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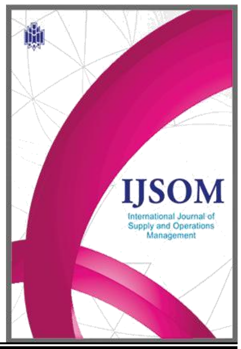

An Integrated Planning Model for a Multi Echelon Supply Chain within Mass Customization

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Abstract

Product customization is considered as the widespread strategy for the actual market trend oriented toward customer focus. In this field, mass customization sights mainly to emerge economy of scale and economy of scope in order to integrate mass production principles with customization abilities. This research views the collaborative management through an integrated procurement, production and distribution mixed integer linear programming (MILP) as a planning modeling approach for a multi-echelon and multi-site supply chain within tactical decision level. The model formulation is based on dyadic relationships according to leaders and followers tradeoffs where the supply chain's stakeholders are depicted as follows, a) customers: Original Equipment Manufacturers (OEMs) identified as leaders and (b) first-tier suppliers: customized products manufacturers (c) second-tier suppliers: raw material suppliers, identified as followers. The feasibility of the proposed model has been provided through its resolution to optimality by an exact method, the decision-making process is focused on the first-tier suppliers' operations in order to satisfy the customized demands taking into account realistic characteristics of mass customization environment for the internal and external constraints through the supply chain. The illustration of the model is performed with an example from the automotive industry, a sensitivity analysis has been conducted in order to provide the main decision points through key parameters, for instance, the capacities threshold according to a defined demand level and its customized structure which contribute to highlight a constructive managerial insights.

Keywords: Multi echelon supply chain; Integrated supply chain; Mass customization; Product variety; Mixed integer linear programming (MILP).

1. Introduction

The final customer position in the supply chain has gained further integration in the last decades. The business orientation is shifted from providing low-cost and standardized products towards fulfilling customers' needs. Thus, the market environment conversion toward customer focus boasts firms to enhance product customization abilities to remain competitive while improving market share. In fact, consumer preferences rise up product variety level to allow that product features fit the highlighted requirements. From supply chain standpoint, it could be perceived as a substantial shift from mass production to mass customization endeavor. While multiple definition of mass customization are proposed in the literature, the main understanding is the ability to provide customized products for a mass market (Coletti et Aichner, 2011; Davis, 1990; Pine et Pine, 1993). (Candelo, 2019) provided the new market characteristics that promote the switch from mass production to mass customization argued by three main factors of change, namely, the limits of mass production process which requires stable inputs, reduction of market homogeneity and demand instability, while these elements depict the fundamental of the economy of scale. Besides, (Olbert et al., 2016) stated that in Europe, 30% of the cars are sold from stock while 70% are built-to-order. Given that delivery times are crucial in a mass customized context, their research presented a queuing theory study to assess the impact of delivery time segmentation according to

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customer order type. In this field, an express order and standard order options have been defined to represent respectively customized and standard segment. Thereupon, the supply chain as a network should encompass the organizational enablers to successfully establish the interrelated processes of production planning and inventory control as well as logistics and distribution (Ballou, 2007). In fact, mass customization is perceived as an operations management perspective due to its impact on the adopted organizational strategies through the supply chain, on the one hand customer integration contribute to strengthening agility of the supply chain, on the other hand internal integration foster the interactions according to higher responsiveness level through flexibility across supply chain actors (Lai et al., 2012; Roh et al., 2014).

Basically, the adopted customer involvement level in the supply chain which is well known as the customer order decoupling point is the principal trigger of the supply chain design for downstream and upstream processes in order to drive value chain stages, namely, design, fabrication, assembly and distribution. The concept is to delay transformation processes as much as possible until customer orders are known. The increased level of customer integration moves the customer order decoupling point to upstream positions to dump speculation activities on products manufacturing (Budiman et Rau, 2019). Therefore, the adopted postponement strategy by the supply chain highlights the forecast and order-driven attributes while the main purpose is to ensure cost efficiency and customer service level (Bonev et al., 2017). In this field, modularity practices for product development and manufacturing are considered as a core structure design to enhance mass customization strategy (Chen et al., 2021). The product features which contribute to generate the different combinations must be developed with a high level of accuracy. Thus, an extensive study for design and variability models is a must to realize a constructive product variability architecture and dump complexities. (Heradio et al., 2016) provided an effective computational algorithms to analyze the compatibility of features' variability through essential, dispensable and highly incompatible features. (Wang et al., 2018) presented a conceptual framework with a survey in order to depict the importance of supply chain coordination and functional coordination to implement product modularity. While the customer-oriented characteristic is considered as the main trigger of mass customization, furthermore, there are some structural pillars from supply chain perspective which have been highlighted by (L. Liu, 2013) as supply chain integration, operations accuracy and agility, push & pull activities combination and information technology development. Hence, a suitable postponement strategy in addition to operational alignment are vital to mass customization capability for the supply chain (Atan et al., 2017; Wu et al., 2019).

The prevailing statement is to ensure firms' capability fulfilment as the implementation necessitates a substantial supply chain actors' alignment to concur the strategic mass customization objectives. In fact, the collaboration leverage through the supply chain provides a considerable yield for the global value. Towards that end, supply chain configuration should be addressed with an integrated business process to encompass the generated operations policies. For instance, to cope with manufacturing uncertainties, make to order policy is perceived as a suitable process to preserve the customer value perception on product development. The supply chain planning with pull system reveals a dynamic capability from management perspective where integration abilities enhance information and physical flows across partners according to the required reliability level through upstream and downstream processing capability. As stated by Liu & Deitz (2011), the literature on mass customization and supply chain management recognized two value creation management competences that should impact the required capability which are customer focused product design and supplier lead-time reduction. It reflects a major fields to sustain the corresponding planning system approach.

The supply chain stakeholders need to adhere within collaboration framework in order to drive the cost performance balance through multiple fields. For instance, resources cost efficiency (e.g. inventory, manufacturing), customer service level and internal operations' flexibility to deal with changing environment. In fact, this necessity arises from the interdependency between actors for different patterns where standalone positions will hinder performance. The resulted coordination mechanism attributes aims to foresee decision-making process to enhance the value chain within a high volatile market environment (Jin et al. 2019). One approach widely adopted is supply chain integration of different planning processes such as production, storage and distribution. Masoud & Mason (2016) proposed an integrated production and transportation planning problem in the automotive industry for the operational level, the resolution process is formulated with hybrid simulated annealing algorithm employing a constructive heuristic and an effective encoding-decoding strategy. Rafiei et al. (2018) formulated a four-echelon supply chain for an integrated production-distribution planning problem, two mixed integer linear programming models have been investigated according to no competitive and competitive market, the elastic constraint method is applied as a resolution approach. Pasandideh et al. (2015) pointed out the strategic, tactical and planning decision making model for a supply chain network in order to determine, respectively, the number and locations of warehouses, transportation channels assigning in addition to production management. For this field, a bi-objective mixed integer non-linear mathematical formulation has been proposed and solved with non-dominated sorting genetic algorithm and non-dominated ranking genetic algorithm. Touil et al. (2019) addressed a mixed integer linear programming model for an integrated production and distribution problem considering different uncertainty sources. The credibility theory is carried out for a constructive framework to cope with uncertainties and the extreme cases of the optimistic and pessimistic criteria are handled with Hurwicz criterion which attempts to drive a balance in order to maximize profit.

Hence, this paper aims to propose a mixed integer linear programming formulation for modeling a multi-echelon, multi-site integrated procurement, production and distribution supply chain within mass customization environment. The tactical decision planning architecture is adopted to draw the root assumptions classes. To the best of our knowledge, there is a lack of mass customization studies with the perspective of an integrated supply chain mathematical modeling through mixed integer linear programming formulation. The illustration of the empirical application from industrial case is the leader and followers dyadic relationships across the automotive industry. This framework is considered as an appropriate scheme due to first-tier suppliers' interactions with main contractors within demand driven supply chain. It is worth mentioning that in the last decade, the automotive industry product portfolio is developed from standardization to fragmented markets concept with a central focus on customer needs (Candelo, 2019; Masoud et Mason, 2016; Sezen at al., 2012). The proposed framework involves (a) customers: original equipment manufacturers (OEM) (b) first tier suppliers: wiring harnesses manufacturers (c) second tier suppliers: raw material suppliers. The integration aspect sights to evolve the dynamic capability underpinning for mass customization enablers outlined mainly through product design with modularity concepts as well as postponement and the corresponding customer order decoupling point in order to address a triggered supply chain according to make to order production policy.
The remainder of this paper is organized as follows. Section 2 provides the model formulation with the adopted assumptions. Section 3 presents the case study in addition to the results of the computational experiments. A sensitivity analysis with managerial insights are considered in section 4, followed by the conclusion in section 5.

2. Model formulation

The supply chain being studied in this paper is a multi-echelon, multi-site for an integrated procurement, production and distribution planning model at tactical decision-making level. The automotive industry is adopted to enhance the empirical framework for model formulations. The considered supply chain consists of leaders and followers dyadic relationships due to mass customization context. The multi-echelon supply chain is built according to a three-echelon basis with the following main partners (a) customers: Original Equipment Manufacturers (OEMs) (b) first-tier suppliers: wiring harnesses manufacturers (c) second-tier suppliers: raw material suppliers as stated in figure 1. For a successful mass customization strategy, upstream and downstream organizational capabilities must be enhanced for which the implementation must be liaised to the corresponding supply chain management mode (Jin et al., 2019).

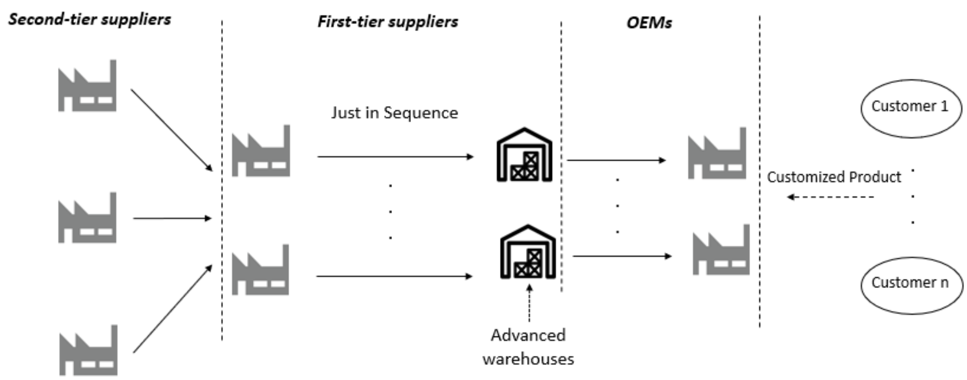

Figure 1. Supply chain structure

Thus, information flow and demand driven supply chain mode are considered among the prevailing factors to sustain the accurate interactions through the supply chain. For instance, the provided demand information with customized orders are transferred from Original Equipment Manufacturers (OEMs) to the first-tier suppliers as well as the agreed capacity level between different stakeholders. In the studied case, customer involvement (i.e. decoupling point) occurs at product features definition level with configurator tools as example, the corresponding position of customization degree is known as customized standardization (Um et al., 2017). The Original Equipment Manufacturers (OEMs) propose a set of options for a vehicle model while customers afford the ability to customize their cars to fit their own needs. Whereby, product modularity approach is applied, the assignment is based on basic modules to include common elements and optional modules for preferences as represented in figure 2. In the studied case, the option preferences are addressed through option penetration rates shared previously by customers to assess the percentage of products that will include an option. The dynamic capability outlines firms' ability to align the required flexibility for internal operations and agility towards customers while the very restricted customers' lead times must be considered for decision-making process. The postponement level is carried out with make to order mode triggered by confirmed orders reception. As the focus of this supply chain is on the first-tier suppliers operations, the heterogeneous lead times from their different raw material suppliers have an important leverage on production function. Thus, the procurement system is based on the previously shared forecasts from Original Equipment Manufacturers (OEMs). Therefore, production and procurement systems are based respectively on confirmed and forecasted demand. The product storage capacity for the first-tier suppliers has a limited behavior, the main storage locations are the advanced warehouses placed generally close to customers. Thus, supplier logistic window (i.e. between first-tier suppliers and Original Equipment Manufacturers (OEMs)) addresses three main timeframe stages as described in figure 3 (i.e. total time in manufacturing sites, total transport time, safety stock). The key figure outlines that in spite of disruptions, it is mandatory to preserve just in sequence deliveries (i.e. according to make to order), which led to highly cost expected solutions (e.g. premium freight). The mentioned finish good safety stock provides a restricted buffer level. The adopted model assumptions are presented as follows:

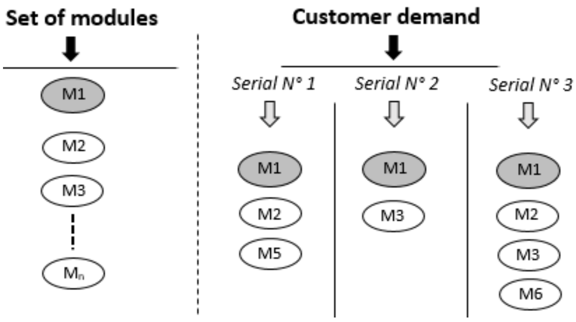

Figure 2. Modular product

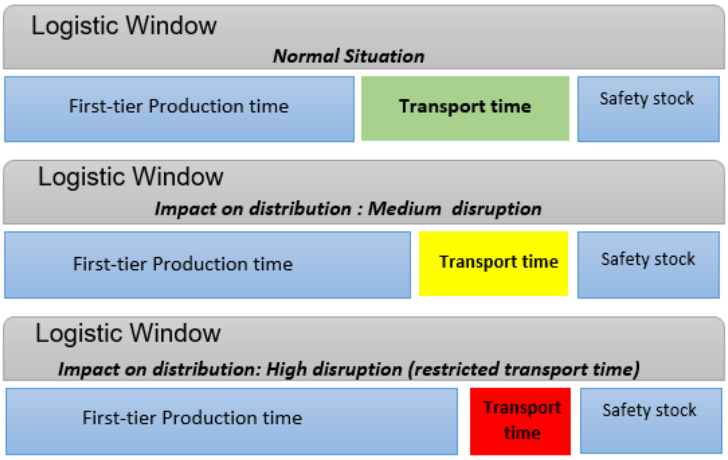

Figure 3. Mass customization logistic window

2.1. Model assumptions

- The supply chain has an integrated structure of several raw material suppliers (second-tier suppliers), manufacturing sites (first-tier suppliers) and customers (Original Equipment Manufacturers OEMs)
- Customer demands are handled by confirmed and forecasted demands
- Customized demands approach is ensured by serial numbers for each product. Each serial number represents the product content in terms of the chosen modules by the customer (figure 2)
- Optional modules preferences are addressed with penetration rates
- Products inventory holding cost are set independently of their content
- The manufacturing sites have a limited production and storage capacities
- Production shortage in manufacturing sites can happen with backorders form, lost sales are not allowed

- The advanced warehouses charge an inventory holding cost to manufacturing sites
- Product storage capacity at the advanced warehouses is limited for each site. However, an overstock can be adopted with penalty cost
- Raw material inventory management is performed with (s,S) policy
- Transportation is outsourced, there is no limit for vehicles availability between nodes while vehicles' capacity is considered
- Uncertainty on the received raw material quantity and the delivered products is not considered

The following list presents the model notation including indexes, parameters and decision variables.

Indexes and sets

$t \in T$	Set of time period	$p \in P$	Set of product families
$o \in O$	Set of customers (OEMs)	$m \in M$	Set of modules
$s \in S$	Set of serial numbers	$f \in F$	Set of raw material suppliers
$c \in C$	Set of raw materials	$v \in V$	Set of advanced warehouses (AW)
$e \in E$	Set of manufacturing sites		

Parameter

Sales

$DR_{o,e,p,t}$	Real demand of product p received from customer o to the site e in period t
$DF_{o,e,p,t}$	Forecasted demand of product p received from customer o to the site e in period t
$D^{min}_{o,e,p,t}$	Minimum demand quantity contracted with customer o and the site e of product p in period t
PR_m	Penetration rate of the module m
$PSF0_{o,e,p,s,t}$	Parameter = 1 to activate the serial number s of the forecasted demand from customer o to site e of the product p at period t
$PSF1_{o,e,p,s,m,t}$	Parameter = 1 to activate the module m that belongs to the serial number s of the forecasted demand of the product p from customer o to site e at period t
$PSR0_{o,e,p,s,t}$	Parameter = 1 to activate the serial number s of the real demand from customer o to site e of the product p at period t
$PSR1_{o,e,p,s,m,t}$	Parameter = 1 to activate the module m that belongs to serial number s of the real demand of the product p from customer o to site e at period t

Production

$BO0_{o,e,p,s}$	Initial backorder level at the site e of product p with serial number s of the customer o
$BOC_{o,e,p,s,t}$	Backorder cost of the customer o at the site e of product p with serial number s at the period t
$IHPS_{o,e,p,t}$	Inventory holding cost at the site e of product p of the customer o in period t
$IPS0_{o,e,p}$	Initial inventory level in the site e of product p of the customer o
$PE^{\max}_{o,e,p,t}$	Maximum storage capacity at the site e of product p of the customer o in the period t
$PQ^{\max}_{o,e,p,t}$	Maximum production capacity of the site e for the customer o of product p in period t
$PQ^{\min}_{o,e,p,t}$	Minimum production capacity of the site e for the customer o of product p in period t
MCS_m	The cost of module m

Procurement

PC_c	Purchase price of component c
$ICS0_{e,c}$	Initial inventory level of raw material c in the site e
$QF^{\min}_{f,e,c}$	Minimum contracted demand between supplier f and the site e for raw material c
$QF^{\max}_{f,e,c}$	Maximum contracted demand between supplier f and the site e for raw material c
$H_{f,e,c,t}$	Parameter = 1 if replenishment from supplier f to the site e of raw material c in period t is allowed and 0 otherwise
$\alpha_{c,m}$	The needed quantity of raw material c in module m (Bill of material)
LT_c	Lead time for the raw material c

Distribution	
$IHPV_{o,v,p,t}$	Inventory holding cost of product p of the customer o in period t in the advanced warehouse v
$CTV_{e,v,t}$	Vehicle trip cost from the site e to the advanced warehouse v in period t
$CTO_{o,v,t}$	Vehicle trip cost from the advanced warehouse v to the customer o in period t
$IPV0_{o,v,p}$	Initial inventory level of product p of the customer o at the advanced warehouse v
$PNC_{o,v,p,t}$	Penalty cost of excess inventory of product p for customer o at the advanced warehouse v in period t
$TLV_{e,v}$	Vehicle load capacity from the site e to the advanced warehouse v
$C_{o,v,p,t}^{\max}$	Maximum contracted capacity at the advanced warehouse v for the product p of the customer o at period t
$TLO_{o,v}$	Vehicle load capacity from the advanced warehouse v to the customer o
$CTV_{e,v}$	Cost of vehicle trip from the site e to the advanced warehouse v
$CTO_{o,v}$	Cost of vehicle trip from the advanced warehouse v to the customer o
M	Big M

Decision variables

Production	
$XQT_{o,e,p,s,t}$	Total produced quantity in the site e of product p for the customer o with serial number s in period t
$XQD_{o,e,p,s,t}$	Binary variable, =1 if the serial number s of the product p of customer o for the site e is produced at the period t to fulfill the real demand, 0 otherwise
$XQB_{o,e,p,s,t}$	Binary variable, =1 if the serial number s of the product p of customer o for the site e is produced at the period t to fulfill the generated backorder, 0 otherwise
$BO_{o,e,p,s,t}$	Binary variable, =1 if the serial number s of the product p of customer o for the site e is backordered in the period t, 0 otherwise
$IPS_{o,e,p,t}$	Inventory level in the site e of product p of the customer o in period t
$CSD_{e,c,t}$	Consumption of the raw material c in the site e at period t from the produced quantity to satisfy demand
$CSB_{e,c,t}$	Consumption of the raw material c in the site e at period t from the produced quantity to satisfy backorders
$CST_{e,c,t}$	Total consumption of the raw material c in the site e at period t
Procurement	
$ICS_{e,c,t}$	Inventory level in the site e of component c in period t
$CRQ_{e,c,t}$	Required quantity assessment by the site e of raw material c in period t
$BS_{e,c,t}$	Net required quantity to purchase of raw material c by the site e in period t
$QS_{f,e,c,t}$	Purchased quantity by the site e of raw material c from supplier f in period t
Distribution	
$IPV_{o,v,p,t}$	Inventory level of product p of the customer o in period t at the advanced warehouse v
$QO_{o,v,p,t}$	Shipping quantity of product p from the advanced warehouse v to the customer o in period t
$QV_{o,e,v,p,t}$	Shipping quantity from the site e to the advanced warehouse v of product p of the customer o in period t
$TRV_{e,v,t}$	Number of vehicle trips from the site e to the advanced warehouse v in period t
$TRO_{o,v,t}$	Number of vehicle trips from the advanced warehouse v to the customer o in period t
$GPL_{o,v,p,t}$	The exceeded storage level of product p of the customer o in period t at the advanced warehouse v
$Y_{o,v,p,t}$	Binary variable, =1 if there is no storage excess of product p of customer o at the advanced warehouse v in period t, 0 otherwise
$ZO_{o,v,p,t}$	Auxiliary variable for maximum function linearization

Using the previously notation, the mixed integer linear programming model is presented as follows:

2.2. Objective function

The main objective of the proposed model is to minimize the total cost of the supply chain simultaneously. It includes various cost elements as shown in the objective function (1), each component is defined from (2) to (10) to highlight the cost of production, raw material holding cost, product inventory holding cost in the manufacturing sites, product inventory holding cost at the advanced warehouses, the penalty cost of the overstock at the advanced warehouses, procurement cost of raw materials, transportation cost consisting of vehicles utilization and backorder cost.

$$\text{Min: TC} = (\text{TP} + \text{TS0} + \text{TS1} + \text{TS2} + \text{TS3} + \text{TD0} + \text{TD1} + \text{TD2} + \text{TB}) \quad (1)$$

$$TP = \sum_{t\in T}\sum_{o\in O}\sum_{e\in E}\sum_{p\in P}\sum_{s\in S}\sum_{m\in M} XQD_{o,e,p,s,t} * PSR1_{o,e,p,s,m,t} * MCS_m + \sum_{t\in T}\sum_{o\in O}\sum_{e\in E}\sum_{p\in P}\sum_{s\in S}\sum_{m\in M} XQB_{o,e,p,s,t} * PSR1_{o,e,p,s,m,t-1} * MCS_m \quad (2)$$

$$TS_0 = \sum_{t\in T}\sum_{e\in E}\sum_{c\in C} ICS_{e,c,t} * PC_c \quad (3)$$

$$TS_1 = \sum_{t\in T}\sum_{o\in O}\sum_{e\in E}\sum_{p\in P} IHPS_{o,e,p,t} * IPS_{o,e,p,t} \quad (4)$$

$$TS_2 = \sum_{t\in T}\sum_{o\in O}\sum_{v\in V}\sum_{p\in P} IHPV_{o,v,p,t} * IPV_{o,v,p,t} \quad (5)$$

$$TS_3 = \sum_{t\in T}\sum_{o\in O}\sum_{v\in V}\sum_{p\in P} PNC_{o,v,p,t} * GPL_{o,v,p,t} \quad (6)$$

$$TD_0 = \sum_{t\in T}\sum_{f\in F}\sum_{e\in E}\sum_{c\in C} PC_c * QS_{f,e,c,t} \quad (7)$$

$$TD_1 = \sum_{t\in T}\sum_{e\in E}\sum_{v\in V} CTV_{e,v,t} * TRV_{e,v,t} \quad (8)$$

$$TD_2 = \sum_{t\in T}\sum_{o\in O}\sum_{v\in V} CTO_{o,v,t} * TRO_{o,v,t} \quad (9)$$

$$TB = \sum_{t\in T}\sum_{o\in O}\sum_{e\in E}\sum_{p\in P}\sum_{s\in S} BOC_{o,e,p,s,t} * BO_{o,e,p,s,t} \quad (10)$$

2.3. Production

In order to fulfill customers' demand on each manufacturing site, constraint 11 represents the total production $XQT_{o,e,p,s,t}$ which is performed by two parts. $XQD_{o,e,p,s,t}$ denotes production to cover the confirmed demands, while $XQB_{o,e,p,s,t}$ represents the fulfillment of the previously generated backorders, in the period t=1 it is equal to 0 as stated by constraint 12:

$$XQT_{o,e,p,s,t} = XQD_{o,e,p,s,t} + XQB_{o,e,p,s,t}, \forall o,e,p \in O \cap E \cap P, \forall\, s \in S, t > 1 \quad (11)$$

$$XQB_{o,e,p,s,t} = 0, \forall o,e,p \in O \cap E \cap P, \forall\, s \in S, t = 1 \quad (12)$$

Constraint 13 defines the backordered products and those to produce. This definition is established from the received demand which is expressed by serial numbers for each product family (i.e. define the serial numbers to produce or to backorder for an upcoming production):

$$XQD_{o,e,p,s,t} = \mathrm{PSR0}_{\mathrm{o,e,p,s,t}} - BO_{o,e,p,s,t}, \forall o,e,p \in O \cap E \cap P, s \leq DR_{o,e,p,t} \ , t \in T \tag{13}$$

Constraint 14 ensures the production capacity of each manufacturing sites:

$$\sum_{s}^{S} XQT_{o,e,p,s,t} \leq PQ_{o,e,p,t}^{\max}, \forall o,e,p \in O \cap E \cap P, t \in T \tag{14}$$

Constraint 15 holds the backorder hurdle that should be less than a defined percentage δ from the confirmed demand during each period:

$$\sum_{s}^{DR_{o,p,t}} BO_{o,e,p,s,t} \leq \delta \cdot DR_{o,e,p,t}, \quad \forall o,e,p \in O \cap E \cap P, t \in T \tag{15}$$

In order to handle the production of backorders, constraint 16 aims to settle it during two periods. Thus, the backordered serial numbers could be produced at either t+1 or t+2. Constraint 17 defines the maximum threshold of backorders production. The constraints 18 and 19 aim to define the backorder treatment during the last period, it has been set to 0 while ensuring the complete production of the generated backorders at the period T-1. At last, as stated by constraint 20, the total generated backorders over the horizon have to be produced completely.

$$\sum_{q=t+1}^{q=t+2} XQB_{o,e,p,s,q} = BO_{o,e,p,s,t} \ , \forall o,e,p \in O \cap E \cap P, \forall\, s \in S, \forall t \in T-1 \tag{16}$$

$$\sum_{s \in S} XQB_{o,e,p,s,t} \leq PQB_{o,e,p,t}^{\max}, \forall o,e,p \in O \cap E \cap P, \forall\, s \in S, \forall t \in T-1 \tag{17}$$

$$BO_{o,e,p,s,t} = 0, \forall o,e,p \in O \cap E \cap P, s \in S \ , t = T \tag{18}$$

$$XQB_{o,e,p,s,t} = BO_{o,e,p,s,t-1}, \forall o,e,p \in O \cap E \cap P, s \in S \ , t = T \tag{19}$$

$$\sum_{t \in T} \sum_{s \in S} BO_{o,e,p,s,t} = \sum_{t \in T} \sum_{s \in S} XQB_{o,e,p,s,t}, \forall o,e,p \in O \cap E \cap P \tag{20}$$

Constraint 21 illustrates production and distribution decisions of the manufactured products for each site through the inventory balance flow. It is given by the inventory from the last period plus the realized production minus the shipped quantity to the advanced warehouses:

$$IPS_{o,e,p,t} = IPS_{o,e,p,t-1} + \sum_{s \in S} XQT_{o,e,p,s,t} - \sum_{v \in V} QV_{o,e,v,p,t}, \forall o,e,p \in O \cap E \cap P, \forall e,v \in E \cap V, \forall t \in T \tag{21}$$

Constraint 22 shows that product's storage capacity in the manufacturing sites has a limited threshold:

$$IPS_{o,e,p,t} \leq PE^{\max}_{o,e,p,t}\ , \forall o,e,p \in O \cap E \cap P, \forall t \in T \tag{22}$$

2.4. Distribution

Constraint 23 calculates the number of vehicle trips from each manufacturing site to the advanced warehouses at every time period based on vehicles' capacity:

$$TRV_{e,v,t} \leq \frac{\sum_{o \in O} \sum_{p \in P} QV_{o,e,v,p,t}}{TLV_{e,v}}, \forall e,v\ \in E \cap V, \forall t \in T \tag{23}$$

Constraint 24 conserves the flow at the advanced warehouses. It indicates the available inventory of product families in each period, which is the reported inventory from the previous period plus the received quantity from manufacturing sites minus the shipped quantity to customers:

$$IPV_{o,v,p,t} = IPV_{o,v,p,t-1} + \sum_{e \in E} QV_{o,e,v,p,t} - QO_{o,v,p,t}, \forall o,v,p \in O \cap V \cap P, \forall t \in T \tag{24}$$

Constraint 25 outlines the restricted minimum quantity to be delivered to customers for each period. Moreover, constraint 26 describes the number of vehicle trips from the advanced warehouses to customers at every time period based on vehicles' capacity:

$$\sum_{v \epsilon V} QO_{o,v,p,t} \geq \sum_{e \in E} D^{min}_{o,e,p,t}\ , \forall o,e \in O \cap E, \forall v,p \in V \cap P, \forall t \in T \tag{25}$$

$$TRO_{o,v,t} \leq \frac{\sum_{p \in P} QO_{o,v,p,t}}{TLO_{o,v}}, \forall o,v,p \in O \cap V \cap P, \forall t \in T \tag{26}$$

Constraint 27 shows that there is a safety stock (i.e. buffer) level to maintain at the advanced warehouses, it is established according to a percentage from the confirmed demand presented here by β:

$$IPV_{o,v,p,t} \geq \beta * \sum_{e \in E} DR_{o,e,p,t}\ , \forall o,v,p \in O \cap V \cap P, \forall t \in T \tag{27}$$

As discussed previously, to express the inventory level agreement between manufacturing sites and the advanced warehouses, the overstock from the contracted limit is accepted. Though, a penalty cost is applied for the additional volume. Constraint 28 highlights the difference between the inventory level and the maximum contracted capacity:

$$GPL_{o,v,p,t} = Max\{(IPV_{o,v,p,t} - C^{\max}_{o,v,p,t})\ ; 0\}, \forall, o \in O, p \in P, v \in V, t \in T \tag{28}$$

In order to cope with the nonlinearity generated by the previous maximum function, constraints 29, 30, and 31 are added to the mathematical model:

$$GPL_{o,v,p,t} \geq IPV_{o,v,p,t} - C^{\max}_{o,v,p,t}, \forall o,v,p \in O \cap V \cap P, \forall t \in T \tag{29}$$

$$GPL_{o,v,p,t} \leq IPV_{o,v,p,t} - C^{\max}_{o,v,p,t} + M * Y_{o,v,p,t}, \forall o,v,p \in O \cap V \cap P, \forall t \in \mathrm{T} \tag{30}$$

$$GPL_{o,v,p,t} \leq M * (1 - Y_{o,v,p,t}), \qquad \forall o,v,p \in O \cap V \cap P, \forall t \in \mathrm{T} \tag{31}$$

2.5. Procurement

Constraint 32 ensures the balance equation of raw material inventory in manufacturing sites. It is equal to the inventory level from the previous period plus the received quantity from raw material suppliers in period t minus the consumed quantity in the sites:

$$ICS_{e,c,t} = ICS_{e,c,t-1} + \sum_{f \in F} QS_{f,e,c,t+LT_c} - CST_{e,c,t}, \forall c \in C, e \in E, t < T - LT_c \quad (32)$$

In order to assess the raw material consumption, constraints 33 and 34 aim to determine the consumed level depicted from production structure (i.e. demand and backorders fulfilment) using the consumption coefficient of each module (i.e. $\alpha_{c,m}$). Constraint 35 comes to add up the total consumption:

$$CSD_{e,c,t} = \sum_{o}\sum_{p}\sum_{s} XQD_{o,e,p,s,t} * \sum_{m} PSR1_{o,e,p,s,m,t} * \alpha_{c,m}, \forall c \in C, e \in E, t \in T \quad (33)$$

$$CSB_{e,c,t} = \sum_{o}\sum_{p}\sum_{s} XQB_{o,e,p,s,t} * \sum_{m} PSR1_{o,e,p,s,m,t-1} * \alpha_{c,m}, \forall c \in C, e \in Et \in T \quad (34)$$

$$CST_{e,c,t} = CSD_{e,c,t} + CSB_{e,c,t}, \forall c \in C, e \in E, t \in T \quad (35)$$

Constraint 36 calculates the required quantity for each raw material based on the forecasted demand. Afterwards, constraint 37 aims to define the net required quantity by subtracting the inventory level of the previous period:

$$\mathrm{CRQ}_{\mathrm{e,c,t}} = \sum_{q=t}^{q=t+LT_c} \sum_{o \epsilon O}\sum_{p \epsilon P}\sum_{s \in S}\sum_{m \in M} PSF1_{o,e,p,s,m,q} \cdot \alpha_{c,m}, \forall o, e, p \in O \cap E \cap P, \forall c \in C, \forall t < T - LT_c \quad (36)$$

$$BS_{e,c,t} \geq CRQ_{e,c,t} - ICS_{e,c,t-1}, \forall c \in C, e \in E, t \in T \quad (37)$$

Constraints 38 and 39 control the purchased quantity based on the net required quantity assessment or the minimum contracted level defined with raw material suppliers. The policy of the replenishment frequency contracted with suppliers is controlled by the parameter $H_{f,\mathrm{e},c,t}$. It is outlined by a binary matrix while the purchased quantity variable is activated when it has a true value (i.e. $H_{f,\mathrm{e},c,t} = 1$). Constraint 40 enforces the activation of the purchased quantity variable according to the matrix value:

$$QS_{f,\mathrm{e},c,t+LT_c} \geq BS_{e,c,t} \cdot H_{f,\mathrm{e},c,t}, \forall f, c, e \in F \cap C \cap E, \forall t < T - LT_c \quad (38)$$

$$QS_{f,\mathrm{e},c,t+LT_c} \geq QF_{f,e,c}^{\mathrm{min}} \cdot H_{f,\mathrm{e},c,t}, \forall f, c, e \in F \cap C \cap E, \forall t < T - LT_c \quad (39)$$

$$QS_{f,\mathrm{e},c,t+LT_c} \leq M \cdot H_{f,\mathrm{e},c,t}, \forall f \in F, c \in C, e \in E, \forall t \in T \quad (40)$$

The raw material supply capacity is represented by constraint 41:

$$QS_{f,\mathrm{e},c,t+LT_c} \leq QF_{f,e,c}^{\mathrm{max}}, \forall f, c, e \in F \cap C \cap E, \forall t < T - LT_c \quad (41)$$

Furthermore, the inventory control is performed considering a safety stock level for each raw material. In fact, Hernandez-Ruiz et al. (2016) proposed an evaluation development to cope with demand variability for modular product structure based on normal distribution of demand in addition to their independency. Constraint 42 represents the adopted expression for the studied case where K reflects a safety factor, it is the inverse cumulative normal distribution coefficient for a target service level highlighting the decision makers' willingness to cope with demand variability:

$$ICS_{e,c,t} \geq K * \left(\sqrt{\sum_{p \epsilon P} \sum_{m \epsilon M} PR_m * \alpha_{c,m} * \sigma_p^2} \right) * \sqrt{LT_c}\ , \forall\, e \in E, c \in C, t \in T \tag{42}$$

3. Numerical results

In this section, a numerical experiment is conducted to validate the proposed model and illustrate its application. The considered example consists of 3 customers, 3 manufacturing sites, 3 advanced warehouses and 6 product families with a cluster of 102 modules. The bill of material structure of all modules includes a set of 670 raw materials. Real and forecasted demands are computed according to the normal distribution while optional module preferences are generated with the uniform distribution. After a defined level of customer demand for each product and each period, a corresponding number of series is generated accordingly. The optional modules affectation to these series depends on their penetration rate. The interaction links between stakeholders and product clusters are presented in table 1. The model planning horizon is assumed to be 10 periods. Due to different possible configurations, the product inventory holding cost at different locations has been set to an average cost. The initial level of backorders and product inventory is set to zero. Besides, the transportation cost between the partners is considered as a fixed one. According to the raw material safety stock to ensure at the first-tier suppliers, the corresponding customer service level in this study has been set to 95% which gives K=1,65.

Table 1. Affectations of OEMs

Customer	Manufacturing site	Advanced warehouse	Product	Range of Modules	Basic Module
o_1	e1	v_1	p_1	M01 -> M17	M01
			p_2	M18 -> M35	M18
o_2	e2	v_2	p_3	M36 -> M53	M36
			p_4	M54 -> M71	M54
o_3	e3	v_3	p_5	M72 -> M89	M72
			p_6	M90 -> M102	M90

Furthermore, the raw material purchase costs have been generated randomly between 0,05 and 12. Subsequently, they are used to define the modules' costs according to their bill of materials. Table 2 provides a summary of numerical input data.

Table 2. Model Parameters

Parameters			
Parameter	Value range	Parameter	Value range
$DR_{o,e,p,t}$	N(300;50)	$PQ_{o,e,p,t}^{\max}$	500
$DF_{o,e,p,t}$	N(300;50)	$PQ_{o,e,p,t}^{\min}$	U(150;180)
$ICS0_{e,c}$	U(1000;1100)	$D_{o,e,p,t}^{min}$	150
PC_c	U(0,05;12)	PR_m	U(0,05;0,9)
$QF_{f,e,c}^{min}$	U (500;700)	$QF_{f,e,c}^{max}$	U (45000;55000)
$BOC_{o,p,s,t}$	5	$H_{f,e,c,t}$	1
$CPO_{o,v,p,t}$	4	$IHPS_{o,e,p,t}$	200
$CPV_{o,v,p,t}$	10	$IPV0_{o,v,p}$	0
$IHPV_{o,v,p,t}$	100	$IPS0_{o,e,p}$	0
$BO0_{o,e,p,s}$	0	$TLO_{o,v}$	50
$TLV_{e,v}$	50	$CTV_{e,v,t}$	500
$CTO_{o,v,t}$	150	$C_{o,v,p,t}^{\max}$	50
$PE_{o,e,p}^{\max}$	50	$PNC_{o,v,p,t}$	150
LT_c	[1,2,3]	-	-

The resolution is performed with exact approach. The model is programmed and solved with GAMS 22.5/CPLEX 12.2 optimization software and all numerical experiments are processed with a Core i5 2.49 GHz computer with 8 GB RAM. Table 3 presents the generated real demand. The total number of the backordered serial numbers for each product is presented in table 4. Table 5 presents a detailed example of the backordered serial numbers for product p_4. The tables 6,7,8 provide a summary of the numerical results for the production quantity for each product, the product inventory level at the advanced warehouses and the corresponding excess perceived during each period. The cost structure of the resolution status is presented in figure 4.

Table 3. Confirmed demand $DR_{o,e,p,t}$

			t1	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**	**t8**	**t9**	**t10**
o1	**e1**	**p1**	303,55	293,86	211,97	299,94	284,23	285,27	243,37	238,78	297,18	307,34
o1	**e1**	**p2**	269,76	364,70	290,28	338,88	271,65	317,55	268,37	305,43	175,92	324,97
o2	**e2**	**p3**	330,10	235,95	264,66	223,80	288,81	247,15	230,03	223,01	254,25	270,22
o2	**e2**	**p4**	264,17	291,69	258,53	287,91	270,92	249,10	254,03	311,45	300,77	269,33
o3	**e3**	**p5**	374,51	382,91	213,48	359,20	401,02	303,70	251,31	322,42	303,38	246,81
o3	**e3**	**p6**	334,82	354,86	268,70	253,28	236,67	336,57	310,81	280,92	242,67	289,21

Table 4. Total backorder for each product from $XQB_{o,e,p,s,t}$

			t2	t4	t6	t7	t8
o1	**e1**	**p1**	28		14	24	
o1	**e1**	**p2**		30		26	30
o2	**e2**	**p3**				5	22
o2	**e2**	**p4**				7	31
o3	**e3**	**p5**	30		30	3	20
o3	**e3**	**p6**			30	10	14

Table 5. Generated Backorder series $XQB_{o,e,p,s,t}$

				t7
o2	**e2**	**p4**	**s35**	1
o2	**e2**	**p4**	**s41**	1
o2	**e2**	**p4**	**s42**	1
o2	**e2**	**p4**	**s43**	1
o2	**e2**	**p4**	**s44**	1
o2	**e2**	**p4**	**s45**	1
o2	**e2**	**p4**	**s46**	1

Table 6. Total produced quantity to satisfy demand (from $XQD_{o,e,p,s,t}$)

			t1	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**	**t8**	**t9**	**t10**
o1	**e1**	**p1**	303	265	211	299	284	271	219	238	297	307
o1	**e1**	**p2**	269	364	290	308	271	317	242	275	175	324
o2	**e2**	**p3**	330	235	264	223	288	247	225	201	254	270
o2	**e2**	**p4**	264	291	258	287	270	249	247	280	300	269
o3	**e3**	**p5**	374	352	213	359	401	273	248	302	303	246
o3	**e3**	**p6**	334	354	268	253	236	306	300	266	242	289

Table 7. Inventory level at the advanced warehouse (from $IPV_{o,v,p,t}$)

			t1	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**	**t8**	**t9**	**t10**
o1	v1	p1	60,71	58,77	42,39	59,99	56,85	57,05	48,67	47,76	59,44	61,47
o1	v1	p2	53,95	72,94	58,06	67,78	54,33	63,51	53,67	61,09	35,18	64,99
o2	v2	p3	66,02	47,19	52,93	44,76	57,76	49,43	46,01	44,60	50,85	54,04
o2	v2	p4	52,83	58,34	51,71	57,58	54,18	49,82	50,81	62,29	60,15	53,87
o3	v3	p5	74,90	76,58	42,70	71,84	80,20	60,74	50,26	64,48	60,68	49,36
o3	v3	p6	66,96	70,97	53,74	50,66	47,33	67,31	62,16	56,18	48,53	57,84

Table 8. Excess inventory at the advanced warehouse (from $GPL_{o,v,p,t}$)

			t1	t2	t3	t4	t5	t6	t7	t8	t9	t10
o1	**v1**	**p1**	10,71	8,77		9,99	6,85	7,05			9,44	11,47
o1	**v1**	**p2**	3,95	22,94	8,06	17,78	4,33	13,51	3,67	11,09		14,99
o2	**v2**	**p3**	16,02		2,93		7,76				0,85	4,04
o2	**v2**	**p4**	2,83	8,34	1,71	7,58	4,18		0,81	12,29	10,15	3,87
o3	**v3**	**p5**	24,90	26,58		21,84	30,20	10,74	0,26	14,48	10,68	
o3	**v3**	**p6**	16,96	20,97	3,74	0,66		17,31	12,16	6,18		7,84

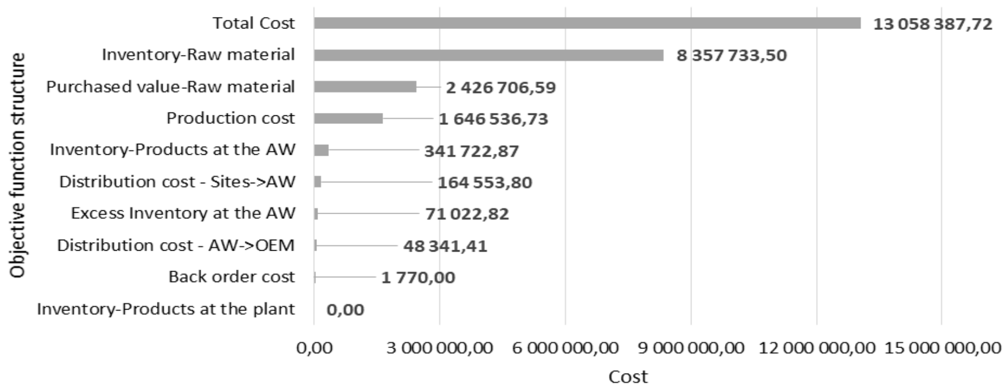

Figure 4. Objective function-Cost summary

4. Sensitivity analysis and managerial insights

In order to explore the quality of the proposed solutions, a sensitivity analysis is performed for some key parameters from the initial nominal value. The improvement of the given right-hand side input data highlights a deep correlation with decision-making process, for instance, those related to capital investment or manpower decisions for the capacity allocation provided in the model by $PQ^{max}_{o,e,p,t}$. Therefore, a local sensitivity analysis according to the one-at-a-time method (OAT) is carried out through 3 scenarios while decreasing the upper bound region in order to analyze the optimality resolution behavior of the model (Borgonovo et Plischke, 2016). In fact, 3 instances have been launched with the same demand range while decreasing the capacity level. Table 9 describes the shifting percentage from the base case to the sensitivity case with the corresponding optimality resolution status. Figure 5 presents the resulted influence for each instance on the objective function which is kept slightly at the same level while decreasing maximum capacity allocation.

Table 9. Resolution status

	$DR_{o,p,t}$ ~N(300;100)		
$PQ^{max}_{o,p,t}$	-10%	-20%	-30%
Solving status	Solved	Solved	Infeasible

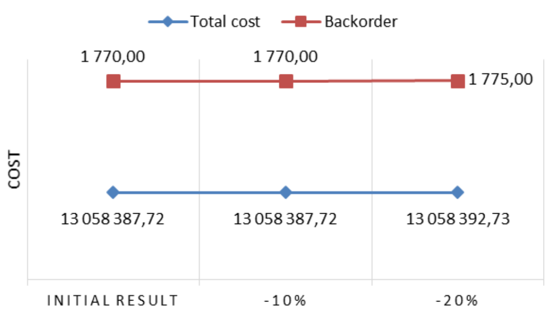

Figure 5. Maximum capacity cost impact

Likewise, a combined variability of the input parameters related to raw material inventory management is implemented. It is triggered by the resulted main level of the objective function presented previously. The considered parameters are the initial inventory level at each site, the minimum order quantity represented by the minimum supplier capacity as well as the contracted maximum capacity. The parameters sensitivity is measured in terms of their simultaneous impact on the optimality solution, the related parameter stability region would represent the suitable upper and lower bounds to be considered for the model. It is worth noting that there is dependency between parameters, for instance, customer demand impacts directly the adopted maximum and minimum capacity. Thus, as stated by Yi Chaojue & Lu Ming (2019), the sensitivity analysis is outlined with how a set of parameters called probe class can vary while another one known as control class is kept unchanged. In this case, the probe class includes the chosen parameters (i.e. initial inventory level, minimum order quantity & maximum capacity), while the control class is defined by the forecasted demand $DF_{o,e,p,t}$ and the maximum production capacity for each site $PQ^{max}_{o,e,p,t}$. From managerial standpoint, improving the bounds quality illustrates the related capacity threshold definition with raw material suppliers which is a considerable asset. Thus, 3 scenarios have been launched while improving the discussed bounds as $QF^{min}_{o,e,p,t}$ and $QF^{max}_{o,e,p,t}$ in addition to the initial level $ICS0_{e,c}$ as presented in table 10. As shown in figure 6, the objective function curve has been decreased to -16% for the second scenario, it is mainly related to the corresponding decrease behavior of raw material inventory (i.e. raw material purchased value and the inventory holding cost).

Table 10. Parameters change and solving status

	$DR_{o,e,p,t}$ ~N(300;50)		
	Scenario 1	**Scenario 2**	**Scenario 3**
Decrease (%)	-10%	-20%	-30%
$QF^{min}_{f,e,c}$	*	*	*
$QF^{max}_{f,e,c}$	*	*	*
$ICS0_{e,c}$	*	*	*
Solving status	Solved	Solved	Infeasible

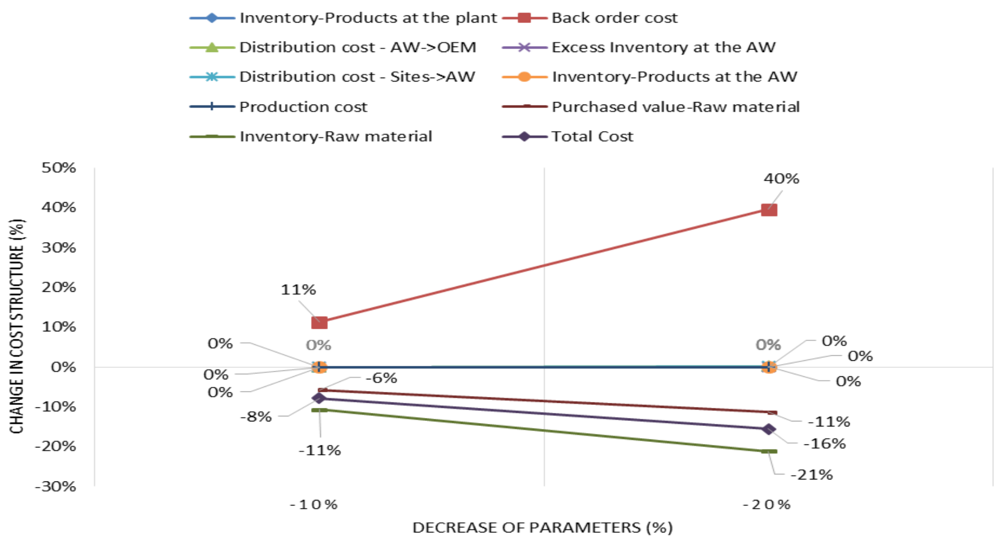

Figure 6. Objective function cost split

5. Conclusion

The increasing importance of supply chain management has been recognized during time from practitioners and academics. Though, dealings with mass customization strategy according to value chain management perspective has not been sufficiently reported. In this paper, the supply chain fundamental framework has been drawn asserting mass customization enablers. The study developed a planning problem through a mixed integer liner programming model for a multi-echelon, multi-site supply chain in order to catch up on the assumptions details of the problem depicted from an industrial application to outline stakeholders' interactions and the related aspects. Accordingly, the model formulation is defined through a tactical decision level while integrating production, procurement and distribution systems. In fact, a three echelon supply chain has been illustrated from the automotive industry according to leaders and followers partnership. Furthermore, the demand driven process inferred from customization products highlights the corresponding decoupling point while production activities are established with make to order policies. A sensitivity analysis has been performed in order to highlight the interdependency between some key parameters. In this respect, the managerial inisghts are driven by cost viability according to capacitiy hurdles of different stakeolders as well as the balance of supply-demand in a customized environment while keeping the global solvability of the problem. Thus, to develop further the presented work towards application potential, testing the model with bigger sizes from real industrial cases is an interesting attempt to assess its resolution status according to exact methods. While approaching the extreme boundaries, a benchmarking between metaheuristics would support to define the best performing algorithm according to solution quality and the related computational time.

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