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Probabilistic Piecewise-Objective Optimization Model for Integrated Supplier Selection and Production Planning Problems Involving Discounts and Probabilistic Parameters: Single Period Case

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Abstract: In manufacturing and retail industries, supplier selection problems deal with allocating the optimal raw material amount that should be purchased to each supplier such that the procurement cost is minimal. Meanwhile, production planning problems deal with maximizing the product amount to be produced. Decision-makers need to take optimal decisions for those problem to gain the maximal revenue. In this paper, a novel mathematical model in the class of probabilistic piecewise programming is proposed as a decision-making support that can be used to find the optimal decision in solving both integrated supplier selection and production planning problems involving discounts and probabilistic parameters. The objective is to gain the optimal performance of the supply chain, i.e., maximizing the profit from the production activity. The model covers multi-raw material, multi-supplier, multi-product, and multi-buyer situations. Numerical experiments were conducted to evaluate the proposed model and to illustrate how the optimal decision is taken. Results showed that the proposed decision-making support successfully solved the problem and provided the optimal decision for the given problem. Therefore, the proposed model can be implemented by decision-makers/managers in industries.

Keywords: Decision-making support, Discounts, Order-allocation, Piecewise-objective, Probabilistic optimization, Production planning, Supplier selection

Introduction

Manufacturing and retail companies keep trying to make optimal decisions in their activities to maximize their profit. The fundamental activities that are crucial to be optimized include supplier selection, or also called order allocation planning, and production planning. For the supplier selection, the decision-maker needs to decide to which suppliers the raw materials or parts has to be purchased and how much it is. The purchased raw materials have to satisfy the number that is needed for the production. Meanwhile, in production planning, the decision-maker needs to decide the number of each product type or brand to produce such that the demand from buyers or customers is fulfilled. Those decisions should be made in such a way that the profit is expected to be maximal. Furthermore, there are some constraints or conditions that should be met by the action taken by the decision-maker, such as suppliers' maximum capacities, production capacities, etc.

Those two topics have been widely studied by researchers and practitioners, and various approaches have been proposed to deal with those problems. The most common approach is building mathematical models of the form

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optimization models or programming. However, each model commonly deals with those problems with its own specifications. A simple linear programming model was built in (Ware et al., 2014), which can be used to solve supplier selection problems. However, it did not consider production planning in the model, and all parameters were certainly known. A slightly more complex model was built in (Sharma et al., 2019) for dealing with deteriorating products. Some other existing models consider various specific situations such as rapid service demand (Alegoz & Yapıcıoglu, 2019) analytical hierarchy process (Manik, 2023) and machine learning (Ali et al., 2023), among others. Those models were built theoretically and simulated with randomly generated data. Meanwhile, some other reports showed practical applications in many fields such as logistics management (Ghorbani & Ramezanian, 2020; Olanrewaju et al., 2020), food companies (Hajiaghaei Keshteli et al., 2023), glove industries (Joy et al., 2023), defense industries (Guneri & Deveci, 2023), etc.

Note that studies that are mentioned above solved the supplier selection problem independently. Regarding the production planning problem, various mathematical models have also been formulated. Again, the models are based on the specifications of the problem. For example, a production planning problem in an uncertain environment has been solved via a linear optimization model in (Singh & Biswal, 2021) or nonlinear optimization in (Li et al., 2021). Some other approaches used single/multi-objective programming in solving production planning problems under sustainability requirements (Lahmar et al., 2022; Wu et al., 2020; Yazdani et al., 2021; Zarte et al., 2022) a mixed integer linear programming under nonconstant consumptions (Adrio et al., 2023) model predictive control approach as a sustainable aggregate approach (May et al., 2023) and many more. In particular, some practical reports are also available from multiple sectors such as food and agriculture (Angizeh et al., 2020) mining (Zhang et al., 2022) and chemical & pharmaceutical companies (Adrio et al., 2023; Lindahl et al., 2023) among others, showing the implementation of the theoretical results in practice.

Even though numerous models have been built and available to use, each model is suitable for problems with the specified conditions or specifications. When the situation is different, a modification or even a new model is often needed to formulate. In this paper, the supplier selection and production planning problems are considered with probabilistic parameters, and are solved in an integrated manner, meaning that the model can handle the flow of the raw materials and products between those two activities in one model. Furthermore, those problems are considered with discounted price features in which price functions such as for raw material prices, transportation costs, and product selling prices may contain discounts. No existing models is available in literature for this situation; this is the main contribution provided in this paper. The problem is modeled in a probabilistic programming with a piecewise objective function. Moreover, in the end of the paper, the proposed model will be demonstrated via numerical experiments.

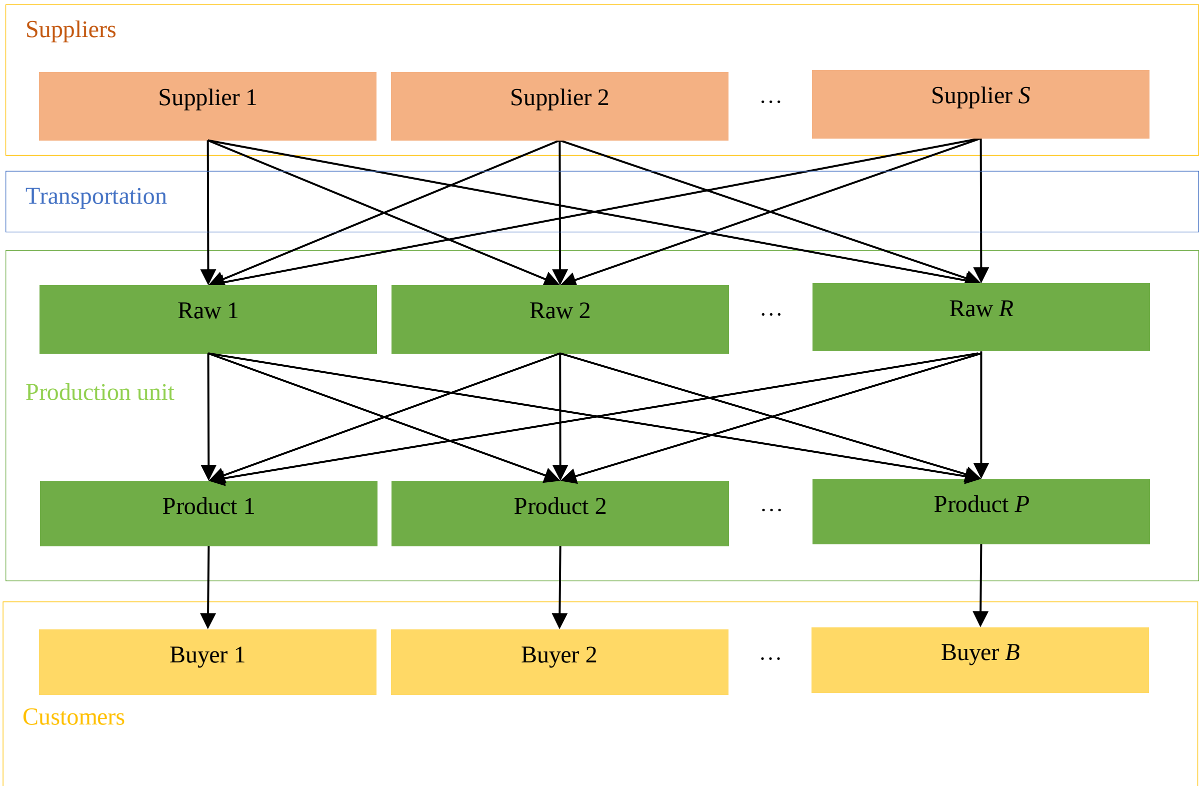

Figure 1. The flow of raw materials and products between suppliers, production units, and buyers

Method

Problem Setup

Suppose that a manufacturing company is planning to produce P product brands from R raw material types. Those raw materials will be purchased to S suppliers or vendors. Produced products will be sold to buyers. The flow of the raw materials and the products are shown in Fig. 1. The objective is to maximize the profit from this production activity subject to some limitations and specific conditions. Those limitations or constraints are explained in the following explanations. The performances of suppliers are varied. This includes the variation of the maximum capacity limit in supplying raw materials, prices, defect rates, transportation costs, and the punctuality. This makes the decision-making process in the raw material procurement is not obvious. Furthermore, the problem contains discounts on prices or cost. This includes discounted prices of raw materials from suppliers, transportation costs from carriers, and prices of products sold to buyers. In this study, the discounted price functions are assumed to follow piecewise constant functions in which prices for more raw materials or products are cheaper with some price break levels or points, for further technical details, see the mathematical modelling section. On the other hand, suppliers have some limitations on supplying raw materials. It includes maximum number of raw materials that can be ordered, some number of raw materials might be rejected when arrived at the manufacturer due to damaged or low quality, and some number of raw materials might be not delivered on time (in this case, those cannot be used in the production). The maximum capacities are known, however, the rate of rejected raw materials and the rate of late delivered raw materials are not known and are uncertain. Nevertheless, historical data are assumed to be available, and thus those uncertain values can be treated as probabilistic parameters with some suitable probability distribution functions such as normal or Gaussian distribution. All decision variables were assumed to have integer measurements in this study; this needs to be taken into account in the model.

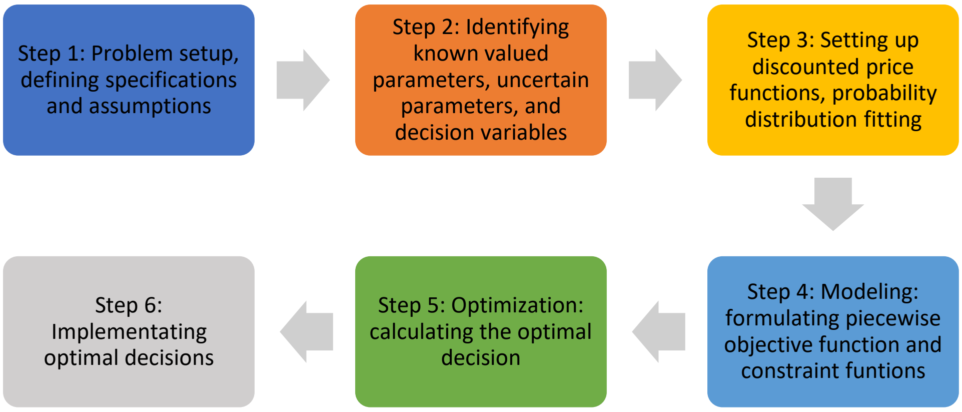

Figure 2. Problem solving steps

Methodology

The methodology is summarized as problem solving steps depicted in Figure 2. The first step has been explained above. In the second step, four uncertain parameters have been considered, i.e., rates of rejected and late delivered raw materials from suppliers, rejected product rate in the production, and product demand from buyers. Meanwhile, the decision variables are the number of each raw material type to be ordered to each supplier, the number of each product brand planned to be produced from the available raw materials, the number of trucks used in the raw material transportation, and artificial decision variables indicating whether a supplier is selected or not in supplying raw materials. The next step is formulating the discounted price/cost functions and probability distribution functions for the uncertain parameters. Piecewise constant functions were utilized in this study, see the mathematical modeling section for further technical details, and normal or Gaussian distribution functions were used, see the numerical experiment results for further explanations. After that, the problem is modeled into a mathematical programming. The objective function is formulated as the profit from the raw material procurement, production, and product selling activities, which was maximized. Constraint functions were formulated based on the problem's specifications described in the previous section, see the mathematical modeling section for more detailed descriptions. Next, the optimal decision is calculated from the derived mathematical programming. The interior point algorithm combined with branch-and-bound to find integer solutions were utilized. Finally, the derived optimal decision is implemented by the decision-maker.

Mathematical Model

The supplier selection and production planning problems defined in the previous section are modeled as follows. First, define the following symbols:

indices

r	:	type raw material;
s	:	index of supplier;
p	:	type of product brand;
B	:	index of buyer;
i, j, k	:	index of discount level;

decision variables:

X_{rs}	:	amount of raw material of type *r* purchased to supplier *s;*
Y_p	:	amount of product type *p* produced by the manufacturer*;*
T_s	:	Delivery number to transport raw materials from supplier *s* to the manufacturer;
Z_s	:	indicator variable for supplier *s* whether some raw materials are purchased to the supplier or not; 1 if yes, 0 if not;

prices or costs with discounts:

$UP_{rs}^{(i)}$	:	discounted price on discount level *i* for one unit of raw material *r* at supplier *s;*
$PP_{pb}^{(j)}$	:	discounted selling price on discount level *j* for one unit of product brand *p* sold to buyer *b;*
$TC_s^{(k)}$	:	discounted transportation cost on discount level *k* for one time of delivery in transporting raw materials from supplier *s* to the manufacturer*;*

probabilistic parameters:

DR_{rs}	:	rates of raw material type *r*'s defect amount that was ordered to supplier *s;*
LR_{rs}	:	rates of raw material type *r*'s late delivered amount that was ordered to supplier *s;*
DP_p	:	rates of product brand *p*'s defect amount.
DE_{pb}	:	amount of product brand *p*'s demand from buyer *b.*

deterministic parameters:

O_s	:	cost to order raw materials to supplier *s;*
PC_p	:	cost to produce one unit of product brand *p;*
SC_{rs}	:	supplier *s*'s maximum capacity limit in supplying raw material type *r;*
TRC	:	maximum capacity of the truck used in transporting raw materials from suppliers to the manufacturer;
PL_{rs}	:	cost to penalize one unit of late delivered raw material type *r* that was ordered to supplier *s;*
PD_{rs}	:	cost to penalize one unit of defected raw material type *r* that was ordered to supplier *s;*
RR_{rp}	:	amount of raw material type *r* that is needed to produced one unit product brand *p*.

Now, we present the scheme of the discounted prices and costs. It is modeled as piecewise constant functions as follows. The discounted prices for raw materials are formulated as

$$UP_{rs} = \begin{cases} UP_{rs}^{(1)} & \text{if} \quad 0 = X_{rs}^{(0)} < X_{rs} \le X_{rs}^{(1)}, \\ UP_{rs}^{(2)} & \text{if} \quad X_{rs}^{(1)} < X_{rs} \le X_{rs}^{(2)}, \\ \vdots & \\ UP_{rs}^{(I)} & \text{if} \quad X_{rs}^{(I-1)} < X_{rs} \le X_{rs}^{(I)}. \end{cases} \tag{1}$$

Similarly, the discounted transport costs are formulated as

$$TC_s = \begin{cases} TC_s^{(1)} & \text{if} \quad 0 = T_s^{(0)} < T_s \le T_s^{(1)}, \\ TC_s^{(2)} & \text{if} \quad T_s^{(1)} < T_s \le T_s^{(2)}, \\ \vdots & \\ TC_s^{(K)} & \text{if} \quad T_s^{(K-1)} < T_s \le T_s^{(K)}. \end{cases} \tag{2}$$

Using the same scheme, the discounted product selling prices are formulated as

$$PP_{pb} = \begin{cases} PP_{pb}^{(1)} & \text{if} \quad 0 = DE_{pb}^{(0)} < DE_{pb} \le P_{pb}^{(1)}, \\ PP_{pb}^{(2)} & \text{if} \quad DE_{pb}^{(1)} < DE_{pb} \le DE_{pb}^{(2)}, \\ \vdots & \\ PP_{pb}^{(J)} & \text{if} \quad DE_{pb}^{(J-1)} < DE_{pb} \le DE_{pb}^{(J)}. \end{cases} \tag{3}$$

As the consequence of the discounted product selling prices defined above, the income (F_{0b}) has also the form of the piecewise function. This is formulated as

$$F_{0b} = \begin{cases} \sum_{p=1}^{P} [PP_p^{(1)} \cdot DE_{pb}] & \text{if} \quad 0 = DE_{pb}^{(0)} < DE_{pb} \le DE_{pb}^{(1)}, \\ \sum_{p=1}^{P} [PP_p^{(2)} \cdot DE_{pb}] & \text{if} \quad DE_{pb}^{(1)} < DE_{pb} \le DE_{pb}^{(2)}, \\ \vdots & \\ \sum_{p=1}^{P} [PP_p^{(J)} \cdot DE_{pb}] & \text{if} \quad DE_{pb}^{(J-1)} < DE_{pb} \le DE_{pb}^{(J)}. \end{cases}$$

Total of seven operational cost components was taken into account. This includes order cost, purchasing cost, delivery cost, penalty cost of late deliveries, penalty cost of defect raw materials, production cost, and penalty cost for defect products. Based on the discounted prices and costs defined above, those cost components are modeled as

$$\begin{aligned} F_1 &= \sum_{s=1}^{S} [OC_s \times Z_s] \\ F_2 &= \begin{cases} \sum_{r=1}^{R} \sum_{s=1}^{S} [UP_{rs}^{(1)} \times X_{rs}] & \text{if} \ X_{rs}^{(0)} < X_{rs} \le X_{rs}^{(1)} \\ \sum_{r=1}^{R} \sum_{s=1}^{S} [UP_{rs}^{(2)} \times X_{rs}] & \text{if} \ X_{rs}^{(1)} < X_{rs} \le X_{rs}^{(2)} \\ \vdots & \\ \sum_{r=1}^{R} \sum_{s=1}^{S} [UP_{rs}^{(d_u)} \times X_{rs}] & \text{if} \ X_{rs}^{(I-1)} < X_{rs} \le X_{rs}^{(I)} \end{cases} \\ F_3 &= \begin{cases} \sum_{s=1}^{S} [TC_s^{(1)} \times T_s] & \text{if} \ T_s^{(0)} \le T_s \le T_s^{(1)} \\ \sum_{s=1}^{S} [TC_s^{(2)} \times T_s] & \text{if} \ T_s^{(1)} < T_s \le T_s^{(2)} \\ \vdots & \\ \sum_{s=1}^{S} [TC_s^{(J)} \times T_s] & \text{if} \ T_s^{(J-1)} < T_s \le T_s^{(J)} \end{cases} \\ F_4 &= \sum_{r=1}^{R} \sum_{s=1}^{S} [PL_{rs} \times LR_{rs} \times X_{rs}] \\ F_5 &= \sum_{r=1}^{R} \sum_{s=1}^{S} [PD_{rs} \times DR_{rs} \times X_{rs}] \\ F_6 &= \sum_{p=1}^{P} [PC_p \times Y_p] \\ F_7 &= \sum_{p=1}^{P} [PDY_p \times DY_p \times Y_p]. \end{aligned} \tag{4}$$

respectively. Based on the formulated income and costs, the expected profit, which needs to be maximized, can now be formulated, this is modeled as the following maximization problem:

$$\max Z = E\left[\sum_{b=1}^{B}[F_{0b}] - [F_1 + F_2 + F_3 + F_4 + F_5 + F_6 + F_7]\right] \tag{5}$$

where $E[\cdot]$ denotes the expectation value. We now present the mathematical modeling parts for the constraint functions based on the problem's specifications and conditions that should be met. First, the available raw materials should be sufficient to satisfy those that are needed to produce products. This is modeled as

$$\sum_{s=1}^{S}[X_{rs} - LR_{rs} \times X_{rs} - DR_{rs} \times X_{rs}] \geq \sum_{p=1}^{P}[RR_{rp} \times Y_p]. \tag{6}$$

Second, the available product amount is expected to be sufficient to satisfy the demand, i.e., the amount of the produced products minus defect ones is expected to be larger or at least equal to the demand; this is modeled as

$$Y_p - DP_p \times Y_p \geq \sum_{b=1}^{B} DE_{pb}]. \tag{7}$$

Third, the total amount of raw materials ordered to supplier *s* should be not exceeding the total capacity of the trucks used in the delivery; this is modeled as

$$\sum_{r=1}^{R} X_{rs} \leq TRC \times T_s. \tag{8}$$

Fourth, the amount of each raw material type ordered to supplier *s* should be not exceeding the supplier's maximum capacity in supplying the corresponding raw material type. This is modeled as

$$X_{rs} \leq SC_{rs}. \tag{9}$$

The fifth constraint function is the indicator variables calculation to assign when supplier *s* is selected to supply raw materials. The indicator is set to be one if the corresponding supplier is selected, otherwise it is set to be zero. This is modeled as

$$Z_s = \begin{cases} 1 & \text{if } \sum_{r=1}^{R} X_{rs} > 0, \\ 0 & \text{otherwise;} \end{cases} \tag{10}$$

The last constraint function is the nonnegativity and integer assignments for the decision variables. This is simply modeled as

$$X_{rs}, T_s, Y_p \geq 0 \text{ and integer.} \tag{11}$$

The optimization problem (5) subject to constraint functions (6)-(11) belongs to probabilistic piecewise linear integer programming since the objective function is a piecewise function and it contains probabilistic parameters. However, the existence of an optimal solution is always guaranteed since the feasible set, as long as not empty, is closed and bounded.

Numerical Experiment Results and Discussion

Numerical experiments in a laboratory were conducted to verify the proposed decision-making support model with randomly generated data. All experiments were carried out with personal computers with standard specifications.

Problem's Specifications

Consider the supplier selection and production planning problems specified in the previous section where the number of raw material types is three (R1, R2, and R3), the number of suppliers is three (S1, S2, and S3), and the number of product types is also three (P1, P2, and P3). Meanwhile, the number of price break points or discount levels is also three (DL1, DL2 and DL3). The price/cost functions for each discounted price/cost are as follows:

The unit price for raw materials ordered to supplier is equal to $UP_{rs}^{(1)}$ if the number of raw materials is less or equal to 50 units, $UP_{rs}^{(2)}$ if the number of raw matrials is larger than 50 units but not larger than 100 units, and $UP_{rs}^{(3)}$ if it is larger than 100 units. Meanwhile, the unit price for products sell to buyers is equal to $PP_{pb}^{(1)}$ if the number of products is less or equal to 100 units, $PP_{pb}^{(2)}$ if the number of products is larger than 100 units but not larger than 200 units, and $PP_{pb}^{(3)}$ if it is larger than 200 units. And, the one time transportation cost from suppliers to the manufacturer is equal to $TC_{s}^{(1)}$ if the number of deliveries is only one time, $TC_{s}^{(2)}$ if the number of deliveries is more than one time but less than 6 times, and $TC_{s}^{(3)}$ if it is more than 5 times. The values for those discounted prices or costs $UP_{rs}^{(i)}$, $PP_{pb}^{(j)}$ and $TC_{s}^{(k)}$ with $i, j, k = 1,2,3$ are shown in Tables 1 to 3.

Table 1. Discounted prices for raw msterials ($UP_{rs}^{(i)}$)

Supplier	Raw material								
	R1			*R2*			*R3*		
	DL1	*DL2*	*DL3*	*DL1*	*DL2*	*DL3*	*DL1*	*DL2*	*DL3*
S1	20	20	18	10	10	10	15	14	13
S2	20	19	18	10	9	9.5	14	14	13
S3	19	19	18	45	9	9	15	14	14

Table 2. Discounted prices for products ($PP_{pb}^{(j)}$)

Product	Buyer								
	B1			*B2*			*B3*		
	DL1	*DL2*	*DL3*	*DL1*	*DL2*	*DL3*	*DL1*	*DL2*	*DL3*
P1	100	90	90	100	90	90	100	90	90
P2	120	115	110	120	115	110	120	115	110
P3	100	95	90	100	95	90	100	95	90

Table 3 Discounted costst of deliveries ($TC_{s}^{(j)}$)

Supplier	Discount level		
	DL1	*DL2*	*DL3*
S1	80	80	75
S2	75	75	75
S3	75	70	70

Table 4. Other parameters

Parameter	Supplier/raw/product type		
	S1/R1/P1	*S2/R2/P2*	*S3/R3/P3*
Order cost	100	120	140
Penalty cost for rejected raw materials	1	2	2
Penalty cost for late delivered raw materials	2	2	1
Penalty cost for defected products	1	0.5	0.5
Production cost	10	15	25
Rates of rejected raw materials (DR_{rs})	$N(0.02,0.005)$		
Rates of late delivered raw materials (LR_{rs})	$N(0.01,0.005)$		
Demands of products from buyers (DE_{pb})	$N(20,5)$		

$N(\mu,\sigma)$: normal distribution with mean μ and variance σ

Table 5. Supplier's Capacity

Supplier	Raw material type		
	R1	*R1*	*R1*
S1	400	250	120
S2	300	180	210
S3	210	150	200

Results and Discussion

All optimization processes were carried out in LINGO 20.0 software with primal simplex algorithm as the solver. The algorithm was combined with the branch-and-bound scheme to calculate integer solutions. The optimal solution regarding the amount of each raw material type that needs to be ordered to each supplier is shown in Figure 3. Note that this optimal solution provides the maximal expectation of the profit and was calculated under the uncertainty of the probabilistic parameters.

It can be seen that all suppliers S1, S2, and S3 were selected to supply raw materials. However, supplier S1 was less likely to be selected with only four units or raw material type R1. The number of raw materials ordered to suppliers S2 and S3 was always in the third discount level with more than 100 units for each type. This shows that ordering with lower numbers in the first or second discount level significantly increases the cost and thus was avoided. Meanwhile, the optimal number of products that should be produced in the production unit is 69 units of brand P1, 75 units of brand P2, and 72 units of brand P3. The maximal profit was expected to be 3499.851 with income 19065.73 and cost 15565.88.

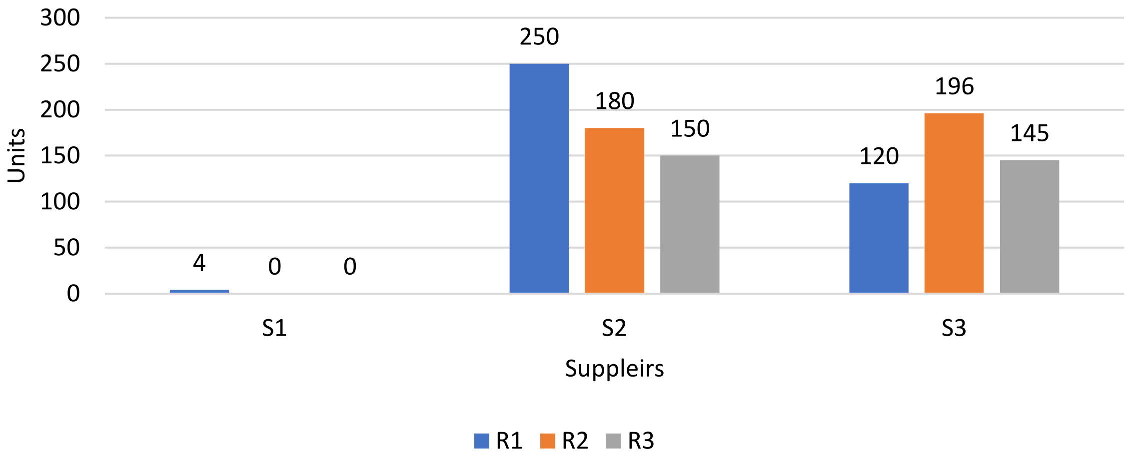

Figure 3. The optimal decision for the amount of raw materials to be ordered from suppliers

The results indicated that the proposed model succesfully solved the problem and provided the optimal solution such that the expectation of the profit was maximed. In particular, based on the mathematical model derived in the modeling and the results of the numerical experiments, some managerial insights can be drawn, which can be considered by decision makers in implementing the proposed model. These are discussed as follows: first, the proposed model did not specify the kind of raw materials and products that can be handled. In principle, any kind of raw materials and products can be handled as long as it meets the specifications of the problem. Nevertheless, the specifications can be slightly modified without significant changes. For example, all raw material types and all product brands were measured as integer numbers. In practice, if the measurement follows real numbers, then the integer constraints can be removed, and in this case, the branch-and-bound scheme is not needed.

Further modifications and additions on the model can also be made. For example, some other operational costs such as maintenance costs on the production machines may be added to the objective function. Some other constraint functions can also be added, for example, limitations on the working hour of the production machines, budget limitations, and maximum number of deliveries, among others.

The numerical experiments were considered with small scale numbers of suppliers, raw materials types, and product brands. The computer used in the experiments completed the optimization process in minutes. Decision-makers need to aware of large-scale problems. Longer computational time might occur, and this should be taken into account especially for problems in which a decision should be made in a short period of time. One may use high-performance computers to solve large scale problems.

Finally, note that all decisions were calculated and executed before the uncertain parameters were known, and the profit provided by the mathematical optimization model was only an expectation. After all uncertain parameters are known, the actual profit can then be calculated, and the actual profit might be different from the value provided by the decision-making support. However, mathematically, this is the best thing the decision-makers can do in dealing with uncertainties.

Conclusion

A newly developed decision-making support has been proposed in this study, which can be utilized by decision-makers in manufacturing and retail industries in dealing with supplier selection and production planning problems under probabilistic uncertainties and discounted prices/costs. The problem was modeled as a probabilistic linear programming with a piecewise objective function. Numerical experiments with randomly generated data were performed to illustrate and evaluate the proposed model. Results showed that the proposed decision-making support successfully solved the problem and provided the maximal expectation of the profit.

Recommendations

The model can be further developed such that it can also handle more complex problems. One may consider other discounted price/cost functions. Moreover, the proposed model can be considered as a foundation in building further models for more complex supply chain schemes such as ones that also cover distributors and carriers. For large-scale problems, one may develop metaheuristic-based optimization algorithms such as customized genetic algorithm and ant colony optimization scheme to solve the corresponding programming models.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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