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Supply chain dynamic configuration as a result of new product development

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ABSTRACT

This study considers supply chain network configuration in an innovative environment while the new product development (NPD) will affect the supply chain configuration (SCC). The time of new product introduction has a significant effect on the market performance while it has an effect on the supply chain configuration. Supplier integration into the new product introduction is the key parameter for successfully new product introduction, which may contribute to supply chain reconfiguration. Consequently By considering the new product development concept, we may face with dynamic supply chain configuration during a planning horizontal time. In this study, a new model is presented to consider the dynamic configuration of a supply chain by developing new products. In the proposed model, the dynamic configuration of a supply chain and the new product launching time is optimized simultaneously. The proposed model considers production, sales and transportation planning for the entire supply chain in order to achieve an integrative and efficient supply as well. Then some numerical analyses have been done to show the applicability of the proposed model. The results show that the new product development has a significant effect on the configuration of supply chain.

1. Introduction

In the recent years by raising competition in the market, products life cycle has shortened and new product design and its introduction to the market is a key factor to be alive in the market. In many industries, firms should reduce the cost of new products development and facilitate the smooth launch of new products in such a competitive environment [1]. Lunching a new product in a firm depends on its designing aspect, as an internal effect, and external aspect in the supply chain (SC) outline. The first one is related to firm's expert's abilities to use technologies and considering customer specifications. Second aspect, depends on supply chain elements and their flexibility and integration to the new product introduction. As noted by Forza et al. [2] supplier selection, their engagement and their involvement timing are critical factors of successful NPD process, which should be decided by product development team. As another study in the literature, Petersen et al. [1] discussed that supplier integration in the new product development process has direct impact on the supply chain configuration decisions. Therefore, SC elements integration, supplier selection, supplier involvement time and an optimal configuration of the supply chain are the requirements for achieving beneficial new product diffusion. Consequently, Supply chain should adapt to market changes to gain sustainable competitive advantage [3] which relies so heavily on marketing and supply chain interactive coordination. By expanding the field of vision, it is obvious that the supply chain configuration should be changed

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by considering the new products because of dynamic marketing demands, so in this study it is assumed that the supply chain configuration is dynamic during the products life cycles.

Rollover strategy, new product introduction and old product phasing out, is highly influential parameter for the SCC and NPD problem. In the case of product rollover, time of introducing new product and phasing out the old product is key parameter and has an effect on firms' performance and their related supply chain as well. We refer to Lim and Tang [4] study for more details about the tradeoff between the introduction and phasing out for an individual firm. We can find two main rollover strategy studied by Billington et al. [5] in the literature. They proposed two product rollover strategies namely single-product roll and dual-product roll. In the single-product strategy, the old product is phased out first then the new product is introduced, consequently the firm produces only one of the old or new products in a moment. Nevertheless, in the dual-product strategy both products can be produced concurrently so the old product phasing out and the new product introduction are occurred distinctly. These strategies should be considered in the supply chain and examine their properties and preferences. In the presented model of this paper, single-product roll is considered as the rollover strategy. In another hand Petrick and Echols [6] categorized the new product production specifications by required system and components in three sections as follows: new product constructed by new component using existing system, new component constructed by new system and the condition which existing component is operated by the new system. This is also the other essential parameter for the proposed problem. As Amini and Li [7] mentioned, after the NPD and SCC decisions and during the product life cycle, production and sales planning for the firms and transportation for the whole supply chain are the only part of big picture.

In this study, we attempt to model interaction of NPD and SCC problems. In the simulated supply chain (SC), we consider a five echelon SC with multiple firms, which individually decide to introduce new products. In the proposed model, the supply chain configuration and the time of new product lunching are optimized simultaneously because of their effects to each other. It is clear that new product lunching should be done in a firm continuously to have the competitive advantage, so in the proposed model it is assumed that the SCC is dynamic and will be changed in different periods according to the new product development. Moreover, production, sales and transportation planning of the supply chain are considered during the new product development and supply chain configuration decisions. For better illustration, a sensitive analysis of more effective parameters of the problem such as reconfiguration cost and product life cycle are considered and their effects on the supply chain configuration and product rollover during different periods are discussed in the paper.

The rest of this paper is organized as follows. In Section 2, a brief literature review of the problem is documented. In Section 3, the proposed model of the dynamic supply chain configuration is presented. For more illustration, numerical studies and a sensitive analysis have been done in Section 4 and finally, conclusions are demonstrated in Section 5.

2. Literature review

Our research is interaction of the two main area of science, covering supply chain configuration and new product introduction. These two aspects are separately and simultaneously discussed in the literature. In this part, we provide a brief review of related studies.

In the case of supply chain configuration, we can categorize the studies in static and dynamic configuration that are presented in the following. Li and Womer [8] presented a modeling framework based on multi-mode resource-constrained project scheduling for configuring the supply chain subjected to explicit resource constraints. Their model includes quality requirement levels and lead time as SC measures. They use constraint programming as solution approach. Altiparmak et al. [9] studied the supply chain network design problem by considering plants and distribution centers opening decisions. They modeled a single-source, multi-product and multi echelon SC that belongs to production–distribution and facility location problem. They developed a steady-state GA algorithm to solve the problem. Piramuthu [10] incorporated machine-learning techniques to develop a dynamic configurable supply chain framework, and evaluate its effectiveness with respect to comparable static supply chains. Nagurney [11] proposed a framework for supply chain configuration design and redesign including determination of the optimal levels of capacity and operational product flows associated with manufacturing, storage, and distribution activities of supply chain. In mentioned study, after the designing stage and obtaining the initial configuration, redesigning is implemented based on the capacities in order to determine the optimal solution. Ramezani et al. [12] designed a multi objective forward/reverse network in the stochastic environment. Their model considers a systematic SCC that maximizes the profit, customer responsiveness and quality. Constructed network has three echelons in forward direction and two echelons in reverse direction. The set of Pareto optimal solutions is presented in the mentioned study. Castillo-Villar et al. [13] generated a model for supply chain design by considering the cost of quality. Goal of their study is computation of cost of quality as a global performance measure for the entire supply chain. They illustrated that how cost of quality function changes depending on various parameters.

Lim and Tang [4] studied about the product rollover strategies. They introduced the timing of introducing the new product and phasing out the old product and their related pricing as key parameters of their product rollover model. Their proposed model is solved considering the two rollover strategies.

There are some studies which consider the supply chain configuration and the new product development simultaneously such a (Amini and Li [7], Wang and Shu [14], Naraharisetti and Karimi [15]). Amini and Li [7] developed an integrated optimization model for configuring the supply chain of new product while considering the impact of demand dynamics during new products' diffusion. Goal of this study is configuration of SC subject to demand dynamics and other SC options such as lead-time and inventory. Wang and Shu [14] investigated SC uncertainties by fuzzy sets and developed a possibilistic SC configuration model for new products in their proposed model. The goal of this study is to determine the option and inventory policy for each stage of SC to minimize the total SC cost and maximize the possibility of fulfilling the target service level subject to cost and lead-time options. In mentioned study, the new product development is not a specific decision. They used Genetic Algorithm to solve the problem. Naraharisetti and Karimi [15] studied the supply chain redesign and new process introduction in multi-purpose plants. Their redesign issues involve facility location, relocation, investment, disinvestment, technology upgrade, production-allocation, distribution, supply contracts and capital generation. They considered some possible production facilities, inventory facility, distribution and customer center that can be added to a supply chain.

In this study supply chain configuration is constructed taking new product introduction into account by considering the new product specifications (bill of material). Unlike the literature studies, the proposed model considers new product lunching and old product phasing out time in the supply chain, which is optimized with supply chain configuration simultaneously. Moreover, in the broad vision we consider sequence of introducing new products respect to their life cycles looking into the future. These may contribute to the dynamic configuration as we discuss about. In addition to the sequential new product introduction and supply chain configuration, production, sales, transportation planning and their lead times are considered in the model. In order to address more realistic environment, our study is considered in a five echelon SC starting from raw material supplier to the customer groups.

3. Proposed model

Consider a five echelon centralized SC consists of raw material suppliers, component suppliers, manufacturer, distribution centers and customer groups while manufacturers can introduce new products according to central decision making. A special manufacturer by analyzing the market should make decision about the quality level of product and the time to design and introduce the new product. For special type of product, there may be different brands with different prices and qualities in the market for the customers with diverse financial afford abilities. Therefore, we consider a quality level decision for the firms to illustrate that the proposed product is designed for which customers' tastes and preferences. Consequently, central decision makers should recognize the different choices of customers to introduce new product for the proposed customer demand. After these decisions, supplier integration should be constructed in the supply chain for the mass production. Firms should make contract with the required suppliers according to new product bill of material (BOM), which have beneficial costs and less lead time and also with distribution centers and customer groups according to market demand. This makes the supply chain configuration to be changeable and our model choose the optimal reconfiguration for the new products lunching by the concept of centralized supply chain. Moreover, in this study the finished products are considered available and supply chain decoupling point is in available finished product stage which is representing make to stock demand response strategy.

After the new product introduction, proposed model embrace the production, sales and transportation planning for the whole supply chain. When the proposed product passes its life cycle, all these issues are taken for the next new product.

As aforementioned in the introduction, Petrick and Echols [6] categorized new product production specification. The proposed model in this paper is based on the first category, i.e. new product synthesis from new component using existing system. New components requirement is one of the reconfiguration reasons in the new product introduction (change in bill of material). Probably new components should be supplied by the new beneficial suppliers. This reconfiguration occurs for the echelons before manufacturer. In addition, for the echelons after manufacturers, reconfiguration can be considered according to Hinojosa et al.'s study [16]. They studied the supply chain network design by changing the customer behavior. The importance of this idea increase by considering new product introduction that may create new demands in the different markets. Consequently change in BOM and market demand are the potential reconfiguration reasons in the new product introduction.

The proposed model consists of lead time and inventory, which can affect SCC and NPD significantly. Lead time is one of the most important measure of SCC and its importance is growing in a competitive world with shortened products life cycles. In the proposed model, we consider three type of lead time such as, transportation lead time, production lead time and new product designing duration. Inventory can decrease the idleness especially in demand fluctuation circumstances during the product life cycle. Producers have two kind of inventories, inventory of components and inventory of final product while the others have only final product inventory.

As we consider product rollover in our study demand pattern is very important and it should be in the life cycle shape. Therefore we consider hypothetical deterministic product life cycle for the old (current) and new product and discretize and quantified it in periods to be conducted in operation research. So, as usual, there are periods which only current product has demand, periods both products have demand and which only new product has demand in the markets. In the proposed model i indicates product index and is one for consideration of the current (old) product while its value will be 2 for the new product. Also it can be increased to consider more products in the model horizon. In the following all indices, parameters and variables have been defined. Then we continue with a brief description about the objective and constraints of the model

Notations and indices:

T	Period	$Nperiod$	Number of periods
R	Raw material supplier	$Nrms$	Number of raw materials supplier
C	Component supplier	Ncs	Number of component supplier
F	Manufacturer	Nm	Number of manufacturer
D	Distributor	Nd	Number of distributor center
G	Customer group	Ncg	Number of customer group
K	Raw material	Nrm	Number of raw material
J	Component	Nc	Number of component
I	Product	Np	Number of product
q, q^*	Product quality level	Nq	Number of quality level

Parameters:

Demand

D^t_{giq} Demand of customer group g for product i with quality q in period t

Production availability

PAr^t_{rk} 1, if raw material supplier r produces raw material k in period t, 0, otherwise
PAc^t_{cj} 1, if component supplier c produces component j in period t, 0, otherwise

Prices

P_{rk} Per unit price of raw material k in the raw material supplier r
P_{cj} Per unit price of component j in the component supplier c
P_{fiq} Per unit price of product i with quality q in the manufacturer f
P_{diq} Per unit price of product i with quality q in the distributor center d

Bill of material

B_{jk} Number of the raw material k needed to produce component j
B_{ij} Number of the component j needed to produce product i

Transportation lead time

l_{rc} Delivering lead time between raw material supplier r and component supplier c
l_{cf} Delivering lead time between component supplier c and manufacturer f
l_{fd} Delivering lead time between manufacturer f and distributor center d
l_{dg} Delivering lead time between distributor center d and customer group g

Production lead time

p^l_{fiq} Production lead time of manufacturer f for product i with quality q
p^l_{ck} Production lead time of component supplier c for component k

NPD duration

dl_{fiq} New product designing duration of product i with quality q in the manufacturer f

Capacities

PC_{cj} Capacity of component supplier c for producing component j
PC_{fi} Capacity of manufacturer f for producing product i
C_d Capacity of distributor d

Production cost

CP_{cj} Cost of producing component j in supplier c
CP_{fiq} Cost of producing product i in manufacturer f with quality q
fCP_{fiq} Fixed cost of producing product i in manufacturer f with quality q

Inventory cost

CI_{ck} Per unit Cost of inventory for raw material k in component supplier c
CI_{cj} Per unit cost of inventory for component j in component supplier c
CI_{fj} Per unit cost of inventory for component j in manufacturer f

CI_{fiq}	Per unit cost of inventory for product i with quality q in manufacturer f
CI_{diq}	Per unit cost of inventory for product i with quality q in distributor center d
Contract cost	
CA_{rc}	Agreement cost between raw material r and component supplier c
CA_{cf}	Agreement cost between component supplier c and manufacturer f
CA_{fd}	Agreement cost between manufacturer f and distributor center d
CA_{dg}	Agreement cost between distributor center d and customer group g
Initial inventory	
II_{ck}	Initial inventory of component supplier c for raw material k
II_{cj}	Initial inventory of component supplier c for component j
II_{fj}	Initial inventory of manufacturer f for component j
II_{fiq}	Initial inventory of manufacturer f for product i with quality q
II_{diq}	Initial inventory of distributor d for product i with quality q
Transportation cost	
TC_{rc}	Transportation cost between raw material supplier r and component supplier c
TC_{cf}	Transportation cost between component supplier c and manufacturer f
TC_{fd}	Transportation cost between manufacturer f and distributor center d
TC_{dg}	Transportation cost between distributor center d and customer group g
$CDNP_{fiq}$	Cost of designing new product i for the manufacturer f with quality q
SS^{t}_{dgiq}	The flow of last echelon for the periods do not reach the customer demand according to corresponding lead time
CUS_f	Cost of unused sources for manufacturer f
lt	Marginal cost of lead time
CDC	Customer dissatisfactory cost (per unit)
DLC	Production delay cost
M	Big number

Variables:

State variables

Inventory

I^{t}_{ck}	Inventory of raw material k for component supplier c at the end of period t
I^{t}_{cj}	Inventory of component j for component supplier c at the end of period t
I^{t}_{fj}	Inventory of component j for manufacturer f at the end of period t
I^{t}_{fiq}	Inventory of product i with quality q for manufacturer f at the end of period t
I^{t}_{diq}	Inventory of product i with quality q for distributor center d at the end of period t

Decision variables

Configuration

Y^{t}_{rc}	Binary variable which links raw material supplier r to component supplier c respect to each period
Y^{t}_{cf}	Binary variable which links component supplier c to manufacturer f respect to each period
Y^{t}_{fd}	Binary variable which links manufacturer f to distributor center d respect to each period
Y^{t}_{dg}	Binary variable which links distributor center d to customer group g respect to each period
Contract	
YY^{t}_{rc}	1, if raw material supplier r and component supplier c make a contract in period t (because of the supply chain reconfiguration), 0, otherwise

(*continued on next page*)

YY^t_{cf}	1, if component supplier c and manufacturer f make a contract in period t, 0, otherwise
YY^t_{fd}	1, if manufacturer f and distributor center d make a contract in period t, 0, otherwise
YY^t_{dg}	1, if distributor center d and customer group g make a contract in period t, 0, otherwise
Flow	
S^t_{rck}	Amount of raw material k transferred from raw material supplier r to component supplier c in period t
S^t_{cfj}	Amount of component j transferred from component supplier c to manufacturer f in period t
S^t_{fdiq}	Amount of product i with quality q transferred from manufacturer f to distributor d in period t
S^t_{dgiq}	Amount of product i with quality q transferred from distributor d to customer group g in period t
Production	
Q^t_{cj}	Production quantity of component j for supplier c in period t
Q^t_{fiq}	Production quantity of product i with quality q for manufacturer f in period t
Product availability	
X^t_{fiq}	Binary variable that shows production availability and new product entering time to the market
Produced products	
XX^t_{fiq}	1, if manufacturer f decide to design product i by q quality in period t, 0, otherwise

Objective function

Maximize

$$Z = Gain(c) + Gain(f) + Gain(d) - Cus.Dis - C.Source - PDIC - PDLC - LTcost, \tag{1}$$

$$\begin{aligned} Gain(c) = {} & \sum_c\sum_f\sum_j\sum_t P_{cj}S^t_{cfj} - \sum_r\sum_c\sum_k\sum_t P_{rk}S^t_{rck} - \sum_c\sum_j\sum_t CP_{cj}Q^t_{cj} - \sum_r\sum_c\sum_t CA_{rc}YY^t_{rc} - \sum_c\sum_k\sum_t CI_{ck}I^t_{ck} \\ & - \sum_c\sum_j\sum_t CI_{cj}I^t_{cj} - \sum_r\sum_c\sum_t TC_{rc}Y^t_{rc}, \end{aligned} \tag{2}$$

$$\begin{aligned} Gain(f) = {} & \sum_f\sum_d\sum_i\sum_t P_{fi}S^t_{fdi} - \sum_c\sum_f\sum_j\sum_t P_{cj}S^t_{cfj} - \sum_f\sum_i\sum_q\sum_t (CP_{fiq}Q^t_{fiq} + fCP_{fiq}XX^t_{fiq}) - \sum_c\sum_f\sum_t CA_{cf}YY^t_{cf} \\ & - \sum_f\sum_j\sum_t CI_{fj}I^t_{fj} - \sum_f\sum_i\sum_t CI_{fi}I^t_{fi} - \sum_c\sum_f\sum_t TC_{cf}Y^t_{cf}, \end{aligned} \tag{3}$$

$$\begin{aligned} Gain(d) = {} & \sum_d\sum_g\sum_i\sum_t P_{di}S^t_{dgi} - \sum_f\sum_d\sum_i\sum_t P_{fi}S^t_{fdi} - \sum_d\sum_i\sum_t CI_{di}I^t_{di} - \sum_f\sum_d\sum_t CA_{fd}YY^t_{fd} - \sum_d\sum_g\sum_t CA_{dg}YY^t_{dg} \\ & - \sum_f\sum_d\sum_t TC_{fd}Y^t_{fd} - \sum_d\sum_g\sum_t TC_{dg}Y^t_{dg}, \end{aligned} \tag{4}$$

$$Cus.Dis = \sum_t\sum_g\sum_i\sum_q CDC \cdot \left(D^t_{giq} - \sum_d S^t_{dgiq}\right), \tag{5}$$

$$C.Source = \sum_t\sum_f CUS_f \cdot \left(1 - \sum_i\sum_q X^t_{fiq}\right), \tag{6}$$

$$PDIC = \sum_t\sum_f\sum_i\sum_q CDNP_{fiq} \cdot XX^t_{fiq}, \tag{7}$$

$$PDLC = \sum_f \sum_i \sum_q \sum_t DLC \cdot XX_{fiq}^t \cdot (XX_{fiq}^t - X_{fiq}^{t+dl_{fiq}}), \tag{8}$$

$$LT\cos t = lt \cdot \sum_t \left(\sum_r \sum_c l_{rc} Y_{rc}^t + \sum_c \sum_f l_{cf} Y_{cf}^t + \sum_f \sum_d l_{fd} Y_{fd}^t + \sum_d \sum_g l_{dg} Y_{dg}^t \right). \tag{9}$$

Constraints:

Inventory

$$I_{ck}^t = I_{ck}^{t-1} + \sum_r S_{rck}^{t-l_{rc}} - \sum_j B_{jk} Q_{cj}^t \qquad \forall c,k,t, \tag{10}$$

$$I_{cj}^t = I_{cj}^{t-1} + Q_{cj}^{t-pl_{cj}} - \sum_f S_{cfj}^t \qquad \forall c,j,t, \tag{11}$$

$$I_{fj}^t = I_{fj}^{t-1} + \sum_r S_{cfj}^{t-l_{cf}} - \sum_i B_{ij} Q_{fi}^t \qquad \forall f,j,t, \tag{12}$$

$$I_{fiq}^t = I_{fiq}^{t-1} + Q_{fiq}^{t-pl_{fi}} - \sum_d S_{fdiq}^t \qquad \forall f,i,q,t, \tag{13}$$

$$I_{diq}^t = I_{diq}^{t-1} + \sum_f S_{fdiq}^{t-l_{fd}} - \sum_g S_{dgiq}^t \qquad \forall d,i,q,t, \tag{14}$$

$$I_{ck,cf,fd,dg}^t = II_{ck,cf,fd,dg}^t, \quad t \in [-\max(pl_{cj,fi}), 0] \qquad \forall k,c,\forall c,f,\forall f,d,\forall d,g. \tag{15}$$

Flow

$$\sum_d S_{dgiq}^{t-l_{dg}} \leqslant D_{giq}^t \qquad \forall g,i,q,t, \tag{16}$$

$$\sum_f S_{fdiq}^{t-l_{fd}} + I_{diq}^{t-1} \geqslant \sum_g S_{dgiq}^t \qquad \forall d,i,q,t, \tag{17}$$

$$Q_{fiq}^{t-pl_{fi}} + I_{fiq}^{t-pl_{fi}-1} \geqslant \sum_d S_{fdiq}^t \qquad \forall f,i,q,t, \tag{18}$$

$$\sum_c S_{cfj}^{t-l_{cf}} + I_{fj}^{t-1} \geqslant \sum_i \sum_q B_{ij} Q_{fiq}^t \qquad \forall f,j,t, \tag{19}$$

$$Q_{cj}^{t-pl_{cj}} + I_{cj}^{t-pl_{cj}} \geqslant \sum_f S_{cfj}^t \qquad \forall c,j,t, \tag{20}$$

$$\sum_r S_{rck}^{t-l_{rc}} + I_{ck}^{t-1} \geqslant \sum_j B_{jk} Q_{cj}^t \qquad \forall c,k,t, \tag{21}$$

$$S_{dgiq}^t = SS_{dgiq}^t, \quad t \in [Nperiod - l_{dg} + 1, Nperiod] \qquad \forall d,g,i,q. \tag{22}$$

Capacity

$$Q_{cj}^t \leqslant PC_{cj} \qquad \forall c,j,t, \tag{23}$$

$$\sum_q Q_{fiq}^t \leqslant PC_{fi} \qquad \forall f,i,t, \tag{24}$$

$$\sum_f \sum_i \sum_q S_{fdiq}^t \leqslant C_d \qquad \forall d,t. \tag{25}$$

Supply allowance

$$\sum_k S_{rck}^t \leqslant M \cdot Y_{rc}^t \qquad \forall r,c,t, \tag{26}$$

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$$\sum_j S^t_{cfj} \leqslant M \cdot Y^t_{cf} \qquad \forall c, f, t, \tag{27}$$

$$\sum_i \sum_q S^t_{fdiq} \leqslant M \cdot Y^t_{fd} \qquad \forall f, d, t, \tag{28}$$

$$\sum_i \sum_q S^t_{dgiq} \leqslant M \cdot Y^t_{dg} \qquad \forall d, g, t. \tag{29}$$

Production allowance

$$Q^t_{fiq} \leqslant M \cdot X^t_{fiq} \qquad \forall f, i, q, t, \tag{30}$$

$$Q^t_{cj} \leqslant M \cdot PA^t_{cj} \qquad \forall c, j, t, \tag{31}$$

$$S^t_{rck} \leqslant M \cdot PA^t_{rk} \qquad \forall r, c, k, t. \tag{32}$$

Product rollover strategy

$$X^{t^*}_{f,i+1,q} \leqslant Nperiod \cdot (1 - X^t_{f,i,q^*}), \quad t^* \leqslant t \qquad \forall f, i, q, q^*, t. \tag{33}$$

Number of producing product constraint

$$\sum_i \sum_q X^t_{fiq} = 1 \qquad \forall f, t. \tag{34}$$

Product introduction constraint

$$\sum_{t^*} XX^{t^*}_{fiq} \geqslant X^{t+dl_{fiq}}_{fiq}, \quad t^* \leqslant t \qquad \forall f, i, q, t. \tag{35}$$

Supply allowance

$$\sum_{t^*} YY^{t^*}_{rc} \geqslant Y^t_{rc}, \quad t^* \leqslant t \qquad \forall r, c, t, \tag{36}$$

$$\sum_{t^*} YY^{t^*}_{cf} \geqslant Y^t_{cf}, \quad t^* \leqslant t \qquad \forall c, f, t, \tag{37}$$

$$\sum_{t^*} YY^{t^*}_{fd} \geqslant Y^t_{fd}, \quad t^* \leqslant t \qquad \forall f, d, t, \tag{38}$$

$$\sum_{t^*} YY^{t^*}_{dg} \geqslant Y^t_{dg}, \quad t^* \leqslant t \qquad \forall d, g, t, \tag{39}$$

$$I, S, Q \geqslant 0 \text{ and integer}, XX, X, YY, Y \in \{0, 1\}. \tag{40}$$

Eqs. (2)–(9) constitute the objectives of the proposed model. For simplifying, we added them and considered it as a single objective function in Eq. (1). All Gains contain supply chain sales, profit, purchasing, inventory, contract and production costs. Eq. (5) demonstrates customers' dissatisfaction by considering per unit shortage cost. Eq. (6) represents the idle resource cost. Eq. (7) shows the new product designing cost. The eighth equation considers penalty for the production delay after designing new products and Eq. (9) is cumulative lead time cost for entire SC and should be minimized.

All Constraints are depicted from (10)–(40) and are described briefly in the following. Eqs. (10)–(14) represent supply chain inventory equations. Eq. (15) defines the initial inventories. Constraints (16)–(21) demonstrate the flow constraints of entire SC by considering lead time and products bill of material. Constraint (22) demonstrates the flow of last echelon for periods do not reach the customer demand according to corresponding lead time. Constraints (23)–(25) are capacity constraints. According to constraints (26)–(29) the supply allowance are constrained in each period according to have been made contracts. Constraint (30) is the manufacturer production allowance, which depends on the new product designing. Constraints (31) and (32) are the production allowance for component and raw material suppliers according to their fixed production strategies. Constraints (33) and (34) conduct the new product rollover strategy, single-product, to the model. Constraint (35) relates designing starting time to production allowance according to corresponding lead time. Finally, constraints (36)–(39) make allowance of having relations for the elements of supply chain that they have made contract with each other.

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4. Experimental study

To show the performance efficiency of the proposed model, in this section a hypothetical numerical example is illustrated. Suppose a five echelon supply chain of an electronic device including raw material suppliers, electronic component suppliers, plants for production of the main device, distribution centers and customer nodes. It is clear that the configuration of the electronic device supply chain depends on the customer demands while the product life cycles are short enough and are dependent to the technology growth, so it is obvious that their supply chains should be more effective according to the changes on the technology and customer demands. In this section, three numerical example of an electronic device is investigated using the proposed model. A summary of fundamental parameters of the electronic device supply chain examples are illustrated in Table 1.

Demands of products have been generated in discrete form for different periods by a predefined continuous life cycle function. Also we consider three different hypothetical BOM of old and new product for the proposed three examples. For more illustration BOM of example three are depicted in Figs. 1 and 2. We consider 6 raw material and 3 component for the proposed example. Raw materials are shown by R and components are shown by C. P1 represents old product and P2 represents new product. As figures show new product need a new component which is constituted from new raw materials and also has one identical component with the old product.

There are some other parameters which affect to the supply chain configuration such as lead time, transportation or production cost, etc., but based on the short life cycle of products in the competitive world, it is reasonable to suppose that mentioned parameters have fixed values during the product life cycle. Hence, in the electronic device supply chain, new product development is the most important factor, which affect to the supply chain configuration.

By considering the lead time for the whole SC, upstream elements should be integrated earlier for the new product introduction. In the numerical example raw material and component suppliers are integrated in the first period while component suppliers and manufacturers integration are shifted by total lead time to components preparation and then other echelons elements are integrated as well. As more illustration we consider a sample example to show Supply chain integration times of the current and new product in Figs. 3 and 4, respectively. According to Fig. 3, the elements of two first echelons should cooperate in sending raw materials of the current product during periods of 1 and 3. Fig. 4 shows that raw materials of the new product should be sent to the component suppliers from 4th period and it will be continued until the 7th period. Then components of new product should be sent to the manufacturer after production affairs, which need 2 periods, so the first finished component of the new product will be available for manufacturer at the 7th period. This cooperation between component suppliers and manufacturers will be continued until 9th period. This sequence will be continued to the end of the

Table 1
Summary of hypothetical electroVnic device supply chain parameters for considered 3 example.

Parameters	Quantity		
	1	2	3
Example			
Nperiod	12	12	12
Nrms	2	3	3
Ncs	3	2	3
Nm	2	2	1
Nd	2	3	3
Ncg	3	2	3
Nrm	4	6	6
Nc	4	3	4
Np	2	2	2
Nq	3	2	2
l, pl, dl	1	1	1

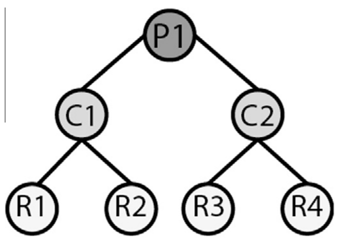


Fig. 1. Old product hypothetical BOM.

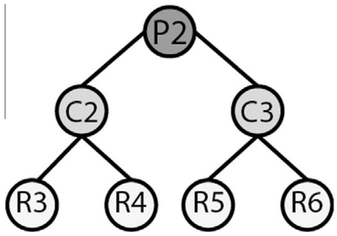


Fig. 2. New product hypothetical BOM.

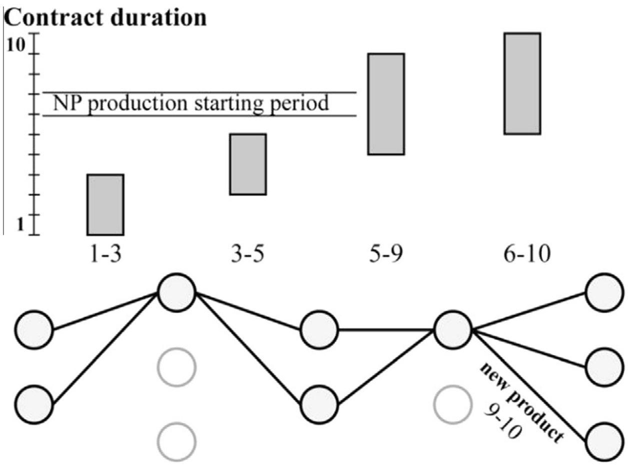


Fig. 3. Integration time of supply chain elements in current product for the simulated example.

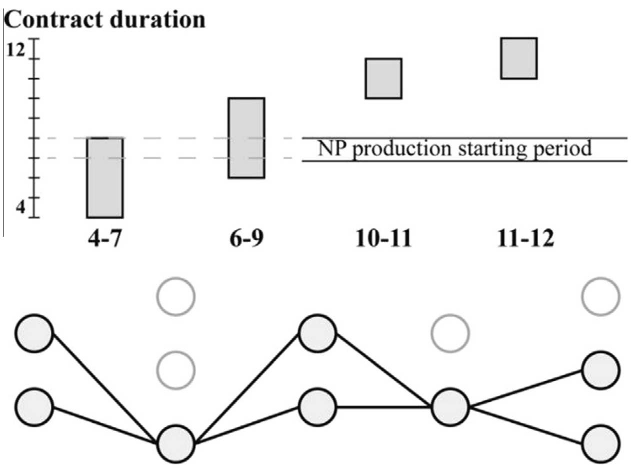


Fig. 4. Integration time of supply chain elements in the new product for the simulated example.

supply chain and the first and final batch of finished new products will be available to customers on 11th and 12th periods, respectively. Comparison of Figs. 3 and 4 clarify that the cooperation duration between the elements after manufacturer echelon for the old product is longer than the new one. The reason is inventory saving of old product for satisfying the subsequent customer demand, which will be delivered after the old product phasing out. The electronic device supply chain example has been solved by CPLEX software. Giving solution approach for the large scale instances can be studied as future research. In the following figures OP and NP stand for old product and new product, respectively.

In Table 2 results of proposed model are depicted for considered examples in Table 1. Examples are different in number of supply chain nodes and components and raw materials. So supply chain network and products hypothetical BOM is different from each other. The results show the optimal configuration before new product introduction and after that.

Table 2
Reconfiguration for the proposed three example.

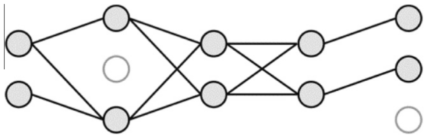
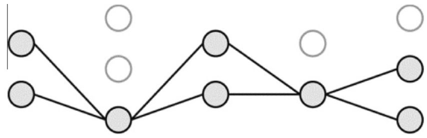
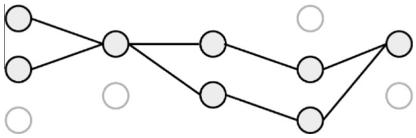
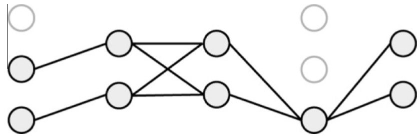
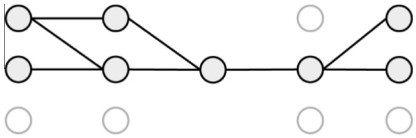
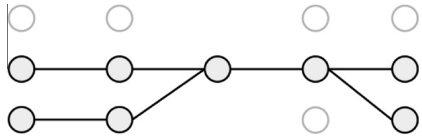
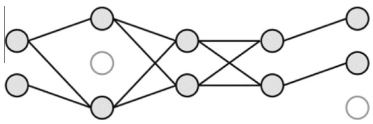
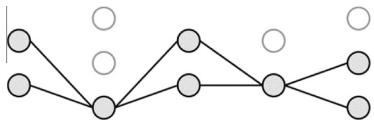
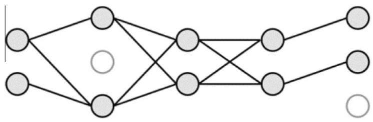
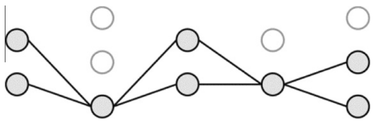
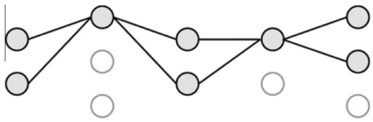
Example	OP configuration	NP configuration
1		
2		
3		

Table 3
Analysis of reconfiguration on the total supply chain cost in the electronic device supply chain example.

	Configuration structure		Objective value
	Old product configuration	New product configuration	
Proposed adaptive SCC			**1.66e+007**
Static configuration based on the old product			8.07e+006
Static configuration based on the new product			1.20e+007
No new product development			4.25e+006

For validation of the proposed model, an analysis on the problem critical parameters and results is performed. In this stage, we assume that the current and new products life cycles meet each other in some periods while the new product should enter to the market during mentioned periods. The numerical results of the considered electronic device supply chain example confirm it. In the example, by considering the new product development as reason of reconfiguration, supplier integration time should be compatible with the time which manufacturer decided to produce the new product. In the example by considering the suppliers integration and manufacturer new product production decision, coordination of supply chain elements in proposed model is detectable. For example, in Fig. 4 it is shown that the manufacturer should start the production of first new product in period 7, which is the optimum reconfiguration time. Similarly, other echelons have reconfigured according to the new product entering time, so the proposed model validity can be proven in this aspect. In Table 3 the other analysis have been taken to the reconfiguration validation of the proposed model. In this analysis, the reconfiguration effect on the electronic device supply chain total benefit is investigated in four states for example 1. Note that new product development may impossible without SC reconfiguration, because the new product may need new components that should be supplied by the new suppliers. Nevertheless, for the reconfiguration necessity confirmation, we assumed that the old product suppliers are adequate for the new one in our analysis of example 1. In the proposed analysis the supply chain benefit is investigated in 4 different scenarios. In the first scenario it is assumed that there is a reconfiguration based on

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Table 4
Reconfiguration impact on objective function.

Example	Proposed method	Static configuration based on old product	Static configuration based on new product	No new product development
1	1.66e+007	8.07e+006	1.20e+007	4.25e+006
2	1.81e+007	3.90e+006	6.33e+006	4.00e+006
3	4.89e+006	−2.30e+006	−1.01e+006	−2.30e+006

Table 5
Sensitivity analysis of reconfiguration cost in the electronic device supply chain example 1.

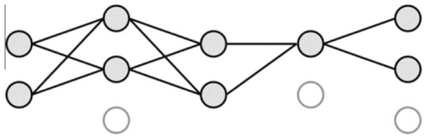
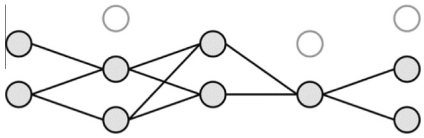
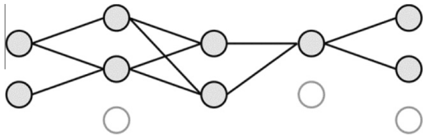
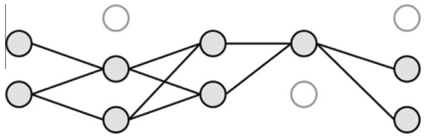
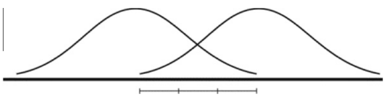
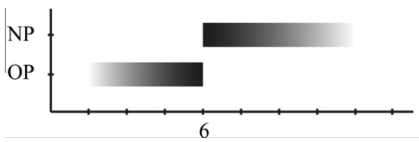
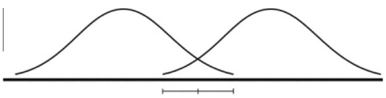
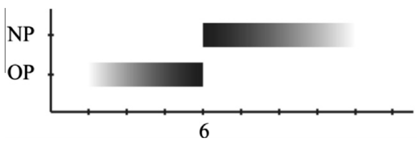
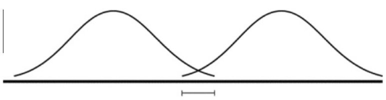
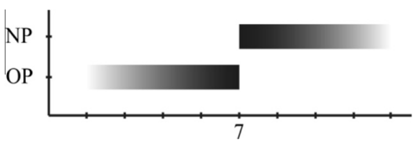
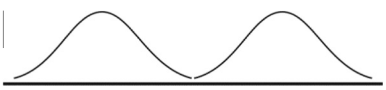
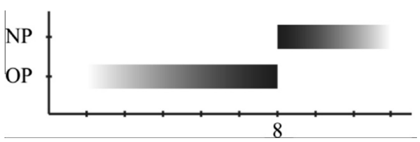
Per unit reconfiguration cost	Supply chain configuration	
	Old product SC configuration	New product SC configuration
<10,000		
>10,000 and <10^6		
>10^6	New product development is not beneficial for the firms	

Table 6
Products life cycle overlap sensitivity analysis for the electronic device supply chain example 1.

Products overlaps	Product rollover time	Configuration status
		– This configuration is considered as a base one and others are compared to this
		– New product contracts duration is increased by one – Firms 1 and 2 make contract with distributor 2 and break it with distributor 1
		– All contracts are shifted by one period – Old product contracts are increased by one period
		– Contracts of both products are increased by one period – All contracts are shifted by one period

the new product entering time, the second one considers the supply chain without any reconfiguration, the third one has static configuration but based on the new product needed configuration and the last one does not consider the new product development. In Table 3 the objective value of proposed adaptive method is better than others which has been highlighted. Furthermore, the proposed analysis is taken for two other examples and results of three examples are indicated in Table 4. According to the results of Table 4, it is observed that the supply chain with a reconfiguration (1st scenario) is more beneficial than others.

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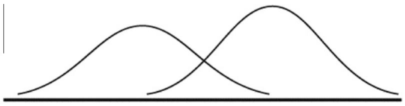
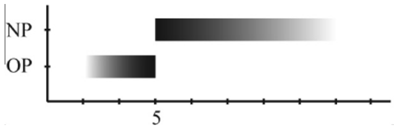
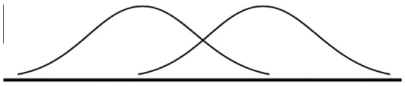
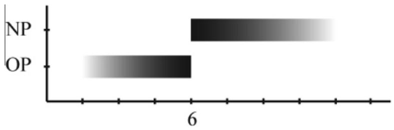
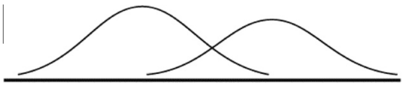
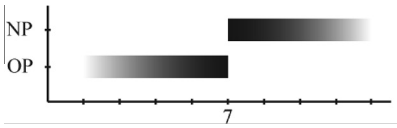
Table 7
Sensitivity analysis of new product life cycle shape for the electronic device supply chain example 1.

New product life cycle shape	Product rollover time	Reconfiguration status
		– Duration of the contracts for new product is increased
		– The base configuration
		– Duration of contracts needed for the new product production is increased

4.1. Sensitivity analysis

To show the performance of the proposed model, a sensitivity analysis is performed for the numerical example 1. In this example because of the electronic device short life cycle in the real world, it is assumed that some parameters such as lead time, delivery and other costs during the product life cycle are fixed. Therefore, the critical parameter for the new product development is the reconfiguration cost, which its effect on the supply chain configuration is depicted in Table 5. It demonstrates that by changing the reconfiguration cost, three states can be observed. Moreover it shows that by higher reconfiguration cost than a defined value (10^6 in this example), new product development is not beneficial.

As other sensitivity analysis, the old and new product life cycles overlap and its effect on the new product introduction time and related configuration has been investigated. Results are reported in Table 6. It shows that by shifting the new product life cycle to the right, the new product lunching time is shifted to the right as well. However, in some cases saving the inventory for the old product is more beneficial than shifting the new product lunching time to the subsequent periods as the second raw of Table 6 is demonstrated. Considering the first and second row of Table 6 shows that the firms have broken their contracts with distributor center 1 and have made with distributor center 2 and contract duration of new product is increased 1 period.

The last analysis is depicted in Table 7 and investigates the new product life cycle shape effect on the new product introduction time and SC configuration.

In Table 7, sensitivity analysis is done for different new product shapes. Three conditions are considered for the new product life cycle against old product life cycle: in the first scenario, the new product demand average is greater than the old one, in the second scenario the new product life cycle is the same as the old one and as the last scenario the new product demand smaller than the old product. For the mentioned scenarios product rollover time and related configurations status are demonstrated in columns 2 and 3, respectively. This analysis shows that rapid growth in new product motivates the firms to lunch the new product earlier.

5. Conclusion

This study attempts to form integrated supply chain for the new product introduction and explicitly handling additional practical issues such as production, sales and transportation planning. The problem horizon starts from old product life cycle and continues to the new product introduction and its subsequent life cycle. By considering the new product introduction in a competitive market a dynamic configuration of supply chain based on the product life cycles were investigated in this study. A new model of supply chain network configuration considering new product development was proposed. In this model dynamic supply chain configuration are optimized while new product introduction time and supplier's engagement and involvement time are determined simultaneously. Three simulated electronic device supply chain was considered to show the applicability of the proposed model. Examples are different in number of supply chain nodes and product bill of material as critical parameters. The results showed that by using the proposed model the supply chain total benefit will be increased because of its reconfiguration and new product development which are interconnected. For each example two configurations are presented, one for old product configuration and other is related to the new one. More over the sensitivity analysis showed that the products demand functions overlaps and new product life cycle shape have a significant effect on the new product lunching time and supplier involvement time and related configuration of a supply chain. Considering a solution approach for large scale instances of the proposed model can be considered as future work. As another suggestion, the problem can be investigated with stochastic parameters such as demand.

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