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Modeling and Optimization of Supply Chain Product Rollover Strategies

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ABSTRACT

Manufacturing companies operate in a fast-paced environment and accordingly, they must continuously respond to customers' requirements for improved and innovative products. The present research studies the application of solo and dual product rollover strategies in a supply chain that consists of manufacturers and distributors, with the focus on the production rollover strategies at the manufacturers echelon. A MILP model is developed for a multi-product multi-echelon multi-period supply chain with the objective of maximizing profit during period where the demand of the new product is replacing that of the old product through optimizing the sales, production, and inventory quantities, as well as the timing of the transition from the old to the new products in production and sales. The developed model considers the effect of demand, manufacturing capacity, inventory holing cost, selling prices, the opportunity cost of the lost sales, as well as the firm's choice of the production rollover strategy. The paper presents the results of a numerical example while considering a case of insufficient capacity and shows that dual production rollover strategy gives better results of total profit and average fill rate than the solo production rollover strategy. Finally, the study includes a sensitivity analysis carried out on the numerical example, from which it was found that the optimal solution for solo production rollover strategy is more sensitive than that of the dual strategy to the increase of the opportunity cost of lost sales as well as the increase in price ratio between the new and old products.

Keywords: Product rollover, new product development, product introduction, product elimination, decision model, substitute products, supply chain, mixed integer linear programming MLIP, pricing, timing

1. INTRODUCTION

Now-a-days, with the faster changing customer preferences and consumer demand patterns, along with the increased technological innovation pace, product life cycles are getting shorter and shorter. Product development is seen by businesses as a competitive advantage that will help them in market leadership. As a result, firms need to introduce new products with higher frequency than before.

Product rollover is the process for releasing a new product and subsequently discontinuing an older one. It was first defined by Billington et al [1].

There are basically two main strategies for withdrawing the old product and introducing the new product [1]. The first one is solo product rollover and the second one is dual product rollover. In solo product rollover, the withdrawal of the old product and the introduction of the new product are done simultaneously. That is, in this strategy, there is only one product in distribution and sales at any given point in time. In the dual product rollover strategy, on the other hand, the introduction of new product takes place before the withdrawal of the old product. In other words, there is a time window in which both products are being sold at the same time.

A product rollover needs to be properly managed throughout the whole supply chain to be successful. According to Katana et al [2], it is the responsibility of the manufacturer to plan the product rollover, and the communication and cooperation with all parties and echelons involved in the rollover execution is crucial. During product rollover, planning decisions get complicated by several factors such as the uncertainty in the demand during the transition phase, production lot sizes, long lead-times as well as the demand cannibalization during the introduction of the new product into the market. Despite the high frequency of new product launches, as Billington et al [1] states, there are many unsuccessful product launches that businesses go through. Poorly planned rollover may lead to high remaining inventory levels after end of production and discontinuation a product from the market causing huge waste costs.

According to Lim and Tang [3], the tradeoff related to the timing issues in product rollovers can be explained as follows: if the company launches the new product too soon, it may cannibalize the demand for the existing product, resulting in lower sales of the existing product. Conversely, if the firm introduces the newer product too late, then it sells the newer product later in the planning horizon and loses potential profit. Also, the firm risks losing potential customers who would want to purchase the old product if the firm phases out the old product too early, or might end up with more remaining inventory of the phased-out product as the customers shift to the newer product. In contrast, a too late phase-out of the old product could reduce the sales of the newer one.

While Billington et al [1] introduced the two strategies of product rollover from the sales in market perspective, Schwarz and Tan [4] differentiated between the market transition and the production transition by introducing the terms of sales rollover and production rollover strategies. They used the terms single sales rollover, dual sales rollover, single production rollover, and dual production rollover.

In this study, a MILP model is developed to find the product rollover optimal inventory and timing decisions in a multi-product multi-period multi-echelon supply chain that consists of manufacturers and distributers. The objective in this study is to integrate inventory, production, sales decisions, as well as the optimal transition time in production at the manufacturers echelon under a pre-determined production rollover strategy.

The results of a numerical example a case where the available capacity is insufficient are demonstrated. Furthermore, in this research, the impact of several parameters on the optimal timing of both the introduction of the new product and the withdrawal of the old product in production is studied under a sensitivity analysis. The parameters involved in this sensitivity analysis are the opportunity cost of lost sales as well as price ratio between the new and the old products, and how these parameters affect the optimal timing of both the launch of the new product and the withdrawal of the old product.

The remainder of the paper is organized as follows. Section (2) reviews the relevant literature. Section (3) presents the problem definition. Section (4) includes the proposed model. Section (5) presents the design of experiments for the numerical example. Section (6) presents the results and discussion for the numerical studies. Section (7) demonstrates the results of the carried-out sensitivity analysis. Conclusions and suggested future research points are included in section (8). Finally, references are listed in section (9).

2. LITERATURE REVIEW

Only recently has product rollover drawn the attention of researchers. It was first defined by Billington et al [1] in the first attempt to study the product elimination and introduction decisions together. They defined the process of product elimination followed by a product introduction as a product rollover. They introduced two main strategies of product rollover: solo and dual strategies, as well as focusing on the risks associated with each strategy.

An extension was provided by Erhun et al [5] in this stream by identifying the risk factors associated with product transitions categorizing them into supply and demand risks, as well as developing a framework to manage product transitions. Later, Billinger and Erhun [6] categorized the product rollover decisions to be timing, pricing, demand forecasting, and supply decisions.

While Billington et al [1], Erhun et al [5] and Bilinger and Erhun [6] studied the product transition with more focus on the marketing decisions side, Schwarz and Tan [4] looked into the critical decisions that need to be made when a manufacturing company is planning for a product rollover, and how to organize these decisions into a rollover framework that can be used for manufacturing companies. In their study, they focused on the decisions of supply chains and investigated the main challenges and risks related to these decisions. Their study categorized the rollover decisions into volumes, capacity allocation, timing of the rollover, and inventory.

Several studies were done in the stream that focused on the optimal pricing. Lim and Tang [3] studied the pricing and timing decisions during a product rollover in a deterministic environment. They derived the optimal pricing for products during a product rollover studying both the solo and dual product rollover strategies, as well as defining the optimal time of rollover. They studied the impact of customer loyalty factors on the duration of selling old and new products in a dual rollover. The study done by Liang et al [7] investigated the relationship between product rollover strategies and strategic customer purchasing behavior to determine the optimal pricing of the products and the best rollover strategy. They looked at the effect of the product's level of innovation on the performance of the rollover strategy in a two-period model where a monopolistic company sells an old version in the first period and introduces a new version in the second period under a solo rollover strategy.

The research of Arslan et al [8], the research studied a monopolistic company that uses a dual rollover strategy to introduce successive product generations. They developed a joint pricing model that determines the optimal pricing and product launch policies in the presence of consumer memory through reference prices. Ye et al [9] focused on the firm's optimal pricing decisions for the old and new products during a rollover while considering the impact of the level of innovation of the product. Their research compared between the two rollover strategies after finding the optimal product prices.

Fewer studies focused on the inventory, capacity and timing decisions related to rollover. The study of Lie et al [10] used dynamic programming to study the inventory decisions under a dual strategy for product rollover. Their model finds the optimal starting inventory quantities of the old and the new products before a dual product rollover when given a deterministic or stochastic rollover time. Later, Li et al [11] investigated the problem of capacity planning during a product transition where demand of the old product is being gradually replaced by a newer generation. They formulated a two-product capacity planning model to determine the optimal purchase of equipment while considering uncertain demand, inventory holding costs, equipment costs, and the flexibility of adding capacity. They develop a solution approach that allows for risk pooling and compare their results to the practices of capacity expansion taking place in Intel production lines. The study of Liao and Seifert [12] derived an analytical solution for the optimal frequency that firms can introduce new product generation to maximize the firm profit assuming that the firm introduces the newer generations at fixed intervals of time under a solo rollover strategy and a product development cost is charged for each product generation release.

More studies combined between the pricing decisions under a product rollover and the inventory, production, and timing decisions. Koca et al [13] studied the optimal choice of the solo or dual product rollover strategies considering final production of the old product and preannouncement of the new with the incorporation of inventory decisions and dynamic pricing assuming that the company is introducing new generations of products at fixed intervals of time.

Koca et al [14] developed an analytical model to find the optimal release date of a new product according to the novelty gap between the old and the new product along with the optimal product pricing and rollover strategy decisions. Their model introduces studying perceived obsolescence combined with product rollover. Their analysis is done on the market of digital goods and shows that the new product release time has a significant effect on the perception of the customer of the obsolescence of the old product, and that in the digital industry, the firm should always deploy a solo rollover and convince the customers to upgrade to the new products. However, multiple reasons can lead to the choice of rollover such as the high inventory levels of the old products, the capacity constraints, or the lack of obsolescence of the old product.

Schwarz and Tan [4] studied the production rollover in the case of finite capacity where the new and old products share the available capacity. They developed an analytical model to maximize the total profit of a company by finding the optimal sales and production quantities as well as the pricing of the new and old products in two planning periods: the pre-introduction period and the introduction period. Their model considers the increase in quality level, the different production costs, the holding cost, and the available capacity in the two planning periods. Using a numerical example, they find that in the case of sufficient capacity, the sales and production rollover strategies are aligned., while as the capacity decreases, the optimal prices increase, and a mismatch between the sales and production rollover strategy becomes optimal.

Kwon et al [15] developed am mixed-integer non-linear programming model to optimize the production plan and inventory quantities during a product transition by minimizing the total cost. Their model also optimizes the length of the production periods for the ramped-down and ramped-down products along with the period of overlap between the two generations while considering the number of setups needed, inventory holding cost, the needed learning in the production rate of the new product, and the variable capacity costs for expanding the capacity. Their model assumes that the capacity of the production resource is shared between both product generations. In their research, they carry out a sensitivity analysis to study the effect of change of demand pattern and the production rates on the total cost of product transition.

Some studies have considered supply chain optimization along with product rollover and new product development simultaneously. Li and Gao [16] studied the impact of information sharing in the supply chain on the pricing decisions during a solo product rollover. Their multi-period supply chain model includes a manufacturer and a retailer whose demand is uncertain. The model also considers the impact of bargain power of the retailer, salvage value of the old product and the holding cost on developing the optimal contract between the manufacturer and retailer. The contract includes the price for the non-obsolete product, buyback price for the obsolete product and price protection rate.

Amini et al [17] created a hybrid optimization model for configuring the supply chain of the new products while explicitly taking into account the effect of demand dynamics throughout the diffusion of new products. Their model concurrently determines the optimal production and sales plan which provides the optimal timing to introduce a new product, as well as the configuration of the supply chain that gives the optimal safety stock level to be kept at each supply chain function, as well as the optimal selection of options from different suppliers.

A multi-objective goal programming approach was presented by Nepal et al [18] for supply chain configuration during new product development. The model uses both production and inventory expenses in addition to other variables like firm compatibility while constructing the supply chain. During the creation of a new product, the supply chain configuration problem is solved using a genetic algorithm. Jafarian and Bashiri [19] investigated how the supply chain network is configured in an innovative environment where new product development has an impact on it while also taking the impact of supplier integration on the NPD process into account. Their model simultaneously optimizes the new product launching time and the supply chain's dynamic configuration which changes over the course of the planning horizon.

Afrouzy et al [20] developed a fuzzy stochastic multi-objective linear programming model to find optimal planning decisions for a multi-echelon multi-period multi-product supply chain under a product rollover maximizing the total supply chain profit, the service level through maximizing the met demand, and the new products in the system which was assumed to be indicated by maximizing the production of the new products in the system.

Papers in the literature studying timing and inventory decisions in the product rollover have their limitations. For example, Li et al [10] assumed no replenishment in the planning horizon without the possibility of demand backlog, while Liang et al [7] did not include the production capacity constraints and production lot sizes. Moreover, the model of Liao and Seifert [12] studied the optimal frequency of introducing a new product without considering inventory or production costs. Also, the stream that combines the new product introduction with supply chain decisions focuses more on new product introductions rather than product transitions. Compared to the present literature on product introductions, literature on product transitions is still limited. The model of Jafarian and Bashiri [19] only studied a solo transition from the old to the new product. Also, although the model of Schwarz and Tan [4] provides the optimal production and sales rollover strategies and studies the impact of available capacity on the product rollover, their model does not a multi-echelon or multi-period and cannot consider several manufacturers and retailers in the supply chain. Also, while Kwon et al [15] optimized the production plan according to the learning curve of the production rates for the ramped-up and ramped-down products, their model focuses only on the total cost from the production perspective and does not study the sales at the retailers or distributers echelon of the supply chain.

The papers of Jafarian and Bashiri [19], Afrouzy et al [20], are the only studies present in literature covering multi-product multi-period and multi-echelon supply chain decisions during a product rollover with considering capacity constraints. Both studies of Jafarian and Bashiri [19] and Afrouzy et al [20] focused only on solo rollover with a lot-for-lot production policy, while including the echelon of the suppliers of components and raw materials, and their models could not be used to compare between the dual and solo rollover strategies.

Despite the significance of product rollover, it has only been recently discussed in the literature. After reviewing the present literature, it was found that majority of product rollover literature focus on pricing decisions for the new products. Their focus is more management and marketing oriented, investigating the impact of competition, customer behavior, innovation level and demand cannibalization on the product rollover. However, inventory management, capacity planning and allocation, as well as supply chain design during a product rollover for the new product are not covered extensively in the literature.

In this work, a MILP model is developed to address the product rollover optimal inventory and timing decisions in a multi-product multi-period multi-echelon supply chain consisting of manufacturers, and distributers. This study aims to close the research gap in the field of product transition planning on the multi-echelon supply chain through presenting a mathematical model that can be used to optimize the production and sales plans in the multi-echelon supply chain with given flexibility to implement any of the pre-determined solo and dual production rollover strategies at the manufacturers echelon while considering the capacity constraints at the manufacturers. Also, the included analysis for the numerical example compares between the optimal solution under both strategies, as well as studying the impact of parameters of opportunity cost and price differences between the old and new products on the optimal solution under both strategies to help decision makers find the best rollover strategy according to the different conditions of operations.

3.PROBLEM DESCRIPTION

Due to continuous shifting preferences in the customers demand, companies strive to respond flexibly to the customers changes to get a competitive advantage in the marketplace. Normally, companies plan to replace existing products with new products or derivatives within the same product family whose development phase is completed and is ready to be introduced to the markets. By this replacement, the company will use the same production platform for the product family without any changes or modifications on the technology front.

Before this transition is implemented, the manufacturing company compares between the two production rollover strategies: solo and dual to choose which strategy to implement. In the solo rollover strategy, the manufacturers can produce either the old product or the new product per product group. As for the dual rollover strategy, the company can produce the new and old products simultaneously. After the rollover is completed, the remaining inventory of the old products become obsolete and is sold at salvage value at the end of the planning horizon.

The company aims to find the optimal new product introduction and old product phase-out times of production to maximize its profit weighing between the trade-offs of the different revenues of the old and new products, stockout costs due to capacity constraints and the holding costs of on-hand inventory.

The problem addressed in this paper is of a general nature facing the majority of companies who strive to continuously develop their products and substituting one for the other in response to market demand while using their same resources and technology platforms. The rollover decisions are to be studied for a hypothetical manufacturing company producing consumer goods within a multi-echelon supply chain model.

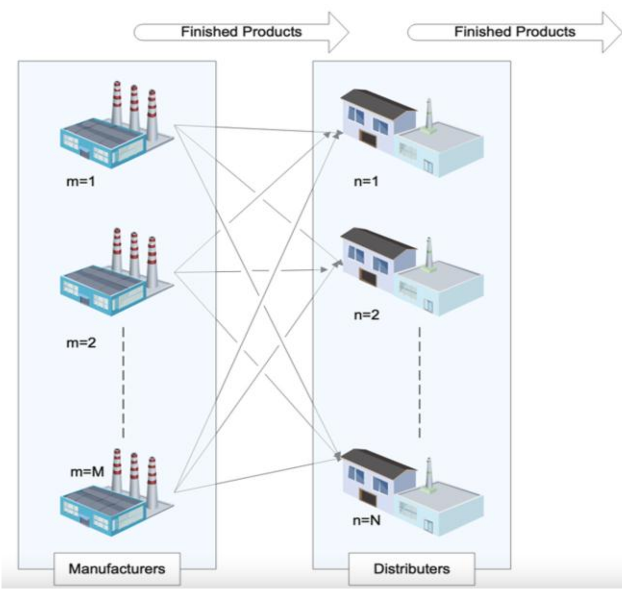


Figure 1: Supply Chain Model

The company produces mostly derivatives of products that belong to products' family on the same product platform within the company supply network (manufacturing facilities). The supply network consists of two echelons: manufacturers, and distributors. The company can produce one product at a time on the production platform. However, during any planning period, it can switch production from producing one product to another. The distributers are responsible for receiving customer orders and issue products' requisition form and forward it to manufacturing facility. The lead times and costs communicating between the supply chain echelons are assumed to be negligible. The manufacturing facilities have limited manufacturing capacity that can be shared between different product families.

The company policy allows distributors to keep inventory from all products to avoid the consequences of products unavailability. In case of product stockout at the distributers' echelon due to the applied rollover strategy or shortage in capacity, the company will suffer from stockout cost in terms of opportunity cost. This will also negatively affect the fill rate and hence customer satisfaction. Figure (1) shows a schematic model of the supply chain considered in the present work. The objective of the developed model is maximizing profit during the rollover period while considering a number of parameters such as, demand from each product, inventory holing cost, and selling price. The mathematical model is designed such that it can accommodate for any number of products, product families, manufacturing facilities and distributors, as well as number of planning periods.

<u>Model Assumptions:</u>

The following are the different assumptions considered in building the developed model:

- Within the study period, the company can adopt any of the two rollover strategies which are solo rollover and dual rollover.
- The optimization problem is capacitated and the required capacity to cover the demand of the two products may exceed the available capacity.
- The supply chain under consideration is a multi-product multi-period consisting of two echelons: manufacturers and distributers.
- The transportation lead times between the different echelons of the supply chain are considered insignificant.
- There are two types of products considered for manufacturing during the rollover period: (A) an old product that is being phased out and (B) a new product that is being phased in following one of the rollover strategies under consideration.
- Both new and old products are being produced on the studied rollover period on the same product platform.
- The products are manufactured entirely at the manufacturers' facility having limited capacity.
- The storage capacity in all the supply chain (SC) nodes is unlimited.

- The model considers inventory holding costs for the products at the manufacturers.
- The model does not consider the ordering and production lot sizes for moving, producing, and purchasing products between the different SC echelons.
- Stockouts may take place at the distributers' echelon. Stockouts incur additional lost sales charges.
- Remaining inventory at the end of the planning horizon from old finished products at the manufacturers echelon are sold at salvage value at the end of the planning horizon, while for new finished products, the remaining inventory is stored at the manufacturers and distributers echelon.

4. MILP FORMULATION

The supply chain under consideration is mathematically modeled in MILP format. This section presents the parameters, decision variables, and the proposed mathematical model for MILP.

The model indices are shown in table (1). The model input parameters are shown in table (2), and the list of decision variables in the model are shown in table (3).

Table 1: Indexing sets in the mathematical model

Indexing Set	
T	Number of periods in the planning horizon (t=0,1,2,.., T)
N	Number of distribution centers (n=1,2,3,..,N)
M	Number of manufacturing plants (m=1,2,3,…,M)
P	Number of finished products (p=2,4,6,…, P)
G	Number of product groups (g=1,2,3,…, G) G=P/2

The products are divided into two categories: old products that are being withdrawn from production, and new products that are being launched. The indices are as following, respectively:

$$p = \begin{cases} i\ (old), & i = 1 \dots G \\ j\ (new), & j = G+1 \dots P \end{cases}$$

Table 2: List of parameters in the mathematical model

Parameters	
DP_{pnt}	Demand of product p from product at distributer n in time period t
PC_{mt}	Production capacity at manufacturer m in time period t
$IIPM_{pm}$	Initial inventory of product p at manufacturer m
p_{pnt}	Selling price of product p at distributer n in time period t
pc_{pm}	Variable manufacturing cost of product p at manufacturer m per unit
sc_{pm}	Fixed setup cost of product p at manufacturer m per period
ecc_m	Cost of running under capacity per unit at manufacturer m
hc_{pm}	holding cost per period for product p at manufacturer m
sv_{pn}	Salvage value of product p at distributer n
$oppc_{pn}$	Opportunity cost of lost sales of product p at distributer n
rs_{mgt}	1 if the manufacturer m decides to produce only one product within product group g in time-period t (solo), 2 if the manufacturer m decides to produce two products of the same product group g concurrently in time-period t (dual)

Table 3: List of decision variables in the mathematical model

Parameters	
PP_{pmt}	Production Quantity of product p at manufacturer m in period t
TP_{pmnt}	Quantity of product p to be dispatched from manufacturer m to distributer n in time period t
RT_{pmt}	Binary variable to decide whether the manufacturer will produce for product p in time period t based on the chosen rollover strategy
$SQty_{pnt}$	Sales quantity of product p at distributer n in time period t
OOS_{pnt}	Stockout quantity of product p at distributer n in time period t
IPM_{pmt}	Ending inventory of product p in manufacturer m in time period t
SPD_{pn}	Quantity of product p that will be sold at salvage value at distributer n at the end of the planning horizon

Objective Function:

$$\begin{aligned} & Maximize \\ & Z = \textstyle\sum_n \sum_p \sum_t (p_{pnt} * SQty_{pnt}) \qquad (1) \\ & + \textstyle\sum_n \sum_p (sv_{pn} * SPD_{pn}) \\ & - \textstyle\sum_n \sum_p \sum_t (oppc_{pn} * OOS_{pnt}) \\ & - \textstyle\sum_m \sum_p \sum_t (hc_{pm} * IPM_{pmt}) \\ & - \textstyle\sum_m \sum_p \sum_t (pc_{pm} * PP_{pmt}) \\ & - \textstyle\sum_m \sum_p \sum_t (sc_{pm} * RT_{pmt}) \\ & - \textstyle\sum_m \sum_t (ecc_m * (PC_{mt} - \sum_p PP_{pmt})) \end{aligned}$$

The objective function in eq. (1) is to maximize the total net profit over the studied time horizon which is calculated as the sum of the revenues minus the sum of the incurred costs across the supply chain layers.

Constraints:

All constraints are represented by equations (2) – (12). Eq. (2) balances the demand quantity of product p at any time period with the sum of stockout quantity and sold quantity of the same product.

$$DP_{pnt} = OOS_{pnt} + SQty_{pnt} \qquad \forall\, p, n, t \qquad (2)$$

Eq. (3) ensures that the ending inventory of product p in manufacturer m in time-period t is equal to initial inventory of product p at manufacturer m at the initial time-period.

$$IPM_{pmt} = IIPM_{pm} \qquad \forall\, p, m, t = 0 \qquad (3)$$

Eq. (4) and eq. (5) represent the balance of the flow of products at each distributer. Since it is assumed that distributers do not hold inventory, eq. (4) shows the balance of flow in all periods of the studied planning horizon with the exception of the last period. The sold quantities at the distributer at each time period t equals the sum of quantities that are dispatched from the manufacturers m to the distributer n in the time period t.

$$SQty_{pnt} = \sum\nolimits_m TP_{pmnt} \qquad \forall\, p, n, m, \; t < T \qquad (4)$$

Eq. (5) represents the balance of the flow of products at each distributer in the last period of the studied planning horizon, as the sum of sold quantities at the distributer in the last time period T along with the quantity of products that will be sold at salvage value equals the sum of quantities that are dispatched from the manufacturers m to the distributer n in the time period T.

$$SQty_{pnt} + SPD_{pn} = \sum\nolimits_m TP_{pmnt} \qquad \forall\, p, n, m, \; t = T \qquad (5)$$

Eq. (6) represents the balance of the flow of products at each manufacturer.

$$PM_{pmt-1} + PP_{pmt} - \sum\nolimits_n TP_{pmnt} = IPM_{pmt} \qquad (6)$$
$$\forall\, p, n, m, t$$

Eq. (7) implements the product rollover strategy for each product group. In case a solo rollover for the period is chosen, only one product from the product group will be produced. In case of a dual rollover, the old and new products within the same product group can be produced simultaneously during the time period.

$$RT_{pmt} + RT_{(p+G)mt} = rs_{mgt} \qquad \forall\, g, n, m, t, p \in i \qquad (7)$$

Eq. (8) and (9) ensure that once the new product introduction is decided and the old product production is stopped, no old products production would be further planned, and only new products would be considered.

$$RT_{pmt} - RT_{pmt-1} \leq 0 \qquad \forall\, p \in i, m, \; t > 1 \qquad (8)$$

$$RT_{pmt} - RT_{pmt-1} \geq 0 \qquad \forall\, p \in j, m, \; t > 1 \qquad (9)$$

Eq. (10) ties between the production quantity of the finished products and the rollover decision at every time period t.

$$PP_{pmt} \leq RT_{pmt} * PC_{mt} \qquad \forall\, p, m, t \qquad (10)$$

Eq. (11) ensures that the total production would not exceed the available capacity at the manufacturer at every time period.

$$\sum\nolimits_p (PP_{pmt}) \leq PC_{mt} \qquad \forall\, p, m, t \qquad (11)$$

Finally, eq. (12) defines the quantities of finished products to be sold at salvage value at the end of the planning horizon.

$$\sum\nolimits_n (SPD_{pn}) = \sum\nolimits_m (IPM_{pmt}) \qquad \forall\, p, m, n, \; t = T \qquad (12)$$

5. DESIGN OF EXPERIMENTS

In order to validate the proposed model and demonstrate its practicality, an assumed numerical example is presented. The assumed supply chain is a simplified one that consists of a single distributer and a single manufacturer transitioning from one old product to a new product which both belong to one group of products in a 6-time-period planning horizon. This example considers a situation in which demand forecast is shifting from the old product to the new product during the planning horizon and the manufacturing company decides on the rollover time and production quantities of both the old and new products under the two rollover strategies: solo and dual. We compare between solo and dual rollover on the total profit, the time of introduction of the new product, as well as the fill rate resulting from each strategy. The input parameters of the example model are presented in tables (4) – (6).

The assumed numerical example considers capacity shortage where the total available capacity in the planning horizon covers only 70% of the total demand in the planning horizon.

For simplicity, the old and new products in the numerical example are assumed to be identical in their selling price, manufacturing cost, setup cost, and holding cost. However, the new product opportunity cost is double that of the old product to represent the pressure the company is facing to introduce the new product as soon as possible. It is assumed that there is no initial inventory of finished products, and that the salvage value of any of the products has no significant effect on profit. Table (4) shows the assumed demand for the new and old products at the distributor. Table (5) shows the available capacity in units at manufacturer. Table (6) enlists the model parameters for the numerical example at the distributer and manufacturer echelons.

Table 4: Demand input for the new and old products at the distributer.

	Period						
Product	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**Total**
Product A (Old)	1000	950	900	800	600	0	**4250**
Product B (New)	0	600	800	900	950	1000	**4250**
Total Demand	**1000**	**1550**	**1700**	**1700**	**1550**	**1000**	**8500**

Table 5: Available capacity in units at manufacturer. (Capacity deficiency)

Manufacturer Capacity (unit)	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**Total**
Available capacity	1000	1000	1000	1000	1000	1000	**6000**

Table 6: Model parameters for the numerical example at the distributer and manufacturer echelons.

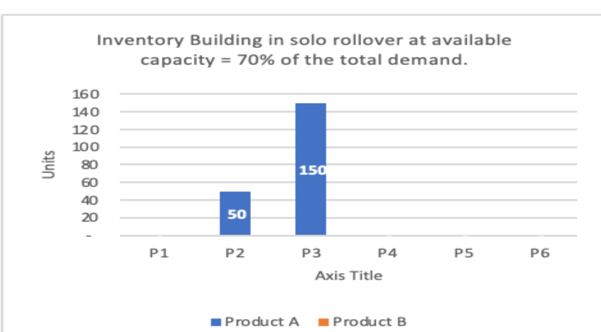
Echelon	**Parameter**	**Product A**	**Product B**
Distributer	**Selling Price (EGP/unit)**	10	10
	Opportunity Cost (EGP/unit)	1	2
Manufacturer	**Initial Inventory (Units)**	0	0
	Holding Cost (EGP/unit/period)	1	1
	Manufacturing Cost (EGP/unit)	5	5
	Setup Cost (EGP/run)	10	10
	Salvage Price (EGP/unit)	0	0
	Unutilized Capacity Cost (EGP/unit capacity)	1	

6. RESULTS AND DISCUSSION

The proposed model is a mixed-integer-linear programming model and is solved using LINGO software program. The solution establishes the production quantities, inventory quantities and lost sales quantities in each of planning periods. Furthermore, the model determines the optimal time at which the new product is phased into production and the optimal time at which the old product is phased out. The results of the optimal solution for both the dual and solo rollover strategies are demonstrated in this section. We compare between the solo and dual rollover in terms of the resulting production plan, introduction time of the new product, stored inventory of each product, lost sales of the old and new products, the fill rate, as well as the total profit elements.

The optimal solutions for production of product A and product B under both solo and rollover strategies in the case of capacity shortage, where the available capacity is 70% of the total demand in the full horizon. The results are shown in figure (2).

Under the solo rollover, the new product production starts in the fourth period. The optimal production plan pre-builds inventory of the old product in the second and third periods utilizing the capacity at 100% before shifting to the new product to reduce the lost sales of the old product after switching to production of the new product. On the other hand, in a dual product rollover, the new product is introduced once its demand starts in the second period. Capacity is fully utilized in the dual



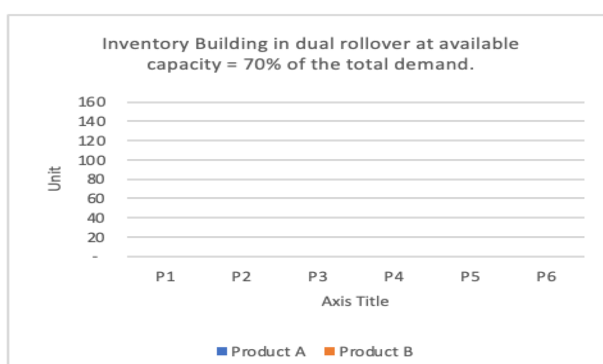


Figure 2: Inventory building in solo and dual rollover strategies at available capacity = 70% of the total demand.

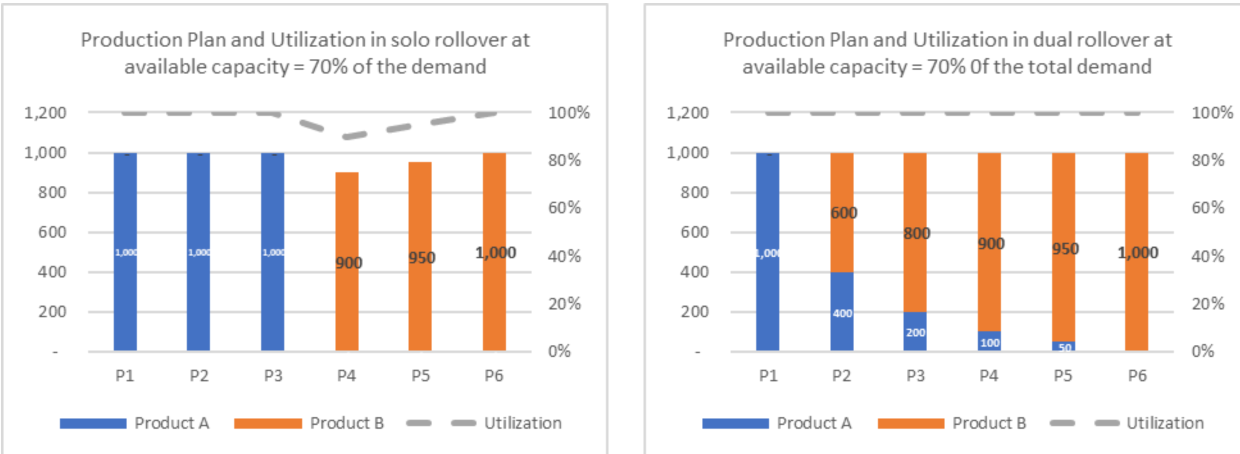


Figure 3: Production plan and capacity utilization in solo and dual rollover strategies at available capacity = 70% of the total demand.

Figure 4: Lost sales in solo and dual rollover strategies at available capacity = 70% of the total demand.

rollover strategy in all periods, and no products are produced and held as inventory for later sales as the produced products are sold in the same period of production. The inventory build of finished goods for the solo and dual rollover strategies is shown in figure (3).

Stockouts occur in both solo and dual rollover strategies and are shown in figure (4). In solo rollover, the stockout occurs from the new product due to the delayed introduction of the new product. Once the new product is introduced, the stockouts occur from the old product since the old product will be no longer produced. However, in the dual rollover, the optimal plan results in lost sales in the old product as the model prioritizes the production of the new product over the old product due to the higher opportunity cost. The average fill rate for both the old and new product under a solo rollover strategy is almost the same as under a dual rollover strategy as shown in figure (5). Solo rollover results in a higher fill rate for the old product due to the delayed introduction of the new product, but dual rollover results in 100% fill rate for the new product as the lost sales are all allocated on the old product.

The breakdown of all cost elements in the total profit function is shown in figure (6) for both the solo and product rollover strategies.

We find that in the case of capacity shortage, dual rollover provides higher total profit for the total supply chain. Quantities produced and sold in dual rollover strategies are higher, resulting in higher manufacturing costs, setup costs, as well as higher sales revenues than that in solo rollover yielding to a higher total profit.

In the assumed numerical example with a capacity shortage, dual rollover provides better service, lower stockout quantities, an earlier introduction for the new product, as well as a higher profit making it the more favorable option for decision makers.

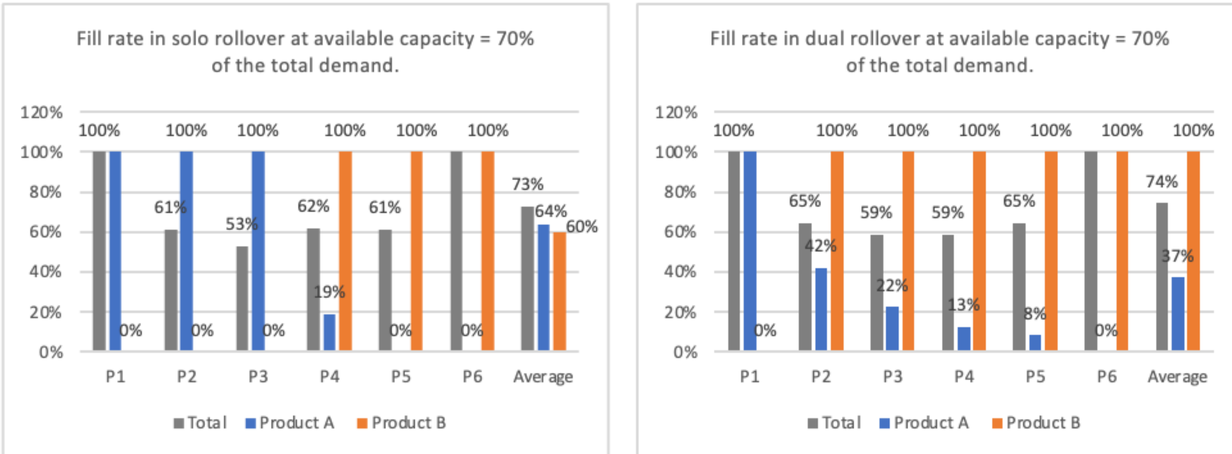


Figure 5: Fill rate in solo and dual strategies at available capacity = 70% of the total demand.

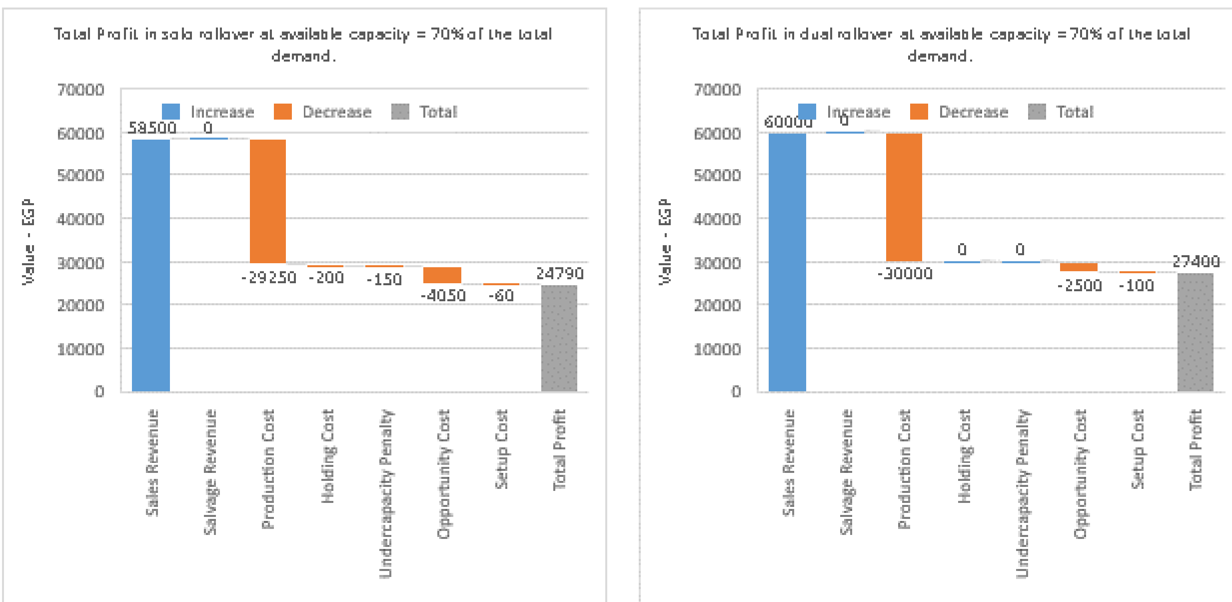


Figure 6: Profit elements in solo and dual rollover strategies at available capacity = 70% of the total demand.

7. SENSITIVITY ANALYSIS

A sensitivity analysis is carried out for the numerical example in this section to study the effect of changing the opportunity cost of the new product and the price difference between the old and new products on the optimal solution under both the solo and dual rollover strategies.

The available capacity is assumed to be leveled across the planning horizon. The available capacity is 1000 units per period, which represents the total available capacity being 70% of the total demand required for the two products.

The varying values of the opportunity cost and selling price of product B relative to that of product A in percentage are given in table (7). The performance of the applied strategy (solo or dual) is measured by the total profit, fill rate, new product introduction time in production at the manufacturer, average fill rate, and capacity utilization.

7.1 Opportunity Cost of the New Product

Opportunity costs present the potential advantages that a company forgoes while deciding between two alternatives. In the present case the alternatives are either applying solo or dual strategy. In this experimentation, the impact of the opportunity cost of the new product on the optimal solution is studied. The analysis is tested by changing the opportunity cost of the new the product from being 0% of the product price to 40% of the product price as provided in table (7). The opportunity cost of the old product is set as 10% of the product price along with keeping the other parameters the same as in table (6).

The impact of changing the opportunity cost of the new product on the total profit is shown in figure (7). It is evident that the total profit is more sensitive to increasing the opportunity cost in solo rollover than in dual rollover strategy. Also, as shown in figure (8), the average fill rate for dual rollover is constant, while it's declining for solo rollover.

In the case of dual rollover strategy, the optimal solution will prioritize the production of first product in the first In the case of dual rollover strategy, the optimal solution will prioritize the production of the first product in the first periods to increase sales revenue at zero opportunity cost. When the opportunity cost of the new product becomes equal or greater than that of the old product, the optimal solution will switch production from the old product to the new product keeping the capacity 100% utilized to maximize profit through increasing sales revenue.

The solution is not sensitive to the increase in the opportunity cost of the new product beyond the old product as optimal solution will always be to prioritize meeting the full demand of the new product and allocating the remaining capacity to the old product which is reflected in the constant opportunity cost beyond the 10% threshold of the opportunity cost of the new product in figure (10) and also reflected in the fill rate in figure (13).

Table 7: Model parameters sensitivity analysis for the numerical example at the distributer and manufacturer echelons.

Echelon	Parameter	value of product B: value of product A in percent				
Distributer	Opportunity Cost (percentage of the product price)	0%	10%	20%	30%	40%
	Selling Price (Ratio between the value of product B to product A in percentage)	60%	80%	100%	120%	140%

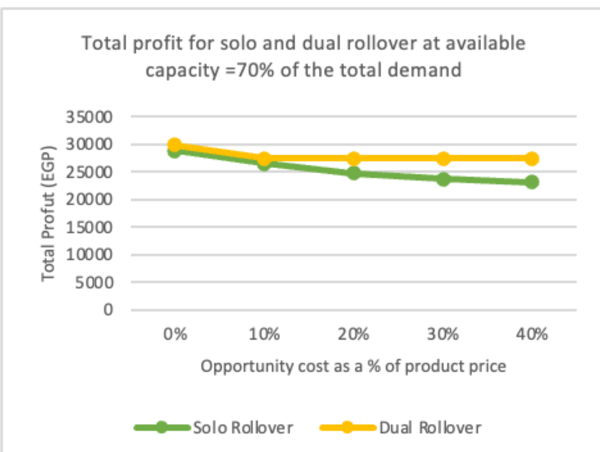


Figure 7: Total profit with varying opportunity cost at available capacity: = 70% of total demand.

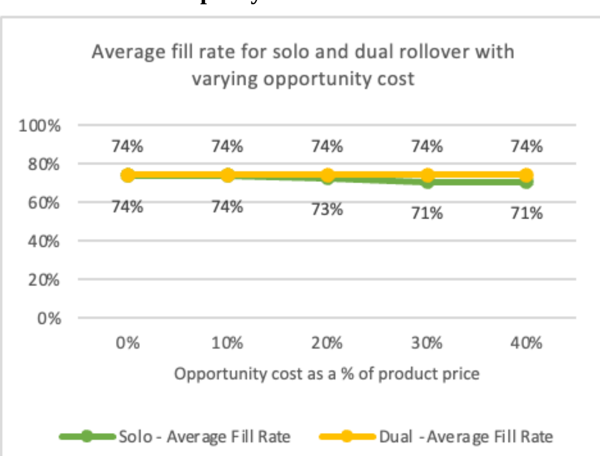


Figure 8: Average fill rate with varying opportunity cost at available capacity = 70% of the total demand.

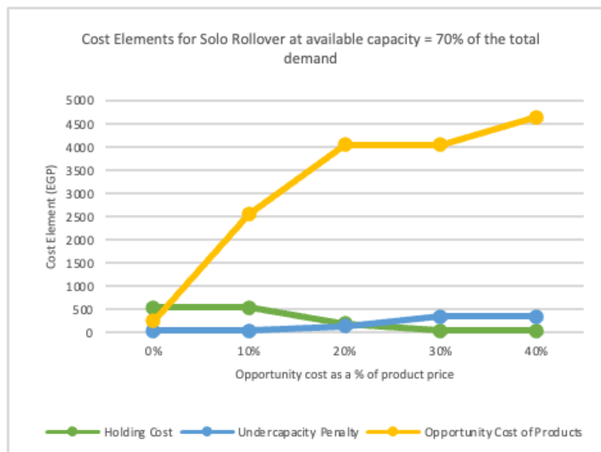


Figure 9: Cost elements of solo rollover strategy when varying the opportunity cost of the new product at available capacity = 70% of the total demand.

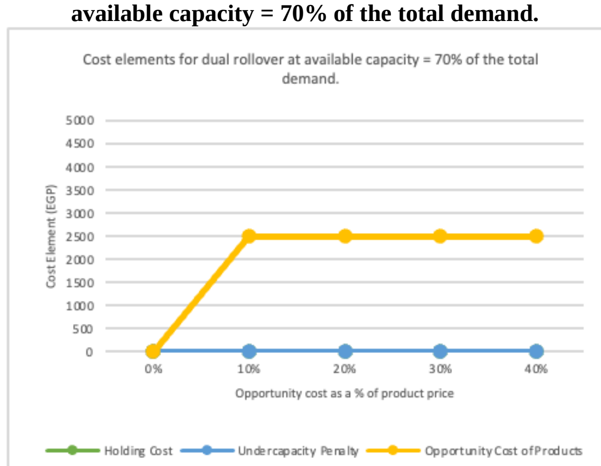


Figure 10: Cost elements of dual rollover strategy when varying the opportunity cost of the new product at available capacity: = 70% of the total demand.

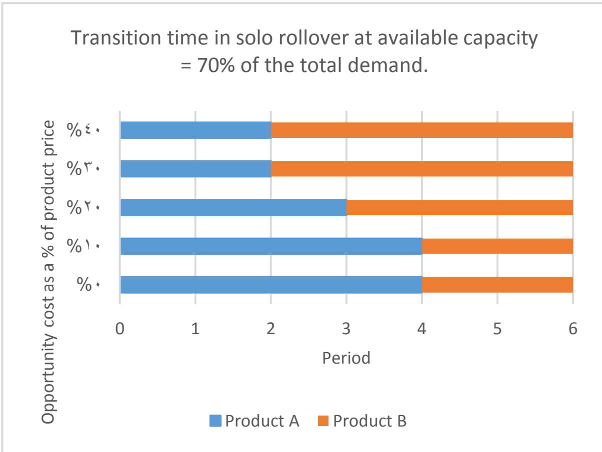


Figure 11: Transition time in solo rollover when varying the opportunity cost of the new product at available capacity case =70% of the total demand.

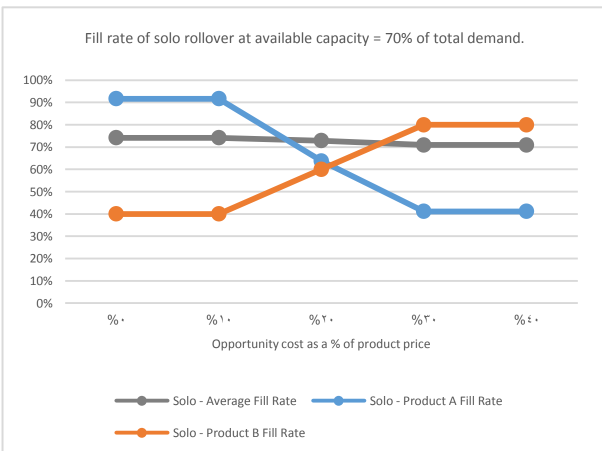


Figure 12: Fill rate of the old and new product for solo rollover with varying opportunity cost at available capacity =70% of the total demand.

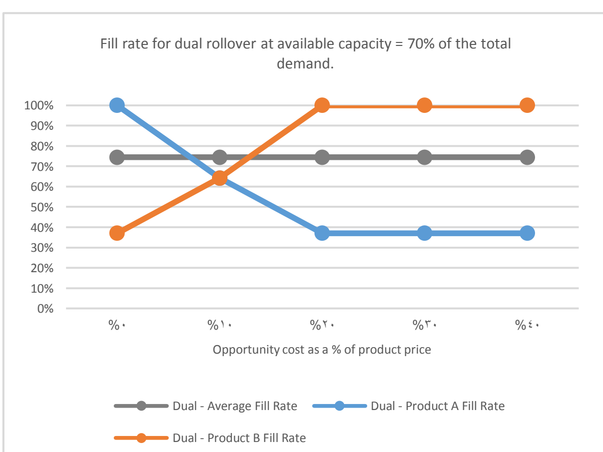


Figure 13: Fill rate of the old and new product for dual rollover with varying opportunity cost at capacity = 70% of the total demand.

As for the solo rollover when the opportunity cost of the new product is lower than or equal to that of the old product, the optimal solution tends to delay the introduction of the new product while producing the old product and building old product inventory to be sold after the new product transition occurs. As the opportunity cost increases beyond the old product, the optimal transition time to the new product becomes earlier to avoid the higher stockout cost as shown in figure (11). The impact of the earlier introduction on the fill rate is shown in figure (12). This leads to lower holding cost from inventory building of the old product as well as higher cost of unutilized capacity since the demand of the new product is lower in the first half of the planning horizon than that of the old product as shown in figure (9).

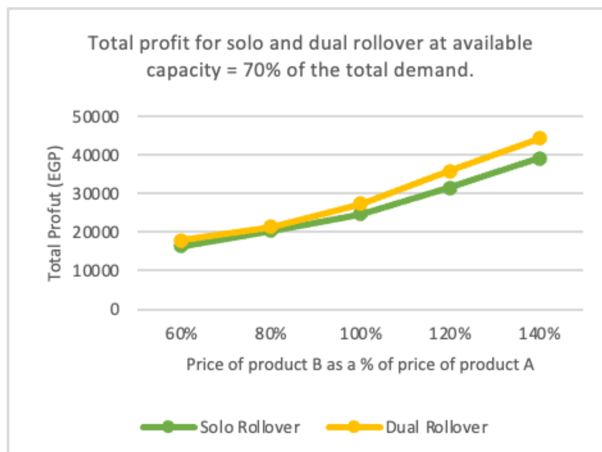


Figure 14: Total profit with varying the price of the new product at of available capacity: = 70% of the total demand.

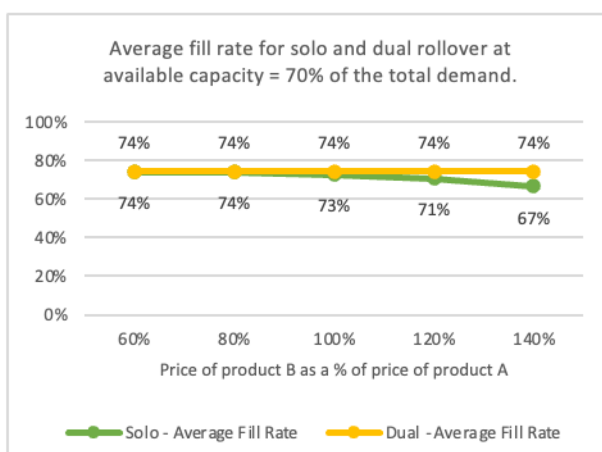


Figure 15: Average fill rate with varying new product price at available capacity case=70% of the total demand.

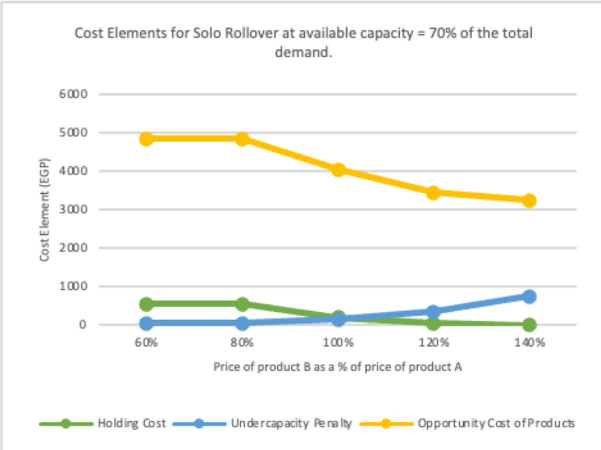


Figure 16: Cost elements of solo rollover strategy when

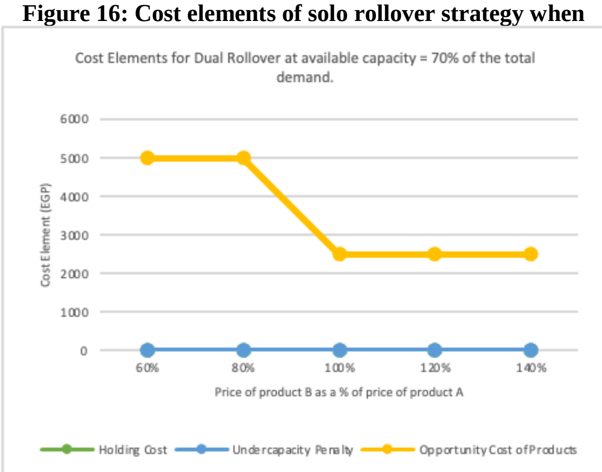


Figure 17: Cost elements of dual rollover strategy when varying the new product price available capacity: = 70% of the total demand.

7.2 Price ratio between the new product and the old product

In this experimentation, we study the impact of the price of the new product on the optimal solution. A sensitivity analysis is done by changing the price of the new product from being 60% to 140% of the price of the old product and their values are provided in table (7). The remaining parameters are the same as in table (6).

The impact of changing the price of the new product on the total profit is shown in figure (14). Intuitively, the total profit in rollover strategies is highly sensitive to the price of the products and will increase with the increase in the product price. However, it can be deducted from figure (15) that the average fill rate of the dual rollover is not sensitive to the price of the products, while in solo rollover as the price difference increases, the average fill rate declines. In the case of constrained capacity, under dual rollover strategy, the optimal production plan will change depending on the price of the new product. When the price of the new product is lower than that of the old product, the production of the old product will be prioritized in the optimal solution, leading to higher fill rate of the old product in figure (18) and higher opportunity costs as shown in figure (17) due to the lost sales of the new product. However, when the new product price is higher than that of the old product, the optimal solution will be to switch the allocation of the available capacity to the new product to increase the sales revenues, reduce the higher opportunity cost, and maximize the total profit. This is also reflected in the reduction in the opportunity cost for different product price in figure (17).

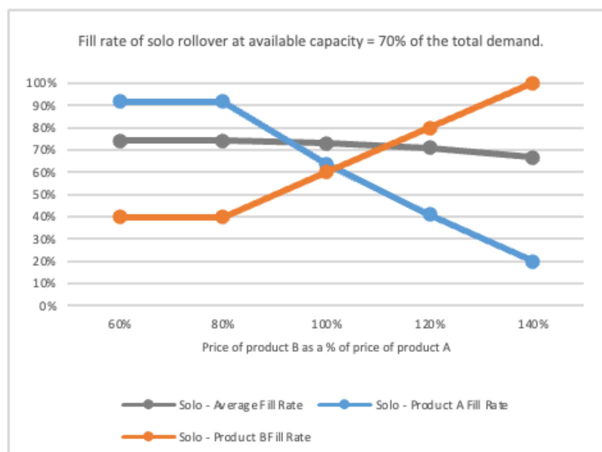


Figure 18: Fill rate of the old and new product for solo rollover with varying opportunity cost at available capacity =70% of the total demand.

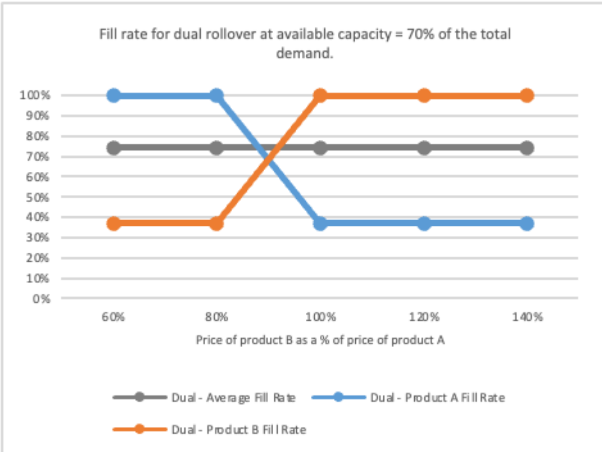


Figure 19: Fill rate of the old and new product for solo rollover with varying opportunity cost at available capacity =70% of the total demand.

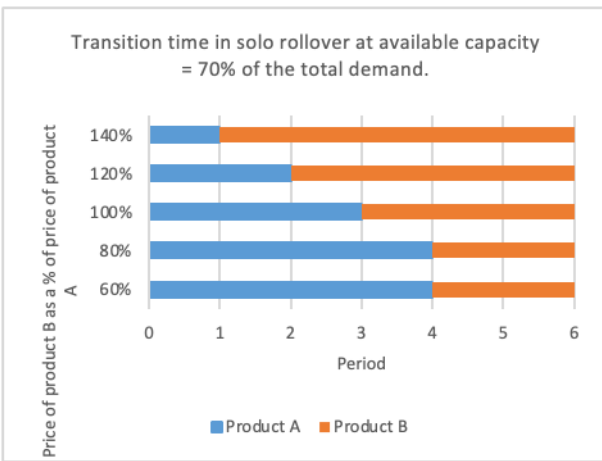


Figure 20: Transition time in solo rollover when varying the new product price at available capacity = 70% of the total demand.

As for the solo rollover when the capacity is constrained, as the price ratio of the new product to the old product increases, the optimal solution will be to introduce the new product earlier as shown in figure (20). The earlier transition results in higher cost of unutilized capacity as shown in figure (16) and lower holding cost since production of the new product starts when the demand of the old product is still higher to maximize the total profit through higher sales revenues. The impact of the earlier transition on the fill rate of the old and new products is shown in figure (18).

8.CONCLUSION

This study attempts to close the research gap in the stream of product rollover in a multi-echelon supply chain by presenting a multi-product multi-echelon MILP model that optimizes the tactical production, inventory, and timing decisions to maximize the total company profit. The presented model provides the decision maker with the optimal production quantities of each product per period, as well as the optimal production rollover time in production between the old and new products while considering the available capacity. Moreover, the presented model is the first to provide flexibility to choose between a solo and dual production rollover strategies at the manufacturer echelon for the decision maker.

This paper also presents the results of a numerical problem to validate the model results, as well as sensitivity analysis of parameters of the model, where the relationship between the parameters of price ration and opportunity cost and the optimal production plan, service level, as well as new product introduction time is demonstrated and discussed for both the solo and dual rollover strategies to help decision makers in their strategy choice.

The results demonstrated in this paper as an outcome from the numerical example under the case of capacity shortage show that the dual production rollover strategy provides better results for the manufacturing company undergoing the rollover execution as it results in an earlier introduction of the new product, lower inventory levels, higher fill rates, and higher profit.

Moreover, the sensitivity analysis shows that optimal production plan under a dual production rollover strategy is less sensitive than that under a solo production rollover strategy to the increase in opportunity cost of lost sales of the new product, as well as the increase in the price ratio between the new and old products. In a solo production rollover, as the opportunity cost of the new product increases, the introduction of the new product pulled earlier. The sensitivity analysis is presented for a case of insufficient capacity. It demonstrates that the optimal solution of total profit is sensitive to the increase in the price ratio between the new and old products when there is a case of capacity shortage.

Despite concluding that the dual production rollover is the better option for manufacturing firms over the solo rollover strategy and the optimal solution being less sensitive to the change in the studied parameters of opportunity cost of the new product and price ratio between the old and new product, there might be industry specific, production, sales, or legal constraints that force a company to pursue a solo rollover. The model presented in this paper helps the decision makers to analyze the costs breakdown within the supply chain coming from the optimal production plan by deploying the chosen production rollover strategy as an input parameter.

We suggest for future research to extend the model to include the components and raw materials that the finished products are composed of, as well as expanding the model to include the supplier's echelon. Future research can also investigate the obsolescence of the components and raw materials used in old generations, and its impact on the optimal introduction time of the newer generation under either a solo or dual production rollover strategy.

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