to redesigned product evolves in each product lifecycle phase.

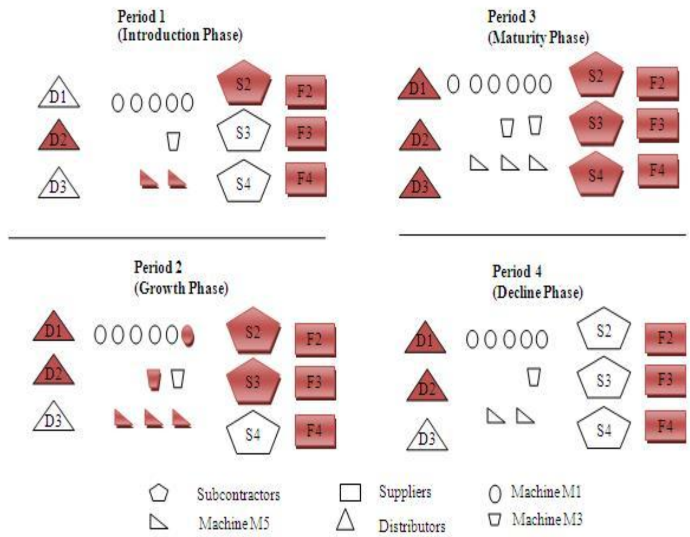


Fig 9. Evolution of the ESC configuration;

## 6 CONCLUSION

This paper goes beyond the traditional aspect of a supply chain, where the principal enterprise undertakes the design and imposes its constraints to its partners, and handles a new approach where all supply chain partners participate in the product design. Indeed, product design and development phases are included into the functions of the supply chain and we study what we have called the “extended supply chain”.

Our work contributes to a recent field which is the simultaneous design of the product and its extended supply chain. Logistics constraints are integrated in the product design phase on one hand, and the product attributes are considered when deciding about supply chain partners on the other hand. We investigate the role of PLM as a key element for the structure of the extended supply chain by assuring the integration of the upstream and downstream supply chain partners at the earlier phases of product design.

We consider that we are in the case of designing a new product starting from an existent old one. The extended supply chain configuration is designed from the existing partners of the existent supply chain related to the old product and by introducing, of course, new ones necessary for the new product achievement.PLM solutions provide many design alternatives (BOMs and Processes). Each alternative is related to its ESC configuration. To reduce the complexity of the product design and its extended supply chain optimization, we consider that the ESC as a set of levels, corresponding to the levels of bill of materials. Each partner of the extended supply chain is in relation with several customers and suppliers. Therefore, the optimization of the extended supply chain design consists on optimizing each level with its

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adjacent level. We mention that outputs of the optimization of a predecessor level are taken as inputs for the optimization of its successor level. For this purpose, a mixed integer linear programming (MILP) formulation was proposed.The design of the product and its extended supply chain that will be chosen is that which provides the best cost and incorporates as many partners of the initial supply chain.

The paper has some limitations that could be studied in future works. Firstly, we studied the case of designing only one product and its supply chain. In our future work, we will discuss the case of designing a family of product derived from a common product platform and possessing specific features or functionality to meet particular customer requirements. Secondly, we will also integrate reverse logistic operations in our model in order to treat all upstream and downstream functions of the supply chain from the design and development till the recycling process. By adding these two considerations, our model will be difficult to solve in terms of complexity especially in the case of industry-wide problems. That is why a heuristic approach has to be investigated in a further work.

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## APPENDIX . Numerical Example Data

Table 1 .Supplier's quantitative data

| | $CA_{c,f,t}$ | | | | | $CF_{f,t}$ | | | | | $q_{c,f,t}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | F4 | F5 | F1 | F2 | F3 | F4 | F5 | F1 | F2 | F3 | F4 | F5 |
| C1 | 6 | 7 | 6 | - | - | 0 | 0 | 0 | - | - | 0.03 | 0.02 | 0.01 | - | - |
| C2 | - | 8 | 7 | - | - | - | 0 | 0 | - | - | - | 0.01 | 0.02 | - | - |
| C3 | 6 | 5 | - | - | - | 0 | 0 | - | - | - | 0.03 | 0.01 | - | - | - |
| C4 | 8 | - | - | 7 | - | 0 | - | - | 80 | - | 0.02 | - | - | 0.01 | - |
| C5 | - | 8 | - | - | 9 | - | 0 | - | - | 80 | - | 0.01 | - | - | 0.02 |
| C6 | - | - | - | 8 | 7 | - | - | - | 80 | 80 | - | - | - | 0.01 | 0.02 |
| C7 | - | - | 9 | 8 | - | - | - | 0 | 80 | - | - | - | 0.01 | 0.02 | - |

Table 2 .Maximum capacity for each supplier

| | Period 1 | | | | | Period 2 | | | | | Period 3 | | | | | Period 4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | F4 | F5 | F1 | F2 | F3 | F4 | F5 | F1 | F2 | F3 | F4 | F5 | F1 | F2 | F3 | F4 | F5 |
| C2 | - | 70 | 60 | - | - | - | 50 | 90 | - | - | - | 80 | 100 | - | - | - | 70 | 60 | - | - |
| C3 | 70 | 60 | - | - | - | 50 | 90 | - | - | - | 80 | 100 | - | - | - | 70 | 60 | - | - | - |
| C4 | 40 | - | - | 60 | - | 60 | - | - | 90 | - | 70 | - | - | 120 | - | 40 | - | - | 90 | - |
| C5 | - | 30 | - | - | 70 | - | 50 | - | - | 90 | - | 70 | - | - | 110 | - | 40 | - | - | 90 |
| C6 | - | - | - | 80 | 80 | - | - | - | 90 | 100 | - | - | - | 80 | 120 | - | - | - | 70 | 90 |
| C7 | - | - | 50 | 80 | - | - | - | 60 | 90 | - | - | - | 60 | 120 | - | - | - | 50 | 80 | - |

Table 3. Machines quantitative data.

| | $\mathbf{Chp}_{m,t}$ | | | | | $\mathbf{CFA}_{m,t}$ | | | | | $\mathbf{CFS}_{m,t}$ | | | | | $Capmax\_prod_{m,t}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | M1 | M2 | M3 | M4 | M5 | M1 | M2 | M3 | M4 | M5 | M1 | M2 | M3 | M4 | M5 | M1 | M2 | M3 | M4 | M5 |
| P1 | 1 | - | - | 2 | - | 100 | - | - | 130 | - | 50 | - | - | 60 | - | 40 | - | - | 50 | - |
| P2 | - | 3 | 1 | - | - | - | 90 | 120 | - | - | - | 40 | 50 | - | - | - | 50 | 60 | - | - |
| P3 | 1 | - | 1 | - | 2 | 100 | - | 120 | - | 110 | 50 | - | 50 | - | 40 | 40 | - | 60 | - | 50 |

Table 4. Machines quantitative data

| | $tpu_m$ | | | | | $\mathbf{NEI}^0_m$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | M1 | M2 | M3 | M4 | M5 | M1 | M2 | M3 | M4 | M5 |
| P1 | 1 | - | - | 2 | - | 5 | - | - | 0 | - |
| P2 | - | 2 | 1 | - | - | - | 2 | 1 | - | - |
| P3 | 2 | - | 1 | - | 1 | 5 | - | 1 | - | 0 |

Table 5. Finished product information

| | $\mathbf{D}_t$ | | | | $MaxST_t$ | | | |
|---|---|---|---|---|---|---|---|---|
| | t1 | t2 | t3 | t4 | t1 | t2 | t3 | t4 |
| P1 | 80 | 130 | 160 | 100 | 20 | 40 | 40 | 20 |
| P2 | 80 | 130 | 160 | 100 | 20 | 40 | 40 | 20 |
| P3 | 80 | 130 | 160 | 100 | 20 | 40 | 40 | 20 |

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Table 6. Demand for components and admissible defect ratio

| | $\mathbf{D}_{c,t}$ | | | | $\mathbf{qa}_{c,t}$ | | | |
|---|---|---|---|---|---|---|---|---|
| | t1 | t2 | t3 | t4 | t1 | t2 | t3 | t4 |
| C1 | 160 | 260 | 320 | 200 | 0.03 | 0.03 | 0.03 | 0.03 |
| C2 | 80 | 130 | 160 | 100 | 0.02 | 0.02 | 0.02 | 0.02 |
| C3 | 80 | 130 | 160 | 100 | 0.03 | 0.03 | 0.03 | 0.03 |
| C4 | 80 | 130 | 160 | 100 | 0.02 | 0.02 | 0.02 | 0.02 |
| C5 | 80 | 130 | 160 | 100 | 0.02 | 0.02 | 0.02 | 0.02 |
| C6 | 80 | 130 | 160 | 100 | 0.02 | 0.02 | 0.02 | 0.02 |
| C7 | 80 | 130 | 160 | 100 | 0.02 | 0.02 | 0.02 | 0.02 |

Table 7.Maximum of machines in each period

| | P1 | | | | P2 | | | | P3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | t1 | t2 | t3 | t4 | t1 | t2 | t3 | t4 | t1 | t2 | t3 | t4 |
| M1 | 10 | 11 | 12 | 10 | - | - | - | - | 10 | 11 | 12 | 9 |
| M2 | - | - | - | - | 8 | 10 | 11 | 8 | - | - | - | - |
| M3 | - | - | - | - | 6 | 7 | 8 | 6 | 6 | 7 | 8 | 6 |
| M4 | 8 | 9 | 10 | 8 | - | - | - | - | - | - | - | - |
| M5 | - | - | - | - | - | - | - | - | 6 | 7 | 8 | 6 |

Table 8. Subcontractor quantitative data

| | $CST_{s,t}$ | | | | $\mathbf{CF}_s$ | | | | $Capmax\_st_{s,t}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S4 | S1 | S2 | S3 | S4 | S1 | S2 | S3 | S4 |
| P1 | 6 | 7 | 8 | - | 0 | 0 | 0 | - | 30 | 40 | 30 | - |
| P2 | 6 | 7 | - | 6 | 0 | 0 | - | 30 | 20 | 20 | - | 40 |
| P3 | - | 7 | 8 | 6 | - | 0 | 0 | 40 | - | 20 | 10 | 40 |

Table 9. Demand of the final product per clients

| $D_{k,t}$ | K1 | K2 | K3 |
|---|---|---|---|
| t1 | 30 | 20 | 30 |
| t2 | 50 | 40 | 40 |
| t3 | 40 | 50 | 70 |
| t4 | 30 | 40 | 30 |

Table 10. Distributor Volume storage capacity

| $V_d$ | D1 | D2 | D3 |
|---|---|---|---|
| P1 | 900 | 1100 | 1000 |
| P2 | 800 | 1000 | 900 |
| P3 | 1000 | 1200 | 1100 |

Table 11. Product volume

| | P1 | P2 | P3 |
|---|---|---|---|
| $v_p$ | 20 | 30 | 15 |

Table 12.Transportation cost from Distributors to clients for P3

| | $\mathbf{CTK}_{d,k}$ | | |
|---|---|---|---|
| | D1 | D2 | D3 |
| K1 | 6 | 7 | 6 |
| K2 | 5 | 6 | 4 |
| K3 | 6 | 6 | 5 |

Table 13.Distributor storage cost

| | $\mathbf{CSD}_{d,t}$ | | |
|---|---|---|---|
| | D1 | D2 | D3 |
| P1 | 5 | 6 | 5 |
| P2 | 6 | 7 | 6 |
| P3 | 5 | 6 | 6 |

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Table16 .Decision variables values for redesign P3

| | $\mathbf{Q_{c,f,t}}$ | $\mathbf{QP_t}$ | $\mathbf{QS_{s,t}}$ | $\mathbf{NEA_{m,t}}$ | $\boldsymbol{Z_{c,f,t}}$ |
|---|---|---|---|---|---|
| Introduction phase | $Q_{2,2,1}=22; Q_{2,3,1}=60$<br>$Q_{7,3,1}=4; Q_{7,4,t}=78$ | $QP_1=60$ | $QS_{2,1}=20$; $QS_{3,1}=0$<br>$QS_{4,1}=0$ | $NEA_{1,1}=0$<br>$NEA_{3,1}=0$<br>$NEA_{5,1}=2$ | $Z_{2,2,t}=1; Z_{2,3,t}=1$<br>$Z_{7,3,t}=1; Z_{7,4,t}=1$ |
| Growth phase | $Q_{2,2,2}=43$; $Q_{2,3,2}=60$<br>$Q_{7,3,2}=43$; $Q_{7,4,2}=60$ | $QP_2=100$ | $QS_{2,2}=20; QS_{3,2}=10$<br>$QS_{4,1}=0$ | $NEA_{1,2}=1$<br>$NEA_{3,2}=1$<br>$NEA_{5,2}=3$ | $Z_{2,2,t}=1; Z_{2,3,t}=1$<br>$Z_{7,3,t}=1; Z_{7,4,t}=1$ |
| Maturity phase | $Q_{2,2,3}=63; Q_{2,3,3}=100$<br>$Q_{7,3,3}=43; Q_{7,4,4}=120$ | $QP_3=120$ | $QS_{2,3}=10; QS_{3,3}=10$<br>$QS_{4,3}=20$ | $NEA_{1,3}=1$<br>$NEA_{3,3}=1$<br>$NEA_{5,3}=3$ | $Z_{2,2,t}=1; Z_{2,3,t}=1$<br>$Z_{7,3,t}=1; Z_{7,4,t}=1$ |
| Decline phase | $Q_{2,2,4}=42; Q_{2,3,4}=60$<br>$Q_{7,3,4}=22; Q_{7,4,4}=80$ | $QP_4=100$ | $QS_{2,4}; QS_{3,4}; QS_{4,4}$<br>$=0$ | $NEA_{1,4}=0$<br>$NEA_{3,4}=1$<br>$NEA_{5,4}=2$ | $Z_{2,2,t}=1; Z_{2,3,t}=1$<br>$Z_{7,3,t}=1; Z_{7,4,t}=1$ |

| | $\mathbf{QTK_{d,k,t}}$ | $\boldsymbol{S_{d,t}}$ | $\mathbf{QT_{d,t}}$ | $\boldsymbol{D_{d,t}}$ |
|---|---|---|---|---|
| Introduction phase | $QTK_{2,1,1}=30; QTK_{2,2,1}=20$<br>$QTK_{2,3,1}=30$ | $S_{2,1}=1$ | $QT_{1,1}=0$; $QT_{2,1}=80$<br>$QT_{3,1}=0$ | $D_{2,1}=1$ |
| Growth phase | $QTK_{2,2,2}=14; QTK_{1,3,2}=28$<br>$QTK_{2,1,2}=43; QTK_{2,3,2}=12$<br>$QTK_{1,1,2}=7$; $QTK_{1,2,2}=26$ | $S_{2,2}=1$<br>$S_{3,2}=1$ | $QT_{1,2}=50; QT_{2,2}=80$<br>$QT_{3,2}=0$ | $D_{1,2}=1$<br>$D_{2,2}=1$ |
| Maturity phase | $QTK_{2,2,3}=14$; $QTK_{2,3,3}=22$<br>$QTK_{1,1,3}=26; QTK_{1,2,3}=17$<br>$QTK_{3,1,3}=14$<br>$QTK_{3,2,3}=19$ $QTK_{3,3,3}=48$ | $S_{2,3}=1$<br>$S_{3,3}=1$<br>$S_{4,3}=1$ | $QT_{1,3}=66; QT_{2,3}=80$<br>$QT_{3,3}=14$ | $D_{1,3}=1$<br>$D_{2,3}=1$<br>$D_{3,3}=1$ |
| Decline phase | $QTK_{2,2,4}=12$;<br>$QTK_{2,1,4}=9; QTK_{2,3,4}=12$<br>$QTK_{1,1,4}=21; QTK_{1,2,4}=28$<br>$QTK_{1,3,4}=18$ | $S_{2,4}; S_{3,4}$; $S_{4,4}=0$ | $QT_{1,4}=20$<br>$QT_{2,4}=80$<br>$QT_{3,4}=0$ | $D_{1,4}=1$<br>$D_{2,4}=1$ |