Optimal inventory control policy of a hybrid manufacturing-remanufacturing system using a possibilistic linear programming approach

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Abstract—**Remanufacturing is the process of converting used products back to like-new products. Production planning of inventory control policies in the remanufacturing of used products with different prioritizations (remanufacturing vs manufacturing) is investigated in this case study. For the hybrid manufacturing/remanufacturing production planning problem, the imprecision of customer demand, related operating costs, and the number of returned used components are considered to be the main uncertainty. As a result, the fuzzy set theory is employed due to the presence of the imprecise information. To defuzzify imprecise data, the Possibilistic Linear Programming (PLP) with the weighted average method is applied. The proposed approach maximizes the most likely value of the profit, minimizes the risk of obtaining a lower profit, and maximizes the possibility of obtaining a higher profit for each production planning policy at the same time. The result shows that the Priority-To-Remanufacturing (PTR) policy shows a higher profit from each objective function and is solved with a higher satisfaction value than the policy of giving more Priority-To-Manufacturing (PTM). For instance, the most likely profits of the PTR policy from each scenario are ranging from \$ 66,774 to \$ 114,280 as compared to \$ 66,610 to \$ 88,882 from the PTM policy and a higher satisfaction values of the linear membership function are ranging from 38.34% to 53.95% from the PTR policy as compared to 39.13% to 53.40% from the PTM policy. As a result, PLP can help decision makers to be well aware of the risks and effects of uncertainty on their plans, so they can prepare in advance for such scenarios.**

Index Terms—**Optimization, Hybrid manufacturing/remanufacturing, Possibilistic Linear Programming.**

I. INTRODUCTION

Many products such as electrical apparatus, toner cartridges, cellular phones, and automotive parts require remanufacturing for recovering components as raw materials to produce finished products [1]. Because of limited resources, remanufacturing of these used products is significantly growing in many countries. According to the Carbon Trust news, remanufacturing in the UK had a market potential of up to £5.6 billion, with benefits to improve business revenues, margins, and stability of supply [2].

Remanufacturing includes the processes of disassembly, cleaning, inspection, and sorting of used products before reassembling to new parts or new products. It can be divided into two groups. First, a stand-alone remanufacturing system is concerned with used products that are supplied for all demands. Second, a hybrid manufacturing/remanufacturing system can be used when remanufacturing is required to work along with the existing manufacturing processes where new components may only be required when there is a shortage of old or used components.

In remanufacturing processes, the uncertainty of quantity, timing, and quality of receiving used products dramatically increases the difficulty of production planning and inventory management. Planners need to make decisions on how many new components or how many used products are required and especially on when such orders should be placed. Moreover, customer demand and related operating costs are very much subject to uncertainty. Customer demand normally varies with time due to errors in forecasting, or lack of information while certain operating costs are difficult to be fixed in advance. To handle such issues, a certain approach can be used to optimize such problems under the uncertainty. Instead of using a typical linear programming where the uncertainty is disregarded, Possibilistic Linear

Programming (PLP) is one of the approaches that can be used to incorporate fuzzy data and optimize a problem. Our main contribution is to introduce the Possibilistic Linear Programming (PLP) model to optimize the profit of the production and inventory planning in a hybrid manufacturing/remanufacturing system can then recommend the best policy between the Priority-To-Remanufacturing (PTR) and Priority-To-Manufacturing (PTM) in an uncertain environment. A sensitivity analysis is carried out with many scenarios to investigate the effects of each policy under the different levels of weight for pessimistic, most likely or optimistic conditions.

The remaining paper is presented as follows. Section 2 presents a literature review. Section 3 shows the methodology for solving the stochastic model based on the Possibilistic Linear Programming model. Section 4 presents a case study of inventory control and optimization in a hybrid manufacturing/remanufacturing in an uncertain environment. Next, Section 5 shows the results and discussion. Section 6 then presents the conclusion.

II. Literature review

Lund (1985) illustrated remanufacturing as "an industrial process in which worn-out products are restored to like-new condition" [3]. The remanufacturing industry boomed during World War II because of insufficient resources. The automotive (industrial) sector has the most experience in remanufacturing [1]. Remanufacturing is a product recovery option. There are many recovery options such as reusing, repairing, refurbishing, and recycling [4]. Remanufacturing is a direct form of reuse that combines returned products, to resell them again like new products. The remanufacturing process can be separated into disassembling the returned products, cleaning disassemble parts, replacing or repairing any worn or damaged components, testing the quality of products, updating some parts of electro-electronic products, and reassembling the products. Products that pass remanufacturing testing can be considered to have the quality of "like-new" products [5].

According to [6], remanufacturing is normally managed under two business strategies: combined and dedicated models. The combined model is mostly applied in European countries. Remanufacturing and manufacturing are combined in the same line as a hybrid process. In contrast, the dedicated model is mostly applied in North America. It is considered a standalone remanufacturing line. For production planning and inventory control problems, attention is placed on different inventory policies such as periodic and continuous reviews. There are many complicated characteristics of remanufacturing such as the uncertain quality of returns and the need to balance the returns and new components with customer demand. Inderfurth demand found that the optimal inventory control policy for the hybrid manufacturing/remanufacturing system under strictly proportional costs and revenues is the order-up-to policy [7]. The system is constructed in a single-period with stochastic returns of used products and customer demand, to substitute remanufactured products with manufactured products when a shortage occurs. Wang investigated the optimal production strategy for short life cycle products with stochastic returned products and customer demand [8]. The objective was to minimize the total costs of this system. The optimal total costs are incurred when applying a mixed strategy, which is a mixture of remanufacturing, manufacturing, and disposal simultaneously. A significant decrease in the total cost can be obtained by setting the suitable values of manufactured products and the ratio of remanufactured products to returned products.

With the complication of inventory control policies, the optimal settings for the operating parameters in an inventory policy are required to obtain the maximum profit of the system. Optimization can be carried out by either analytical or heuristics models. The analytical models always give global optimal solutions but consume a longer running time. The heuristics optimization may provide only local optimal solutions, which can be good enough solutions, with a shorter running time. Proper solving method selection is a trade-off between solution quality and computational time. In addition, analytical models need the simplification of assumptions and provide static results. Without the uncertainties, solutions are compromised in real-world problems. Hence, the fuzzy logic is introduced to take care of uncertainties and to provide results that, can reflect real-world problems. As a result, fuzzy linear programming can provide practical optimal results under realistic circumstances [9].

In practice, input data or related parameters for production planning and control problems are imprecise/fuzzy, such as costs of operations, customer demand, and number of returned products. These imprecise/fuzzy data occur because some information is incomplete or uncontrollable. These problems cannot be solved and optimized by a traditional mathematical analytical model such as linear programming becasue it only operates under deterministic circumstances. To incorporate the uncertainty, introduced the fuzzy set theory into traditional linear programming problems. His study considered linear programming problems with fuzzy goals and constraints [10]. presented the theory of possibility, which is related to the theory of fuzzy sets by applying the concept of a possibility distribution as a fuzzy restriction, acting as an elastic constraint [11]. In addition, presented Possibilistic Linear Programming (PLP) in standard form with no equality constraints [12]. Then, applied two-phase PLP combined with the fuzzy Analytical Hierarchical Process (AHP) to optimize multi-objective linear programming [13]. Our study applies the PLP approach for solving the production planning and inventory control policy for hybrid manufacturing/remanufacturing with imprecise forecast demand, related operating costs, and number of returned components. The proposed approach attempts to maximize the most likely value of the imprecise total profits, minimize the risk of obtaining a lower profit, and maximize the possibility of obtaining higher profits for each policy simultaneously. This approach can provide realistic results, which are better than a typical deterministic approach as it can handle fuzzy data and recommend a range of possible optimal objective values. This helps decision makers to be aware of possible outcomes in all scenarios from the most likely, optimistic, and pessimistic cases. Therefore, decision makers can well prepare themselves in advance for such scenarios

III. Methodology

Two optimization solving methods are introduced to measure their performances on a hybrid manufacturing/remanufacturing system in an uncertain environment. The system is modeled with both deterministic and stochastic conditions, using

Mixed-Integer Linear Programming (MILP) and Possibilistic Linear Programming (PLP), respectively. Fig. 1 shows the approach for each solving method.

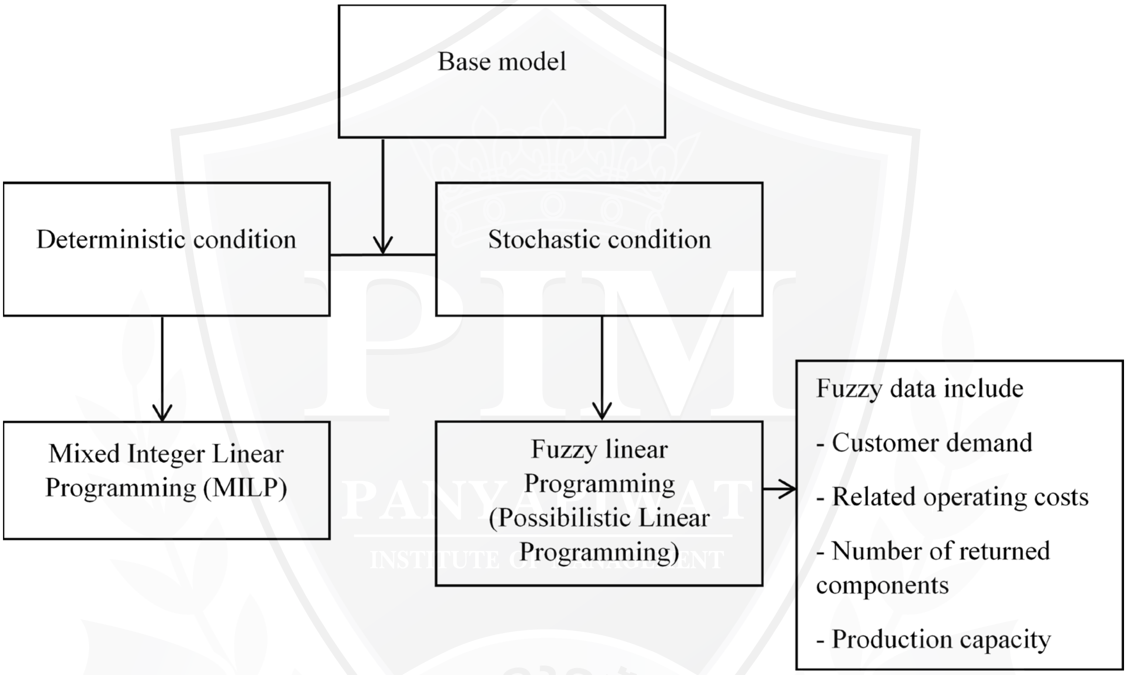

Fig. 1. Method of approach.

A. Deterministic condition using MILP

The system is modeled, and the profit of the model is optimized using MILP. There is no uncertainty in this situation. As a result, the ideal solution from this method is be used as a benchmark for a comparison.

B. Stochastic condition using PLP

The PLP method can handle a problem with uncertainty. An uncertain environment in this case contains uncertain customer demand in each week, related operating costs, and number of arriving returned components in each week. The PLP converts these uncertain/fuzzy data to crisp data. There are four main steps to solve the PLP:

1) Model the uncertainty data with triangular (possibility) distribution

Figure 2 presents the triangular distribution of an uncertain coefficient $\tilde{x} = \left(x^P, x^M, x^O\right)$.. In general, the triangular distribution is based on the three important data values as follows.

1.1) The most pessimistic value (x^P) that has the lowest possibilistic degree for the set of available values (possibilistic degree = 0)

1.2) The most likely value (x^M) that has the highest possibilistic degree for the set of available values (possibilistic degree = 1)

1.3) The most optimistic value (x^O) that has the lowest possibilistic degree for the set of available values (possibilistic degree = 0)

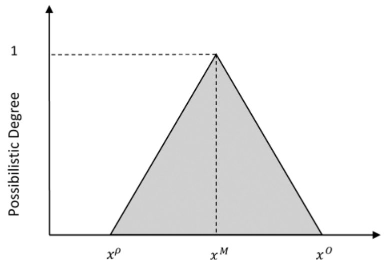

Fig. 2. Triangular possibility distribution of $\tilde{x}$

2) Develop three new crisp objective functions of multi objective linear programming (MOLP)

The imprecise objective function in this model has a triangular distribution $\tilde{z} = \left(z^P, z^M, z^O\right)$. This imprecise objective function is defined by three important points $\left(z^P,0\right),\left(z^M,1\right)$, and $\left(z^O,0\right)$. The imprecise objective can be maximized by pushing three important points to the right. Because the vertical coordinate of important points is fixed at either 1 or 0, only three horizontal coordinates are considered. Solving the imprecise objective requires simultaneously maximizing z^P, z^M, and z^O. Instead of simultaneously maximizing z^P, z^M, and z^O, the proposed approach maximizes the profit z^M, minimizes the range of the profit of (z^M-z^P) and, maximizes the range of the profit of (z^O- z^M). This proposed approach involves maximizing the most likely value of the imprecise total profit z^M, minimizing the risk of obtaining a lower profit (z^M-z^P), and maximizing the possibility of obtaining a higher profit (z^O- z^M). Fig. 3 presents the strategy for maximizing the imprecise objective functions.

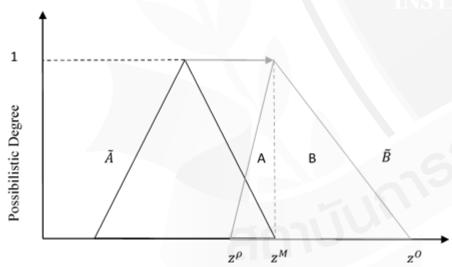

Fig. 3. Strategy for maximizing the imprecise objective function

As presented in Fig. 3, the possibility distribution $\tilde{A}$ is preferred to the possibility distribution $\tilde{B}$. The results for three new crisp objective functions are presented as follows:

Max $z_1 = z^M$ (1)

Min $z_2 = (z^M\text{-}z^P)$ (2)

Max $z_3 = (z^O\text{-}\ z^M)$ (3)

Equation (1) to Equation (3) are equivalent to simultaneously maximizing the most likely value of the total profit, minimizing the risk of obtaining a lower profit (area A of the possibility distribution in Fig. 3), and maximizing the possibility of obtaining a higher profit (area B of the possibility distribution in Fig. 3).

3) Convert uncertainty constraints into crisp constraints using the weighted average method

We consider the situation where the number of returned products, related operating costs, and customer demand are uncertain and have the triangular distribution with the most likely and least possible values. The problem is to obtain crisp numbers for the uncertainty of the number of returned products, related operating costs, and customer demand by applying the weighted average method to convert them into crisp values, where w_1, w_2, and w_3 denote the weight of the pessimistic, most likely, and optimistic cases respectively. The weights w_1, w_2, and w_3 can be determined by the experience of decision makers and $w_1 + w_2 + w_3 = 1$.

4)Specify the linear membership functions for three new objective functions, and then convert the auxiliary MOLP problem into an equivalent linear programming model using the fuzzy decision method

4.1) Find the lower bound and the upper bound of each objective

To convert the auxiliary MOLP problem into an equivalent single-goal linear programming problem, the fuzzy decision method from [10], and the [14]. fuzzy programming method are employed. The Negative Ideal Solution (NIS) and Positive Ideal Solution (PIS) of three objective functions from step two are required. Three new crisp objective functions of the multi objective linear programming can be stated as follows:

$z_1^{PIS} = \max z^M,\ z_1^{NIS} = \min z^M$ (4)

$z_2^{PIS} = \min (z^M\text{-}z^P),\ z_2^{NIS} = \max (z^M\text{-}z^P)$ (5)

$z_3^{PIS} = \max (z^O\text{-}\ z^M),\ z_3^{NIS} = \min (z^O\text{-}\ z^M)$ (6)

4.2) Find the corresponding linear membership function of each objective function

The corresponding linear membership function for each objective function is defined by

$$f1(z1) = \begin{cases} 1 & , z_1 < z_1^{PIS}, \\ \dfrac{z_1 - z_1^{NIS}}{z_1^{PIS} - z_1^{NIS}} & , z_1^{NIS} \le z_1 \le z_1^{PIS}, \\ 0 & , z_1 > z_1^{NIS}, \end{cases} \tag{7}$$

$$f2(z2) = \begin{cases} 1 & , z_2 < z_2^{PIS}, \\ \dfrac{z_2^{NIS} - z_2}{z_1^{NIS} - z_2^{PIS}} & , z_2^{PIS} \le z_2 \le z_2^{NIS}, \\ 0 & , z_2 > z_2^{NIS} \end{cases} \tag{8}$$

$$f3(z3) = \begin{cases} 1 & , z_3 < z_3^{PIS}, \\ \dfrac{z_3 - z_3^{NIS}}{z_3^{PIS} - z_3^{NIS}} & , z_3^{NIS} \le z_3 \le z_3^{PIS}, \\ 0 & , z_3 > z_3^{NIS}. \end{cases} \tag{9}$$

Each linear membership function can be obtained by using a case study to specify an imprecise objective value in an interval (0-1). Fig. 4. shows a graph of the linear membership functions for Equation (7) and Equation (9). Fig. 5. shows a graph of the linear membership functions for Equation (8).

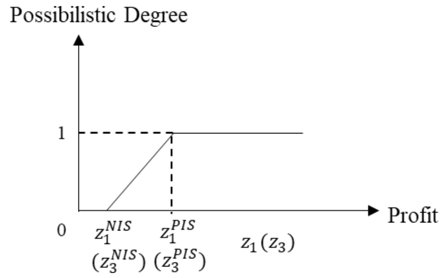

Fig. 4. Linear membership function of z_1 and z_3.

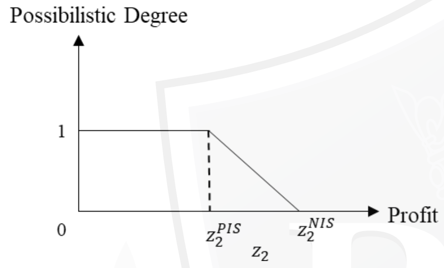

Fig. 5. Linear membership function of z_2.

4.3) Find the maximum overall satisfaction

The fuzzy decision method from [10]., and [14]. is used to formulate a single goal linear programming model, which is minimax of the satisfaction values from the three above mentioned objective functions.

Max **λ**

Subject to

$\lambda \leq f_i(z_i)$, $i = 1,2,3$

$0 \leq \lambda \leq 1$

i = number of linear membership functions of each objective.

IV. Case Study

For this case study of production planning and inventory control optimization in a hybrid manufacturing/remanufacturing in an uncertain environment, Fig. 6 shows a flow diagram of the system. It requires two types of components for production: new components and returned components. Returned components indicate the used parts that are returned from customers. Returned components use the reorder cycle policy to control their inventory, as returned components come in a batch at the beginning of each week. A certain percentage of returned components need to be disposed of to prevent excess inventory. Accepted returned components are then kept in a Returned Component Inventory (RCI), pending for the remanufacturing processes. It is assumed that the remanufacturing time of the returned components is negligible. However, the remanufacturing cost per unit can be more expensive than the manufacturing cost per unit depending the quality of the returned components as poor-quality components could incur more expense to produce.

There is also a New Component Inventory (NCI), which is also reviewed every week. The ordering lead time for the new components is constant at one week. Upon arrival, these new components are kept in the NCI before they are used in the manufacturing processes. One calendar week is considered for a manufacturing week. Finished products are then kept in a Finished Product Inventory (FPI), waiting for the customer demand.

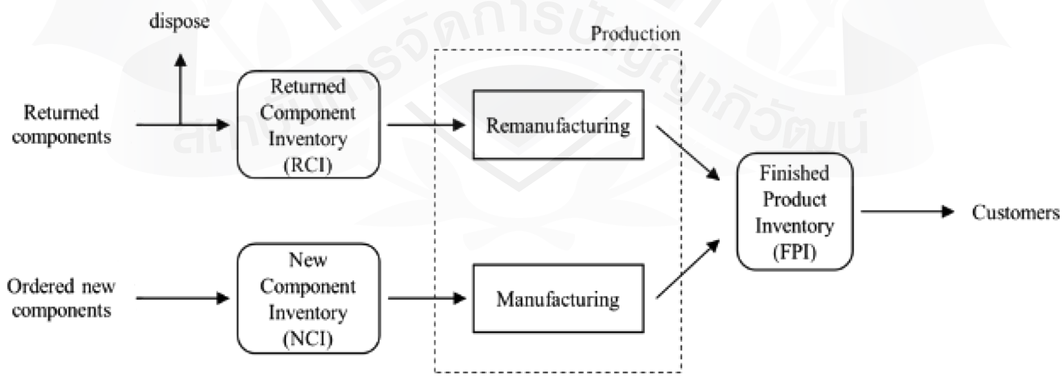

Fig. 6. General flowchart of the studied system.

Customer demand arrives every week. Lost sales cost incurs when there are not enough finished products. Otherwise, customers buy the finished products from the FPI. For finished products, the quality from manufacturing and remanufacturing is considered to be the same. When the inventory level of the FPI is reduced, the system requests for the production. The purpose is to fill back the inventory level of the FPI. The initial inventory quantity is set to be equal to the FPI target inventory level, which is one of the decision variables. Two inventory control policies (Priority-To-Remanufacturing vs Priority-To-Manufacturing) are experimented here to decide which process (remanufacturing vs manufacturing) has a higher priority. As shown in Fig. 7, the operation flow of each policy is shown as follows:

A. Priority-To-Remanufacturing (PTR)

With priority-to-remanufacturing, returned components are assigned with a higher priority than new components unless they are not available. Manufacturing production is provoked only when there are not enough returned components in the RCI. The interested controlled decision variables in this policy include Disposal Rate (disR), Target Inventory Level of NCI (TinvN), and Target Inventory Level of FPI (TinvF). Certain returned components are disposed of depending on disR. Then, new components are ordered up to TinvN in every review cycle (a week). The initial inventory level of NCI is set to be equal to TinvN. When finished products are sent to customers, upstream components are pulled to replenish the taken products by filling the FPI back to TinvF where the initial inventory level of FPI is equal to TinvF.

B. Priority-To-Manufacturing (PTM)

In contrast to PTR, new components are assigned with a higher priority over returned components. Returned components are used for production only when there is a shortage of new components. Inventories are regulated by the decision variables, similar to PTR.

The system is investigated for one year or (50 weeks). With 5 days a week and 8 hours a day, there are 40 hours a week. Table 1 presents the cost structure. Other relevant information is described below.

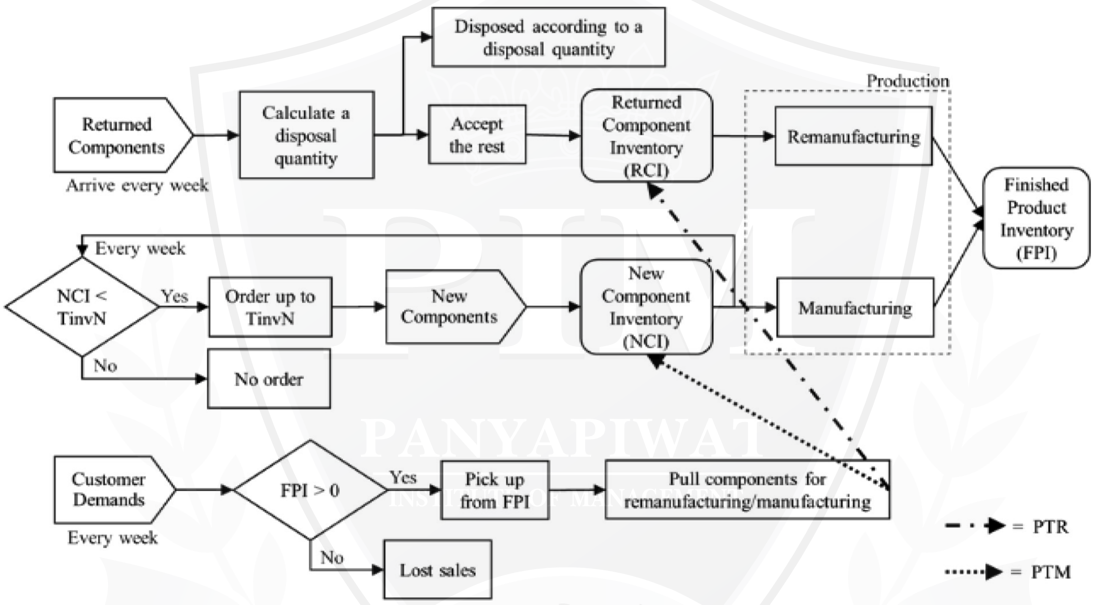

Fig. 7. Flow diagram of the PTR and the PTM policies.

C. Other relevant information

1) The maximum levels of the target inventory for new component inventory and finished product inventory depend on the maximum of production capacity, which is subject to uncertainty.

2) The overall customer service level in this case study is set to at least 85%.

3) The returned component ratio is set at 0.6: This ratio presents arriving returned components per total customer demand. Both arriving returned components and total customer demand distribute under the normal distribution in an uncertain environment. The means and standard deviations for the arriving returned components is 60 and 10 units per week, consecutively and for total customer demand is 100 and 20 units per week, consecutively.

4) A supplier has the ability to send new components, but not more than 60 units per week.

5) The holding cost is 40% per year for a unit (i.e., new component cost, returned component preparation cost, finished product cost). It is assumed that the finished product holding costs per unit of both manufacturing (FHm_y) and remanufacturing (FHr_y) products are the same based on the average unit cost value from both types of products.

6) The symbol "~" refers to ambiguous data that are determined to be fuzzy in this study

TABLE I
Cost structure

Parameters	Notation	Cost ($ per unit)
Returned component disposal cost	RD_u	0
New component cost	NC_u	(26,30,35)
Returned component preparation cost	RP_u	(4,5,7)
Manufacturing cost	MM_u	(9,10,13)
Remanufacturing cost	RM_u	((9*(2-y), (10*(2-y)), (13*(2-y)) *
Returned component holding cost	RH_y	(1.6,2,2.4) per year
New component holding cost	NH_y	(10,12,15) per year
Finished product holding cost (from returned components)	FHr_y	(9.5,11,14) per year
Finished product holding cost (from new components)	FHm_y	(9.5,11,14) per year
Lost sales cost	LS_u	(45,50,58)
Sales price	$Price_u$	(45,50,58)

Remark: * y is the yield of returned components, which is set equal to (0.3,0.65,1). For example, the remanufacturing cost of the most likely case is calculated as (10*(2-0.65)) = $ 13.5 per unit.

LP formulation (Deterministic case)

The mathematical model presented in this case study is formulated as the linear programming model. Notations and the formulation of the analytical model are presented below where t refers to the time in weeks, ranging from 1 to 50.

D. Parameters

ReA_t = Arriving returned components in week t
$dispose_t$ = Returned components (disposed of) in week t
$R0_t$ = Returned components accepted to inventory in week t
RCI_t = Ending inventory level in the Returned Component Inventory (RCI) in week t
$R1_t$ = Returned components sent to remanufacturing in week t
$R2_t$ = Finished products from remanufacturing in week t
$FPIr_t$ =Ending inventory level in Finished Product Inventory (FPI) from remanufacturing in week t
$R3_t$ = Finished products from remanufacturing sent to customer in week t
$order_t$ = New components ordered in week t
NCI_t = Ending inventory level in the New Component Inventory (NCI) in week t
$M1_t$ = New components sent to manufacturing in week t
$M2_t$ = Finished products from manufacturing in week t
$FPIm_t$ = Ending inventory level in the Finished Product Inventory (FPI) from manufacturing in week t
$M3_t$ = Finished products from manufacturing sent to customer in week t
FPI_t = Ending inventory level in the Finished Product Inventory (FPI) in week t
D_t = Customer demand in week t
LS_t = Lost sales in week t
PC_t = Production capacity to produces a product in week t
Cost parameters ($)
RD = Total returned component disposal cost
LS = Total lost sales cost
RMM = Total remanufacturing and manufacturing cost
NC = Total new component cost
RP = Total returned component cost
CH = Total component holding cost
FH = Total finished product holding cost
TC =Total costs
Revenue = Total income from selling finished products
Profit = Total income after deducting total costs

E. Decision Variables

$TinvN$ = Target inventory level in NCI (unit)
$TinvF$ = Target inventory level in FPI (unit)
$disR_t$ = Disposal rate in week t (%)

F. Objective Function:

$$Maximize\ Profit = Revenue - TC \tag{10}$$

subject to
inventory balance constraints:

$$ReA_t = (disR_t * ReA_t) + R0_t \quad for\ all\ t \tag{11}$$

$$R2_t = R1_t \quad for\ all\ t \tag{12}$$

$$M2_t = \begin{cases} 0 & where\ t = 1 \\ M1_{t-1} & where\ t = 2\ to\ t = 50 \end{cases} \tag{13}$$

$$R3_t + M3_t + LS_t = D_t \quad \text{for all } t \tag{14}$$

$$FPI_t = FPIr_t + FPIm_t \quad \text{for all } t \tag{15}$$

$$PC_t \geq R1_t + M1_t \quad \text{for all } t \tag{16}$$

$$RCI_t = \begin{cases} R0_t - R1_t & \text{where } t = 1 \\ RCI_{t-1} + R0_t - R1_t & \text{where } t = 2 \text{ to } t = 50 \end{cases} \tag{17}$$

$$NCI_t = \begin{cases} TinvN - M1_t & \text{where } t = 1 \\ NCI_{t-1} + order_{t-1} - M1_t & \text{where } t = 2 \text{ to } t = 50 \end{cases} \tag{18}$$

$$FPIr_t = \begin{cases} R2_t - R3_t & \text{where } t = 1 \\ FPIr_{t-1} + R2_t - R3_t & \text{where } t = 2 \text{ to } t = 50 \end{cases} \tag{19}$$

$$FPIm_t = \begin{cases} TinvF - M3_t & \text{where } t = 1 \\ FPIm_{t-1} + M2_t - M3_t & \text{where } t = 2 \text{ to } t = 50 \end{cases} \tag{20}$$

where ReA_t, and D_t are uncertainty coefficients with the triangular distribution. The objective function (constraint (10)) is to maximize the profit. Constraint (11) and Constraint (12) are inventory balance constraints. For Constraint (11), some of the returned components are disposed of depending on the disposal rate in every week, and the rest is sent to the Returned Component Inventory (RCI). Constraint (12) ensures that the quantity of returned components sent to remanufacturing processes are the same quality as the finished products coming out of the remanufacturing processes within the same week and the remanufacturing time is negligible. Constraint (13) states that the manufacturing lead time is one week. For Constraint (14), customer demand is satisfied by the finished products, otherwise, lost sales occur. For Constraint (15), total units of finished products in manufacturing and remanufacturing are combined in the FPI. Constraint (16) describes the constraint of production capacity for remanufacturing and manufacturing, in which the number of components sent to the manufacturing process must be less than or equal to the production capacity. Constraints (17) to (20) describe the constraints for returned components, new components, and finished products for remanufacturing and manufacturing. The ending inventory is equal to the previous ending inventory (week) plus the incoming inventory minus the outgoing inventory. In the first week, the ending inventory is equal to the incoming inventory minus the outgoing inventory.

G. The PTR constraints:

$$RCI_t = \begin{cases} 0 & \text{if } D_t \geq R0_t & \text{where } t = 1 \\ 0 & \text{if } D_t \geq R0_t + RCI_{t-1} & \text{where } t = 2 \text{ to } t = 50 \\ \text{any integers} & \text{otherwise} & \text{for all } t \end{cases} \tag{21}$$

$$R0_t = \begin{cases} D_t & \text{if } D_t < ReA_t & \text{for all } t \\ ReA_t & \text{if } ReA_t < D_t & \text{for all } t \end{cases} \tag{22}$$

$$R1_t = \begin{cases} D_t & \text{if } D_t < R0_t + RCI_{t-1} & \text{for all } t \\ \text{any integers} & \text{otherwise} & \text{for all } t \end{cases} \tag{23}$$

where ReA_t, and D_t are uncertain coefficients with the triangular distribution. Constraints (21) and (23) describe the policies of the PTR. All returned components in RCI are sent to remanufacturing when the customer demand is greater than the incoming returned components plus the number of the previous week's ending inventory. Otherwise the number of returned components sent to remanufacturing is equal to the customer demand.

H. The PTM constraints

$$NCI_t = \begin{cases} 0 & if\ D_t \geq TinvN \quad where\ t = 1 \\ order_{t-1} & if\ D_t \geq NCI_{t-1} \quad where\ t = 2\ to\ t = 50 \\ any\ integers & otherwise \quad for\ all\ t \end{cases} \tag{24}$$

$$M1_t = \begin{cases} D_t & if\ D_t < NCI_{t-1} \quad for\ all\ t \\ any\ integers & otherwise \quad for\ all\ t \end{cases} \tag{25}$$

where D_t are uncertain coefficients with the triangular distribution. Constraints (24) and (25) describe the policies of the PTM, where the number of new components in the NCI that is sent to manufacturing is equal to the customer demand when it is less than the number of new components. Otherwise, all of the returned components are sent to manufacturing. The ending level of inventory in the NCI is equal to the incoming orders from the previous week when the customer demand is greater than the previous period's ending inventory level.

I. Economic constraints

$$RD = \sum_t RD\_u * dispose_t \quad for\ all\ t \tag{26}$$

$$LS = \sum_t LS\_u * LS_t \quad for\ all\ t \tag{27}$$

$$RMM = \sum_t RM\_u * R1_t + \sum_t MM\_u * M1_t + MM_u * TinvF \quad for\ all\ t \tag{28}$$

$$NC = \sum_t NC_u * \left(order_t + initial\ NCI + TinvF\right) \quad for\ all\ t \tag{29}$$

$$RP = \sum_t RP\_u * R0_t \quad for\ all\ t \tag{30}$$

$$\begin{aligned} CH = &\left(\frac{RH\_y}{50} * \left(R0_1 + RCI_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{RH\_y}{50} * \left(R0_t + RCI_{t-1} + RCI_t\right)\right)/2 + \\ &\left(\frac{NH\_y}{50} * \left(initial\ NCI + NCI_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{NH\_y}{50} * \left(order_{t-1} + NCI_{t-1} + NCI_t\right)\right)/2 \end{aligned} \tag{31}$$

$$\begin{aligned} FH = &\left(\frac{FHr\_y}{50} * \left(R2_1 + FPIr_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{FHr\_y}{50} * \left(R2_t + FPIr_{t-1} + FPIr_t\right)\right)/2 + \\ &\left(\frac{FHm\_y}{50} * \left(M2_1 + TinvF + FPIm_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{FHm\_y}{50} * \left(M2_t + FPIm_{t-1} + FPIm_t\right)\right)/2 \end{aligned} \tag{32}$$

$$TC = RD + LS + RMM + NC + RP + CH + FH \tag{33}$$

$$Revenue = \sum_t Price\_u * \left(R3_t + M3_t\right) \quad for\ all\ t \tag{34}$$

$$Profit = Revenue - Total\ costs \tag{35}$$

where LS_t, RM_u, MM_u, NC_u, RP_u, NH_y, RH_y, FHr_y, FHm_y, and $Price\_u$ are uncertain coefficients with the triangular distribution. Constraints (26) to (32) describe the cost parameters to calculate the total cost (TC). The TC consists of the Returned Component Disposal Cost (RD), Lost Sales Cost (LS), Remanufacturing and Manufacturing Cost (RMM), New Component Cost (NC), Returned Component Preparation Cost (RP), Component Holding Cost (CH), and Finished Product Holding Cost (FH). All holding costs are calculated based on the average level of inventory. Constraint (35) states that the profit is calculated by the revenue (Constraint (34)) minus total costs (Constraint (33)).

Decision Variables:

$$order_t = TinvN \quad NCI_t \quad for\ all\ t \tag{36}$$

$$R1_t + M1_t = TinvF - FPI_t \quad for\ all\ t \tag{37}$$

$$disR_t = 100 * (dispose_t / ReA_t) \quad for\ all\ t \tag{38}$$

For Equation (36), the order of new components depends on $TinvN$. Equation (37) shows that the total number of new and returned components sent to production equal the number of finished products. Equation (38) describes the disposal rate, which is the percentage of disposed of components over the returned components.

Possibilistic Linear Programming (PLP)

We develop the possibilistic linear programming method to solve this problem under uncertainty by developing three new crisp objective functions of the multi-objective linear programming (MOLP) to replace Equations (1)-(3)

$$\text{Max } z_1 = Profit^M = Revenue^M - TC^M = Revenue^M - RD^M + LS^M + RMM^M + NC^M + RP^M + CH^M + FH^M \quad (39)$$

$$\text{Min } z_2 = Profit^{P-M} = Revenue^{P-M} - TC^{P-M} = Revenue^{P-M} - RD^{P-M} + LS^{P-M} + RMM^{P-M} + NC^{P-M} + RP^{P-M} + CH^{P-M} + FH^{P-M} \quad (40)$$

$$\text{Max } z_3 = Profit^{M-O} = Revenue^{M-O} - TC^{M-O} = Revenue^{M-O} - RD^{M-O} + LS^{M-O} + RMM^{M-O} + NC^{M-O} + RP^{M-O} + CH^{M-O} + FH^{M-O} \quad (41)$$

As the demand of customers, quantity of returned components, and related operation cost are fuzzy, a defuzzification method using the weighted average method is applied to solve the imprecise data. Constraint (11), (14), (16), (21), (22), (23), (24), and (25) need to be transformed to crisp constraints as follows:

$$w_1 ReA_t^P + w_2 ReA_t^M + w_3 ReA_t^O = dispose_t + R0_t \quad \text{for all } t \quad (42)$$

$$R3_t + M3_t + LS_t = w_1 d_t^P + w_2 d_t^M + w_3 d_t^O \quad \text{for all } t \quad (43)$$

$$w_1 PC_t^P + w_2 PC_t^M + w_3 PC_t^O \geq R1_t + M1_t \quad \text{for all } t \quad (44)$$

$$RCI_t = \begin{cases} 0 \quad if \ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \geq R0_t & where \ t = 1 \\ 0 \quad if \ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \geq R0_t + RCI_{t-1} & where \ t = 2 \ to \ t = 50 \\ any \ integers \quad otherwise & for \ all \ t \end{cases} \quad (45)$$

$$R0_t = \begin{cases} w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \\ if \ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O < w_1 ReA_t^P + w_2 ReA_t^M + w_3 ReA_t^O & for \ all \ t \\ w_1 ReA_t^P + w_2 ReA_t^M + w_3 ReA_t^O \\ if \ w_1 ReA_t^P + w_2 ReA_t^M + w_3 ReA_t^O \leqq w_1 D_t^P + w_2 D_t^M + w_3 D_t^O & for \ all \ t \end{cases} \quad (46)$$

$$R1_t = \begin{cases} w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \\ if \ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O < R0_t + RCI_{t-1} & for \ all \ t \\ any \ integers \quad otherwise & for \ all \ t \end{cases} \quad (47)$$

$$NCI_t = \begin{cases} 0 & if \ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \geq TinvN & where \ t = 1 \\ order_{t-1} & if \ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \geq NCI_{t-1} & where \ t = 2 \ to \ t = 50 \\ any \ integers & otherwise & for \ all \ t \end{cases} \quad (48)$$

$$M1_t = \begin{cases} w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \quad if \ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O < NCI_{t-1} & for \ all \ t \\ any \ integers \quad otherwise & for \ all \ t \end{cases} \quad (49)$$

where $w_1 + w_2 + w_3 = 1$ and the weights of w_1, w_2, and w_3 can be determined by the experience and knowledge of decision makers.

The linear membership functions for three new objective functions are specified, and we convert the auxiliary MOLP problem into an equivalent linear programming model by the fuzzy decision method. To find the Negative Ideal Solution (NIS) and the Positive Ideal Solution (PIS) of each objective, the fuzzy decision method as presented in Equations (4) to (6) is introduced to solve MOLP by finding the corresponding linear membership function of each objective function.

$$z_1^{PIS} = \max Profit^M \quad , \quad z_1^{NIS} = \min Profit^M \quad (50)$$

$$z_2^{PIS} = \min Profit^{P-M} \quad , \quad z_2^{NIS} = \max Profit^{P-M} \quad (51)$$

$$z_3^{PIS} = \max Profit^{M-O} \quad , \quad z_3^{NIS} = \min Profit^{M-O} \quad (52)$$

Equations (7) to (9) are applied to the corresponding linear membership functions for each objective function in this case study as follows:

$$f1(z1)=\begin{cases}1 & , \quad z_1 < z_1^{PIS}, \\ \dfrac{z_1 - z_1^{NIS}}{z_1^{PIS} - z_1^{NIS}}, & z_1^{NIS} \le z_1 \le z_1^{PIS}, \\ 0 & , \quad z_1 > z_1^{NIS},\end{cases}$$

$$f2(z2)=\begin{cases}1 & , \quad z_2 < z_2^{PIS}, \\ \dfrac{z_2^{NIS} - z_2}{z_1^{NIS} - z_2^{PIS}}, & z_2^{PIS} \le z_2 \le z_2^{NIS}, \\ 0 & , \quad z_2 > z_2^{NIS},\end{cases}$$

$$f3(z3)=\begin{cases}1 & , \quad z_3 < z_3^{PIS}, \\ \dfrac{z_3 - z_3^{NIS}}{z_3^{PIS} - z_3^{NIS}}, & z_3^{NIS} \le z_3 \le z_3^{PIS}, \\ 0 & , \quad z_3 > z_3^{NIS}.\end{cases}$$

Find the maximum overall satisfaction:
Max λ
Subject to
$\lambda \le f_i(z_i)$, where i = 1,2,3
i = number of linear membership function of each objective.
$0 \le \lambda \le 1$

$$w_1 ReA_t^{P} + w_2 ReA_t^{M} + w_3 ReA_t^{O} = dispose_t + R0_t \quad for\ all\ t,$$

$$R2_t = R1_t \quad for\ all\ t,$$

$$R3_t + M3_t + LS_t = w_1 D_t^{P} + w_2 D_t^{M} + w_3 D_t^{O} \quad for\ all\ t,$$

$$FPI_t = FPIr_t + FPIm_t \quad for\ all\ t,$$

$$w_1 PC_t^{P} + w_2 PC_t^{M} + w_3 PC_t^{O} \ge R1_t + M1_t \quad for\ all\ t,$$

$$RCI_t = \begin{cases} R0_t - R1_t & where\ t = 1, \\ RCI_{t-1} + R0_t - R1_t & where\ t = 2\ to\ t = 50,\end{cases}$$

$$NCI_t = \begin{cases} TinvN - M_t & where\ t = 1, \\ NCI_{t-1} + order_{t-1} - M1_t & where\ t = 2\ to\ t = 50,\end{cases}$$

$$FPIr_t = \begin{cases} R2_t - R3_t & where\ t = 1, \\ FPIr_{t-1} + R2_t - R3_t & where\ t = 2\ to\ t = 50,\end{cases}$$

$$FPIm_t = \begin{cases} TinvF - M3_t & where\ t = 1, \\ FPIm_{t-1} + M2_t - M3_t & where\ t = 2\ to\ t = 50,\end{cases}$$

For the PTR

$$RCI_t = \begin{cases} 0 \quad if\ w_1 D_t^{P} + w_2 D_t^{M} + w_3 D_t^{O} \ge R0_t & where\ t = 1, \\ 0 \quad if\ w_1 D_t^{P} + w_2 D_t^{M} + w_3 D_t^{O} \ge R0_t + RCI_{t-1} & where\ t = 2\ to\ t = 50, \\ any\ integers \quad otherwise & for\ all\ t,\end{cases}$$

$$R0_t = \begin{cases} w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \\ \quad if\ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O < w_1 ReA_t^P + w_2 ReA_t^M + w_3 ReA_t^O & for\ all\ t \\ w_1 ReA_t^P + w_2 ReA_t^M + w_3 ReA_t^O \\ \quad if\ w_1 ReA_t^P + w_2 ReA_t^M + w_3 ReA_t^O < w_1 D_t^P + w_2 D_t^M + w_3 D_t^O & for\ all\ t \end{cases}$$

$$R1_t = \begin{cases} w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \\ \quad if\ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O < R0_t + RCI_{t-1} & for\ all\ t \\ any\ integers \quad otherwise & for\ all\ t \end{cases}$$

For PTM

$$NCI_t = \begin{cases} 0 & if\ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \ge TinvN \quad where\ t = 1, \\ order_{t-1} & if\ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \ge NCI_{t-1} \quad where\ t = 2\ to\ t = 50, \\ any\ integers & otherwise \quad for\ all\ t, \end{cases}$$

$$M1_t = \begin{cases} w_1 D_t^P + w_2 D_t^M + w_3 D_t^O \quad if\ w_1 D_t^P + w_2 D_t^M + w_3 D_t^O < NCI_{t-1} & for\ all\ t, \\ any\ integers \quad otherwise & for\ all\ t, \end{cases}$$

$$RD = \sum_t RD\_u * dispose_t \quad for\ all\ t,$$

$$LS = \sum_t LS\_u * LS_t \quad for\ all\ t,$$

$$RMM = \sum_t RM\_u * R1_t + \sum_t MM\_u * M1_t + MM_u * TinvF \quad for\ all\ t,$$

$$NC = \sum_t NC_u * \left(order_t + initial\ NCI + TinvF\right) \quad for\ all\ t,$$

$$RP = \sum_t RP\_u * R0_t \quad for\ all\ t,$$

$$CH = \left(\frac{RH\_y}{50} * \left(R0_1 + RCI_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{RH\_y}{50} * \left(R0_t + RCI_{t-1} + RCI_t\right)\right)/2 +,$$
$$\left(\frac{NH\_y}{50} * \left(initial\ NCI + NCI_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{NH\_y}{50} * \left(order_{t-1} + NCI_{t-1} + NCI_t\right)\right)/2,$$

$$FH = \left(\frac{FHr\_y}{50} * \left(R2_1 + FPIr_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{FHr\_y}{50} * \left(R2_t + FPIr_{t-1} + FPIr_t\right)\right)/2 +$$
$$\left(\frac{FHm\_y}{50} * \left(M2_1 + TinvF + FPIm_1\right)\right)/2 + \sum_{t=2}^{50}\left(\frac{FHm\_y}{50} * \left(M2_t + FPIm_{t-1} + FPIm_t\right)\right)/2,$$

$$TC = RD + LS + RMM + NC + RP + CH + FH,$$

$$Revenue = \sum_t Price\_u * \left(R3_t + M3_t\right) \quad for\ all\ t,$$

$$Profit = Revenue - Total\,costs\ .$$

V. Results and Discussion

5.1) Deterministic case with linear programming model

An LP model is built and solved by IBM ILOG CPLEX Optimization Studio software. The deterministic results of the PTR and the PTM policies are shown in Table II.

Table II compares the solutions obtained from these two policies. The result shows that the PTR policy is better than the PTM policy under the deterministic case, because the PTR policy shows a higher profit than the PTM policy. From the result, the PTR policy does not dispose of any returned components, but the PTM policy disposes of 75 units. This is due to the fact that the PTR policy requires that the returned components be used first while it this not a requirement for the PTM policy. Only the PTM policy has lost sales. This is because the PTR policy only requires remanufacturing, which does not require production time while the PTM policy requires the full production time. As a result, it would take a longer time to fill the FPI, which can cause lost sales and the PTM policy needs to keep a higher amount of inventory at FPI at the beginning of the first week, to prevent lost sales during the first week. However, it should be noted that the difference of the profit from these two policies is close, with less than a 4% gap.

TABLE II

PTR and PTM results

		Policy	
		PTR	PTM
Decision Variables	TinvN (units)	49	40
	TinvF (units)	39	166
	Number of units disposed (units)	0	75
Cost Parameters	LS ($)	0.00	50.00
	NC ($)	63,030.00	66,180.00
	RP ($)	15,380.00	15,005.00
	RMM ($)	62,046.00	62,174.00
	CH ($)	408.16	499.66
	FH ($)	782.76	592.79
	TC ($)	141,646.92	144,501.45
	Revenue ($)	256,400.00	256,350.00
	Profit ($)	114,753.08	111,849.05

5.2) Stochastic case with Possibilistic Linear Programming model (PLP)

With the lower bound and the upper bound of each objective (Constraints (50) to (52)), Tables 3-4 show the Negative Ideal Solution (NIS) and the Positive Ideal Solution (PIS) of each objective of the PTR and the PTM policies, respectively.

TABLE III

Upper and lower boundary of the PTR policy

PTR	
MOLP	Profit ($)
$z_1^{PIS} = \max Profit^{M}$	128,793.88
$z_1^{NIS} = \min Profit^{M}$	13,974.39
$z_2^{PIS} = \min Profit^{P-M}$	54,202.454
$z_2^{NIS} = \max Profit^{P-M}$	85,202.597
$z_3^{PIS} = \max Profit^{M-O}$	82,221.444
$z_3^{NIS} = \min Profit^{M-O}$	52,182.069

TABLE IV

Upper and lower boundary of the PTM policy

PTM	
MOLP	Profit ($)
$z_1^{PIS} = \max Profit^{M}$	125,372.9
$z_1^{NIS} = \min Profit^{M}$	0
$z_2^{PIS} = \min Profit^{P-M}$	52,917.918
$z_2^{NIS} = \max Profit^{P-M}$	86,251.638
$z_3^{PIS} = \max Profit^{M-O}$	82,903.386
$z_3^{NIS} = \min Profit^{M-O}$	51,129.002

According to Constraints (42) to (49) of the possibilistic linear programming model, the process of defuzzifying imprecise customer demand, number of arriving returned components, and production rate with the weighted average method is subject to the pattern of weight allocation. Different patterns of weight allocation can have an impact on the obtained solution. As a result, a sensitivity analysis of this weight allocation should be carried out among pessimistic, most likely, and optimistic cases to investigate the impact of such weight allocation on the overall satisfaction of the linear membership functions of each objective function. For a demonstration, a sensitivity analysis is performed in 4 scenarios by varying the weights of pessimistic, most likely, and optimistic values. Tables 5-6 present the results of the sensitivity analysis for both the PTR and the PTM policies.

TABLE V
Result of the sensitivity analysis of the PTR policy

	Scenario I			Scenario II			Scenario III			Scenario IV		
	P	M	O	P	M	O	P	M	O	P	M	O
	33%	33%	33%	80%	10%	10%	10%	80%	10%	10%	10%	80%
Overall satisfaction	53.46%			38.34%			53.95%			40.08%		
Z1 ($)	109,350			66,774			114,280			99,616		
Z2 ($)	68,630			66,774			68,479			72,778		
Z3 ($)	68,241			63,701			68,388			71,421		
Maximum the most likely value of profit ($)	109,350			66,774			114,280			99,616		
Minimize the risk of obtaining lower profit ($)	40,720			0			45,801			26,838		
Maximize of the possibility of obtaining a higher profit ($)	177,591			130,475			182,668			171,037		

For example, in Table V with Scenario I, equal weights (33%) are assigned to the pessimistic, most likely, and optimistic values. It is found that the overall satisfaction is 53.46%, and the outcomes of the maximum most likely value of profit, minimum possibility of obtaining a lower profit, and maximum of the risk of obtaining a higher profit are $109,350, $40,720, and $177,591, respectively.

The result of this sensitivity analysis also shows that Scenario III, which set the weight of the most likely value at 80% and the weight of optimistic and pessimistic values at 10%, gives the highest overall satisfaction of 53.95%. Scenario III also gives the highest possible value of the most likely profit, obtaining the highest possibility of a higher profit and the highest profit from the risk of obtaining a lower profit.

However, the profit generated from Scenario IV, which is supposed to be the highest as it is the most optimistic case, is not the highest. This is due to the fact that the amount of optimistic demand is too high for the manufacturing process. As a result, a large shortage cost needs to be paid.

TABLE VI
Result of the sensitivity analysis of the PTM policy

	Scenario I			Scenario II			Scenario III			Scenario IV		
	P	M	O	P	M	O	P	M	O	P	M	O
	33%	33%	33%	80%	10%	10%	10%	80%	10%	10%	10%	80%
Overall satisfaction	53.00%			39.13%			53.40%			42.40%		
Z1 ($)	84,866			66,610			88,882			73,055		
Z2 ($)	68,586			66,610			68,450			72,117		
Z3 ($)	67,968			63,562			68,098			69,531		
Maximum the most likely value of profit ($)	84,866			66,610			88,882			73,055		
Minimize the risk of obtaining lower profit ($)	16,280			0			20,432			938		
Maximize of the possibility of obtaining a higher profit ($)	152,834			130,172			156,980			142,586		

For example, in Table VI with Scenario I, equal weights (33%) are assigned to the pessimistic, most possible, and optimistic values. It is found that the overall satisfaction is 53.00%, and the outcomes of maximum most possible value of profit, minimum possibility of obtaining a lower profit, and maximum of the risk of obtaining a higher profit are \$84,866, \$16,280, and \$152,834, respectively.

The best result of the PTM policy is from setting the weight of the most likely value at 80% and 10% at both pessimistic and optimistic values (Scenario III). Similar to the PTR policy, the profit generated from Scenario IV (the optimistic case) is lower than from Scenario III. This is because the manufacturing process cannot fulfill the optimistic demand. As a result, a lower revenue and a higher shortage cost incur.

As for a comparison between the two policies, it was found that the PTR policy can outperform the PTM policy in terms of profit in all objective functions. However, the profit of the PTR policy in Scenario II when it is likely to be a pessimistic condition is not much higher than the profit of the PTM policy. In fact, they are equal (at 0) when we try to minimize the risk of obtaining a lower profit. In addition, when the returned component ratio is further reduced to be lower than 60% (0.6), the profit of the PTM policy is shown to be even higher than the profit of the PTR policy. This is because the PTR policy cannot gain an advantage from using the returned components (which are cheaper) and needs to use more new components. This shows the vulnerability of the PTR policy in the case of future pessimistic and uncertain conditions. It is more subject to uncertainty and the instability of returned components.

TABLE VII
RESULT COMPARISON

The PTR Policy		
Priority-To-Remanufacturing policy (PTR)	Linear Programming (LP) model	Possibilistic Linear Programming (PLP) model from Scenario III
Objective function λ	Max z	Max λ
(overall degree of satisfaction)	100%	54.08%
z (Profit)	\$ 114,753.08	(\$45,801, \$114,280, \$182,668)
The PTM Policy		
Priority-To-Manufacturing policy (PTR)	Linear Programming (LP) model	Possibilistic Linear Programming (PLP) model from Scenario III
Objective function λ	Max z	Max λ
(overall degree of satisfaction)	100%	50.71%
z (Profit)	\$ 111,849.05	(\$20,432, \$88,882, \$156,980)

Comparison between the deterministic and the best stochastic results

Table VII compares the results between the optimal LP result under a deterministic condition and the best PLP result under a more realistic stochastic condition. As seen in Table VII, the most likely profits that are generated from the uncertain circumstance are lower as compared to the profits under no uncertainty as the overall degree of satisfaction is lower. This is because the result was recommended from the scenario that yields the lowest degree of satisfaction among the three objectives, which are maximizing the most likely value of profit, minimizing the risk obtaining a lower profit, and maximizing the possibility of obtaining a higher profit. The PTR policy and the PTM policy under Scenario III show the best result among experimental scenarios, whereas The PTR policy generates a higher profit than the PTM policy in all cases. With the range of profit from each scenario obtained from PLP, decision makers are well prepared for any expected outcome. This is an important feature for decision makers to build the production planning and inventory control subject to an uncertain environment.

VI. Conclusions

Production planning and inventory control is intermediate planning for finding suitable levels of disposal units, production units, lost sales, inventory, and stock outs to meet uncertainty in the forecast demand and fluctuation of related operating costs, number of returned components, and machine productivity. This study finds the optimal inventory control policy of a hybrid manufacturing/remanufacturing system under two priority policies, Priority-To-Remanufacturing (PTR) and Priority-To-Manufacturing (PTM). Possibilistic linear programming is introduced to optimize and find the optimal result in this uncertain environment. It maximizes the most possible value of the imprecise profit, minimizes the risk of obtaining a lower profit, and maximize the possibility of obtaining a higher profit by pushing the three prominent points with the triangular distribution towards the right (as profit maximization). Results from this deterministic case show that the PTR policy is slightly better than the PTM policy. The results from the stochastic case also confirm that the PTR policy is better than the PTM policy in terms of having a higher most likely value of the profit in every scenario. However, the profit of the PTR policy when it is likely to be pessimistic is not much higher than the profit of the PTM policy. In fact, they are equal (at 0) when we try to minimize the risk of obtaining a lower profit. In addition, when the returned component ratio is further reduced to be lower than 60% (0.6), the profit of the PTM becomes higher than the profit of the PTR policy.

As in the case study, the proposed method can be used to solve real-world planning problems involving imprecise datas through an interactive decision-making process. The proposed method constitutes a systematic framework that helps the decision-making process, enabling a decision maker to interactively modify the imprecise data until a satisfactory solution is found. Notably, the optimal goal values using the LP approach are imprecise since the forecasted demand, related operating costs, and the number of returned components are always imprecise in nature. This brings the results closer to real-world problems. Decision makers should have some knowledge in advance to prepare and take necessary action for future uncertainty.

This study focuses on multi-periods with a single product from a hybrid manufacturing/remanufacturing problem. It also provides information on different policies in response to any designed variations. Additionally, the approach also considers the actual tradeoff between the PTM and the PTR policies in each circumstance. This lets us know how each policy would be beneficial or vulnerable depending on uncertain conditions.

The main limitation of our case study is the assumption of the triangular distribution that represents imprecise data. Decision makers should make use of and obtain appropriate distributions based on true judgment on past resources. Future researchers can also explore different levels of the relative importance of individual goals and different types of distributions, to make their models to be better suited to their practical applications.

VII. References

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[4] W.-K. Chen, Linear Networks and Systems. Belmont, CA: Wadsworth, 1993, pp. 123–135.

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[7] E. P. Wigner, "Theory of traveling-wave optical laser," *Phys. Rev*., vol. 134, pp. A635-A646, Dec. 1965.

[8] E. H. Miller, "A note on reflector arrays," *IEEE Trans. Antennas Propagat*., to be published.

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[11] J. H. Davis and J. R. Cogdell, "Calibration program for the 16-foot antenna," Elect. Eng. Res. Lab., Univ. Texas, Austin, Tech. Memo. NGL-006-69-3, Nov. 15, 1987.

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Example for papers presented at conferences (unpublished):

[28] D. Ebehard and E. Voges, "Digital single sideband detection for interferometric sensors," presented at the 2nd Int. Conf. Optical Fiber Sensors, Stuttgart, Germany, Jan. 2-5, 1984.

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[29] J. K. Author, "Title of patent," U.S. Patent x xxx xxx, Abbrev. Month. day, year.

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[39] B. Smith, "An approach to graphs of linear forms," unpublished.
[40] A. Brahms, "Representation error for real numbers in binary computer arithmetic," IEEE Computer Group Repository, Paper R-67-85.

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