An optimization model for multi-type pallet allocation over a pallet pool

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Abstract
Pallets are widely used around the world. Pallet pooling, as a useful management method of pallets, has become more and more popular. It is very important to allocate pallets over a pallet pool efficiently. However, there is very little literature on the pallet allocation problem as to our knowledge. This article addresses a pallet allocation problem where some uncertain parameters can be estimated through historical data, while some others cannot be. To address this problem, with the method of stochastic chance constrained programming and scenario planning, we propose an optimization model in which sustainable factors and customer priority factors are taken into account. The sustainable factors are used to measure the sustainable development costs of pallets. The customer priority factors are used to measure the customers’ rating. It is proved by experimental tests that the model can help pallet pool managers make more effective pallet allocation schemes against uncertainty. It is also suggested by the results that we should pay attention to sustainable factors and customer priority factors when making decisions.

Keywords
Pallet pool, allocation, uncertain programming, sustainable, customer priority

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Introduction
Pallets move the world.1 In the United States, an estimated 4 billion pallets are in daily service. Nationwide, on an annual basis, an estimated 441 million new pallets are manufactured and 357 million pallets are repaired or rebuilt from discarded pallets.2 As pallets are viewed as assets, their management becomes essential to fully reap their benefits and to receive a measurable return on investment. Historically, pallets have been managed by one of three methods (transfer of ownership, pallet exchange, and pallet pooling), and pallet pooling has increasingly become popular over the last two decades.3

Pallet pools have been studied for a long time. Auguston,4 McKerrow5 and Witt6 stated pool participants could reap a variety of benefits from pallet pooling. Lacefield7 suggested a company should create a cross-functional team to make the decision on whether to rent or own pallets. Ray et al.8 found that rental pallet systems were, on average, more costly to the customers through the supply chain than purchased pallet systems, by at least US$1.00 per pallet trip. Brindley9 introduced that the economic feasibility study by Penn State confirmed profit potential for new, industry cooperative block pool in the United States. Brindley10 analyzed the effect of Costco’s suggestion which was that iGPS (Intelligent Global Pooling Systems), PECO (PECO pallet), and CHEP (Commonwealth Handling and Equipment Pool) block pallets in North America should be regarded as the

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primary options for Costco’s suppliers. Brindley11 analyzed what was happening in pallet pool industry and how it could influence this industry. Brindley12 found that LOSCAM had taken a dominant position in Asia and LOSCAM executives offered insight on the Asian pallet market, particularly the huge growth potential in China.

It is very important to allocate pallets efficiently. Brindley13 pointed out that pallet logistics had become one of the most crucial aspects of being in the pallet business, and repositioning pallets could make or break a pallet pool. Almost all the big pallet rental companies, like CHEP, iGPS, and PECO, were struggling to figure out how to put the right number of pallets in the right place at the right time. Mosqueda14 said the trip cost was the real number to watch not the issue fee, and the trip cost included all of the pricing elements combined together to equal your real cost to use the rental pallet. In most cases, your US$5.00 issue fee would turn into a US$7–US$10 pallet, depending on how well you work the program.

However, there is very little literature on the pallet allocation problem to our knowledge. Ren and Zhang15,16 presented an integer programming model and a stochastic programming model for a modified pallet pool. Ren and Zhang17 developed a two-stage stochastic chance constrained programming model that regarded the minimization allocation cost as the target. Ren et al.18 proposed a multi-scenario model for multi-type pallet allocation over a pallet pool considering the uncertain future without adequate historical data. Their deterministic model assumed perfect knowledge of the information that will be available and may yield low-quality allocation plans. The stochastic optimization models required a good knowledge of uncertain parameter distributions to be adopted successfully. The scenario optimization model aimed to allocate pallets when historical data were inappropriate for estimating uncertain parameters.19 However, we disappointedly found that there is no paper that addresses a pallet allocation problem where some uncertain parameters can be estimated through historical data, while some others cannot be.

In fact, managers of pallet pools always could have a good knowledge of distributions of its own stock capacity, supply capacity, and loading and unloading capacity. As to the distributions of customers’ stock capacity, supply capacity, loading and unloading capacity, and transportation capacity, they are correspondingly difficult to obtain when needed. To address this problem, we developed an optimization model for multi-type pallet allocation over a pallet pool with the method of stochastic chance constrained programming and scenario planning.

The remainder of the article is organized as follows: section “Problem descriptions” presents the pallet pool, and we address and describe its main components and characteristics. Section “Modeling” is dedicated to the development of the mathematical formulation of this problem. We tested our optimization model in section “Experimental results.” Conclusions are drawn in section “Conclusion.”

Problem descriptions

Typical pallet pools include, but are not limited to, the following:

1. Third-party owned pool. Pallets are owned by a third-party that manages all aspects of the pallet pool.3
2. Cooperative pool. The pallet pool is managed by an organization with a lot of members who own and exchange pallets. An example of third-party-owned pool companies is CPC (The Canadian Pallet Council).
3. Third-party managed pool. The pallets are owned by the user, but all aspects of the pallet pool are managed by a third party.3
4. Private pool. The manufacturer owns the pallets and manages all aspects of the pallet pool.3

We will develop a model suit for the four kinds of pallet pool because they have some basic common features as follows. A pallet pool always consists of several pallet service suppliers and some pallet service demanders. As for a third-party owned pool, the service station of the pallet rental company is a pallet service supplier and its customers are demanders. As for a cooperative pool, a member who provides recycling, leasing, repairing, or other services is a supplier and a member who requires services is a demander. As for a third-party managed pool, a third-party management company is a supplier and the companies who own the pool are demanders. As for a private pool, a pallet management department is a supplier and those departments using pallets are demanders.

A pallet service demander could be a demand customer or supply customer. A demand customer requires that one or several types of pallets be delivered at its site, while a supply customer has one or several types of pallets that need to be taken away. A pallet service supplier has many depots to provide pallet services for pallet service demanders. The most important job of a pallet service supplier is to satisfy the demand customers’ requests and take away the pallets from supply customers. In order to allocate pallets more efficiently, a pallet service supplier move pallets not only from their own pallet service depots to demand customers (distribution) but also from supply customers to demand customers (reposition). If there are surplus pallets at a
supply customer after reposition, its pallet service supplier is supposed to recover them (recovery). A pallet service supplier can also purchase pallets from outside pools to satisfy demand customers’ requests if necessary. The basic allocation process consists of four stages (purchase, distribution, reposition, and recovery), which is shown in Figure 1.

As sustainable development is concerned, the costs of purchasing new pallets are completely different from reusing old ones. So we put sustainable factors into consideration in our model. The sustainable factors are used to measure the sustainable development costs of pallets which are refer to costs of resource consumption and environmental pollution.

From the perspective of customer strategy, in order to maximize the economic benefit of the pallet pool, managers have to adopt different strategies to meet different customers’ demand. So in the model that will be proposed, customer priority factors will be considered. The customer priority factors are used to measure the customers’ rating.

**Modeling**

To describe the system, it is important to introduce the following notations for the multi-type pallet allocation model.

There are several pallet service suppliers, supply customers, and demand customers in a pallet pool. \(i(i = 1, 2, \ldots , l)\), \(j(j^0 = 1, 2, \ldots , j^0)\), and \(j^1(j^1 = 1, 2, \ldots , j^1)\) represent a depot of a pallet service supplier, a supply customer, and a demand customer, respectively. In this pool, there are several types of pallet and they couldn’t replace each other. \(p(p = p_1, p_2, \ldots , p_m)\) represents a kind of pallet type. Different type pallets could be different in materials or in dimension. The value and application of different types of pallets are different, so they couldn’t replace each other.

The multi-type pallet allocation plan is scheduled in a certain period of time, and the managers of the pool have to make some decisions. \(X^s_{ip}p\) indicates the number of type \(p\) pallet to be moved from \(i\) to \(j^0\) under scenario \(s\). \(X^s_{ip}j^1\) means the number of type \(p\) pallet to be moved from \(j^1\) to \(j^0\) under scenario \(s\). \(X^s_{ip}p\) implies the number of type \(p\) pallet to be moved from \(j^1\) to \(i\) under scenario \(s\). If there are not enough pallets to meet requests, the pallet service supplier will purchase pallets from outside pools.

There is no limit to purchase. \(H^s_{ip}\) represents the number of type \(p\) pallet to be purchased from outside pools by \(i\) under scenario \(s\). The parameter \(s(s = s_1, s_2, \ldots , s_n)\) implies a kind of scenario. Each scenario represents a possible realization of the uncertain future. \(w_s\) represents the weight assigned to a scenario \(s\).

The unitary cost of transportation, storage, loading and unloading, and purchasing have been estimated. \(C^0_{ip}, C^1_{ip},\) and \(C^p_{ip}\), respectively, suggests the unitary delivery cost of a type \(p\) pallet from \(i\) to \(j^0\), from \(j^1\) to \(j^0\), and from \(j^1\) to \(i\). \(C_{ip}\) represents the unitary storage cost of a type \(p\) pallet at \(i\), and \(K^s_{ip}\) is the number of type \(p\) pallet stored at \(i\) at the end of the period when scenario \(s\) is realized. \(C^0_{ip}, C^1_{ip},\) and \(C^p_{ip}\) represent the unitary loading and unloading cost of a type \(p\) pallet at \(i\), \(j^1\), and \(j^0\). \(C^0_{ip}\) represents the unitary cost of a type \(p\) pallet to be purchased from outside pools.

The pallet service supplier has to pay punishment cost if it fails to recover all the pallets from a supply customer. The higher the customer priority, the more the punishment cost. \(C^0_{Kp}\) indicates the unitary punishment cost of failing to recover a type \(p\) pallet from a supply customer, and \(K^s_{ip}\) represents the number of type \(p\) pallet which have not been taken away from \(j^1\) at the end of the period when scenario \(s\) is realized. \(C^0_{Kp}\) is a customer priority factor of \(j^1\).

A pallet service supplier has to pay punishment cost if it fails to satisfy the requests of a demand customer or exceeds them. The punishment cost of failing to satisfy requests is higher than the cost of exceeding them for inadequate supply, which will lead to losing customers. The positive correlation between punishment cost and customer priority is assumed in the model. \(C^0_{Kp}\) indicates the unitary punishment cost of failing to fulfill or exceed the requests for a type \(p\) pallet when scenario \(s\) is realized, and \(K^s_{ip}\) indicates the number of type \(p\) pallet stored \(j^0\) at the end of the period when scenario \(s\) is realized. \(L^0_{Kp}\) represents the unitary punishment cost of exceeding the requests for a type \(p\) pallet. \(M^0_{Kp}\) represents the unitary punishment cost of failing to satisfy the request for a type \(p\) pallet. \(C^0_{Kp}\) is a customer priority factor of \(j^0\).

The sustainable development cost of using a new pallet is higher than reusing an old one. The sustainable development costs of pallets which are made from different materials are not the same. \(C^0_{df}\) is a sustainable factor that represents the unitary sustainable development cost of a new type \(p\) pallet. \(C^0_{df}\) is a sustainable factor that represents the unitary sustainable development cost of an old type \(p\) pallet.
We assume that part of the supply, storage capacity, and loading and unloading capacity of pallet service supplier’s depots are deterministic and the other parts are stochastic. The deterministic one is resulting from perfect information which is received prior to the beginning of the planning horizon. The stochastic one is corresponding to the forecast but uncertain future, and the distribution of the stochastic supply, storage capacity, and loading and unloading capacity of pallet service supplier’s depots can be estimated. \( S_{ip} \) represents the deterministic supply of type \( p \) pallet available at \( i \), while \( \alpha_{ip} \) represents the stochastic supply of type \( p \) pallet available at \( i \). \( K_{ip} \) represents the deterministic storage capacity available at \( i \), while \( \kappa_{ip} \) is the stochastic storage capacity available at \( i \). \( L_{i} \) represents the deterministic loading and unloading capacity available at \( i \), while \( h_{i} \) suggests the stochastic loading and unloading capacity available at \( i \). The model will be proposed with the method of stochastic chance constrained programming, and \( \delta \) represents the confidence level of a constraint.

The historical data are inappropriate for estimating some parameters including requests of demand customers, available pallets that have to be taken away from supply customers, pallet damage ratio for each supply customer, loading and unloading capacity of all customers, and transportation capacity. \( D^p_{ij} \) shows the requests for type \( p \) pallet at \( j \) under scenario \( s \). \( S^p_{ij} \) means the number of type \( p \) pallet that have to be taken away from \( j \) under scenario \( s \). \( \tau_{ij}^p (0 \leq \tau_{ij}^p \leq 1) \) represents the damage rate of type \( p \) pallets at \( j \) under scenario \( s \). \( L^p_{ij} \) and \( L^p_{ij} \) each represents the loading and unloading capacity available at \( j \) and \( i \) under scenario \( s \). \( M^p_{ij} \) and \( M^p_{ij} \) are the transportation capacity from \( i \) to \( j \), from \( j \) to \( i \), and from \( j \) to \( i \) under scenario \( s \).

The weight of each type of pallet occupying transportation capacity, storage capacity, and loading and unloading capacity have been estimated. \( v_p, v^p, \) and \( v^p \) denote the weight of a type \( p \) pallet occupying transportation capacity, storage capacity, and loading and unloading capacity.

The objective function set (1) minimizes the expected total cost of allocation pallets over a pallet pool. The total cost includes pallet delivery cost (distribution, reposition, and recovery) between locations, holding cost at pallet service supplier’s depots, purchasing cost of pallets from outside pools, loading and unloading cost, punishment cost of failing to satisfy requests or exceeding them, punishment cost of failing to recover pallets from supply customers, and sustainable development cost of using new pallets and old ones. The numbers of old pallets are the number of old pallets to be moved from pallet service suppliers to demand customers plus the number of pallets to be moved from supply customers to demand customers. And the number of old pallets to be moved from pallet service suppliers to demand customers is the number of all pallets to be moved from pallet service suppliers to demand customers minus the new pallets purchased from outside pools.

The constraint set (2) ensures that the number of pallets moved from a pallet service supplier’s depot to all demand customers do not exceed the sum of its supply capacity and the number of pallets purchased from outside pools. The constraint set (3) guarantees that the number of pallets moved from a pallet service supplier’s depot is more than the number of pallets purchased from outside pools.
The constraint set (4) makes sure that the number of pallets moved from a supply customer to demand customers does not exceed the available pallets that are in good condition at this supply customer. The number of available pallets that are in good condition is derived from the number of pallets that have to be taken away from a supply customer by the intact proportion (1 – damage percentage) of pallets at this supply customer

\[
\sum_{j' = 1}^{p_2} X_{j'p}^s \geq H_{ip}^s
\]  

(3)

The constraint set (5) shows the available stock of pallets at a pallet service supplier’s depot. The pallet stock is derived from the number of supply capacity (or initial inventory) at a pallet service supplier’s depot plus the number of pallets purchased from outside pools and inflow of pallets from supply customers, then minus outflow of pallets to demand customers. According to constraint (6), pallets stored at a pallet service supplier’s depot are not supposed to over storage capacity

\[
K_{ip}^s = S_{ip}^s + H_{ip}^s - \sum_{j' = 1}^{p_2} X_{j'p}^s + \sum_{j' = 1}^{p_1} X_{j'p}^s
\]

\[
\Pr\left\{ \left( \sum_{p = p_1}^{p_2} \nu_p K_{ip}^s - K_{0i} \right) \leq \kappa_{0i} \right\} \geq \delta_{0i}
\]  

(4)

The constraint set (7) shows the number of pallets which has not been recovered. It is derived from the number of pallets that have to be taken away from a supply customer minus the outflow of pallets to demand customers and to pallet service supplier’s depots. The constraint set (8) ensures the number of pallets which has not been recovered is non-negative

\[
K_{ip}^t = S_{ip}^t - \sum_{j' = 1}^{p_2} X_{j'p}^t - \sum_{i = 1}^{l_2} X_{ip}^t
\]

\[
K_{ip}^t \geq 0
\]  

(7)

The constraint set (9) shows the number of pallets exceeding or failing to satisfy the requests of a demand customer. It is derived from the inflow of pallets from pallet service’s depots and supply customers minus the requests of this customer. The constraint set (10) shows the unitary punishment cost. If the inflow of pallets from pallet service supplier’s depots and supply customers is more than the requests of a demand customer, the unitary punishment cost will be the cost of exceeding the requests. Otherwise, it will be the cost of failing to satisfy the requests

\[
K_{ip}^a = D_{ip}^a - \sum_{i = 1}^{l_2} X_{ip}^a - \sum_{j' = 1}^{p_2} X_{j'p}^a
\]

\[
C_{ip}^a = \begin{cases} L\text{C}_{ip} & K_{ip}^a \geq 0 \\ M\text{C}_{ip} & \text{else} \end{cases}
\]  

(9)

The constraint sets (11), (12), and (13) impose an upper transportation capacity on the number of pallets that can be moved between two locations

\[
\sum_{p = p_1}^{p_2} \nu_p X_{ip}^p \leq MA_{ip}^p
\]

\[
\sum_{p = p_1}^{p_2} \nu_p X_{ip}^p \leq MA_{ip}^p
\]

\[
\sum_{p = p_1}^{p_2} \nu_p X_{ip}^p \leq MA_{ip}^p
\]  

(10)

The constraint sets (14), (15), and (16) impose a loading and unloading capacity on the number of pallets loaded or unloaded at a pallet service supplier’s depot, a supply customer, and a demand customer, respectively

\[
\Pr\left\{ \sum_{p = p_1}^{p_2} \sum_{i = 1}^{l_2} X_{ip}^a + \sum_{p = p_1}^{p_2} \sum_{j' = 1}^{p_2} X_{j'p}^a - L_i \leq h_i \right\} \geq \delta_i
\]

\[
\sum_{i = 1}^{l_2} \nu_p X_{ip}^a + \sum_{j' = 1}^{p_2} \nu_p X_{j'p}^a \leq L_j^a
\]

\[
\sum_{i = 1}^{l_2} \nu_p X_{ip}^a + \sum_{j' = 1}^{p_2} \nu_p X_{j'p}^a \leq L_j^a
\]  

(11)

The constraint sets (17), (18), (19), and (20) are congruity constraints

\[
H_{ip}^1 = H_{ip}^2 = \ldots = H_{ip}^m
\]

\[
X_{ip}^1 = X_{ip}^2 = \ldots = X_{ip}^m
\]

\[
X_{ip}^1 = X_{ip}^2 = \ldots = X_{ip}^m
\]

\[
X_{ip}^1 = X_{ip}^2 = \ldots = X_{ip}^m
\]  

(12)

The constraint set (21) indicates that all decision variables are non-negative integer values

\[
X_{ip}^s, X_{ip}^a, X_{ip}^t, H_{ip}^s, I_{ip}^a, I_{ip}^t, I_{ti} \geq 0, \text{ and int}
\]  

(13)

This model is suit for each of those four kinds of pallet pools. As long as managers could assign a role for
each member in a pool, they could use this model to make better decisions.

**Experimental results**

We simulated the behavior of a pallet pool. In this system, there are two pallet service supplier’s depots \((i = a, b)\), two supply customers \((j^1 = c, d)\), two demand customers \((j^0 = e, f)\), and two types of pallet \((p = p_1, p_2)\). The priority of \(c, d, e, f\) is 1.2, 1, 1, and 2, respectively. The sustainable development cost of a new \(p_1\) pallet and \(p_2\) pallet is 1 and 2, respectively. The sustainable development cost of both an old \(p_1\) pallet and \(p_2\) pallet is 0.

The purchasing cost of a \(p_1\) pallet is 1 and cost of \(p_2\) pallet is 2. The damage percentage of \(p_1\) pallets at two supply customers is 0.5. The weight of a \(p_1\) pallet and \(p_2\) pallet occupying each kind of capacity is 1 and 1.1. The confidence levels of all constraints are 0.95. The other parameters values are shown in Tables 1–4.

We will analyze three significant scenarios as follow. \(S_1\) assumes that (1) the number of \(p_2\) pallets that have to be taken away from \(c\) is 50% less than the expected value; (2) the requests for \(p_1\) pallets of the two demand customers are 50% less than the expected value; (3) the requests for \(p_2\) pallets of the two demand customers are 100% less than the expected value; (4) the transportation capability from \(d\) to \(e\) is equal to the expected value; (5) the storage capability at \(b\) is 10% less than the expected value; and (6) the damage proportion of \(p_2\) pallets at two supply customers is 0.5. \(S_2\) assumes that the damage percentage of \(p_2\) pallets at two supply customers is 0.1 and the other uncertain parameters are equal to the expected values. \(S_3\) assumes that (1) the number of \(p_2\) pallets that have to be taken away from \(c\) is 50% more than the expected value; (2) the requests for \(p_1\) pallets of the two demand customers are 50% more than the expected value; (3) the requests for \(p_2\) pallets of the two demand customers are 100% more than the expected value; (4) the transportation capabilities of \(d\) to \(e\) are 0.5.

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**Table 1. Unitary transportation cost.**

| \(p_1/p_2\) | \(a\) | \(b\) | \(c\) | \(d\) | \(e\) | \(f\) |
|--------------|-------|-------|-------|-------|-------|-------|
| \(a\)        | \(\_\) | \(\_\) | 3/5   | 4/5   | 5/7   | 6/7   |
| \(b\)        | \(\_\) | \(\_\) | \(\_\) | 2/3   | 4/5   | 5/7   |
| \(c\)        | 3/5   | \(\_\) | \(\_\) | \(\_\) | 7/8   | 8/8   |
| \(d\)        | 4/5   | 2/3   | \(\_\) | \(\_\) | 2/4   | \(\_\) |
| \(e\)        | 5/7   | 4/5   | 7/8   | \(\_\) | \(\_\) | \(\_\) |
| \(f\)        | 6/7   | 5/7   | 8/8   | \(\_\) | \(\_\) | \(\_\) |

**Table 2. Transportation capability.**

| \(S_1/S_2/S_3\) | \(a\) | \(b\) | \(c\) | \(d\) | \(e\) | \(f\) |
|------------------|-------|-------|-------|-------|-------|-------|
| \(a\)            | \(\_\) | \(\_\) | 1000  | 1000  | 400   | 500   |
| \(b\)            | \(\_\) | \(\_\) | \(\_\) | \(\_\) | 300   | 500   |
| \(c\)            | 1000  | 0     | \(\_\) | \(\_\) | 400   | 700   |
| \(d\)            | 1000  | 700   | \(\_\) | \(\_\) | 300/300/0 | 0    |
| \(e\)            | 400   | 300   | 400   | \(\_\) | \(\_\) | \(\_\) |
| \(f\)            | 500   | 500   | 700   | \(\_\) | \(\_\) | \(\_\) |

**Table 3. Supplies and demands.**

| Supplies \((p_1/p_1)\) | The number of pallets that have to be taken away \((p_1(S_1/S_2/S_3)/p_2(S_1/S_2/S_3))\) | Requests \((p_1(S_1/S_2/S_3)/p_2(S_1/S_2/S_3))\) |
|------------------------|--------------------------------------------------------------------------------|--------------------------------------------------|
| \(a\)                  | \(\{105/N(10,9)\}/50\)                                                      | \(\_\)                                           |
| \(b\)                  | \(200/100\)                                                                   | \(\_\)                                           |
| \(c\)                  | \(\_\)                                                                       | \(\_\)                                           |
| \(d\)                  | \(\_\)                                                                       | \(\_\)                                           |
| \(e\)                  | \(\_\)                                                                       | \(\{100/200/300\}\)/(0/100/200)                   |
| \(f\)                  | \(\_\)                                                                       | \(\{200/400/600\}\)/(0/200/400)                   |

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capability from \(d\) to \(e\) is 0; (5) the storage capability at \(b\) is 10% more than the expected value; and (6) the damage percentage of \(p_2\) pallets at two supply customers is 0.

**Case 1**

We assumed \(w_1 = 0\): \(2\), \(w_2 = 0\): \(4\), \(w_3 = 0\): \(4\). Then we have an optimal allocation scheme, which is shown in Table 5.

**Case 2**

We assumed \(w_1 = 0\): \(4\), \(w_2 = 0\): \(4\), \(w_3 = 0\). The optimal allocation scheme is shown in Table 6.

As analyzed in Table 7 (D.F. (demand fulfillment) and R.F. (recovery fulfillment)), our model can help managers of a pallet pool make an effective multi-type pallet allocation scheme against uncertainty.

1. The important effects of sustainable factors on decision making

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### Table 4. Other parameters.

| Storage capacity (S1/S2/S3) | Unitary holding cost (unitary punishment cost) \((p_1/p_2)\) | Loading and unloading capacity | Unitary loading and unloading cost \((p_1/p_2)\) |
|-----------------------------|----------------------------------------------------------|--------------------------------|-----------------------------------------------|
| \(a\) 2000                 | 1/1                                                      | 2500/N(20,4)                   | 2/2                                           |
| \(b\) 1800/2000/2200       | 2/2                                                      | 2200                           | 2/2                                           |
| \(c\) –                     | 10/12                                                    | 500                             | 3/4                                           |
| \(d\) –                     | 10/12                                                    | 1000                           | 2/4                                           |
| \(e\) –                     | (6,10)/(7,11)                                           | 1500                           | 1/2                                           |
| \(f\) –                     | (6,10)/(7,11)                                           | 1500                           | 1/3                                           |

### Table 5. Optimum scheme for case 1.

| \(p_1/p_2\) | \(a\) | \(b\) | \(c\) | \(d\) | \(e\) | \(f\) | Purchase |
|-------------|------|------|------|------|------|------|---------|
| \(a\)       | 0/0  | 110/50 | 0/0 |
| \(b\)       | 100/0 | 190/100 | 90/0 |
| \(c\)       | 100/50 | 0/0 |
| \(d\)       | 0/0  | 100/50 |
| Stock       | 95/50 | 400/100 |

### Table 6. Optimum scheme for case 2.

| \(p_1/p_2\) | \(a\) | \(b\) | \(c\) | \(d\) | \(e\) | \(f\) | Purchase |
|-------------|------|------|------|------|------|------|---------|
| \(a\)       | 0/0  | 0/0  | 0/0  |
| \(b\)       | 100/0 | 100/0 |
| \(c\)       | 100/50 | 0/0 |
| \(d\)       | 0/0  | 100/50 |
| Stock       | 205/100 | 400/200 |

### Table 7. Analysis.

|          | D.F. of all (%) | D.F. of \(p_1\) (%) | D.F. of \(p_2\) (%) | R.F. of all (%) | R.F. of \(p_1\) (%) | R.F. of \(p_2\) (%) | Total cost |
|----------|-----------------|----------------------|----------------------|-----------------|----------------------|----------------------|------------|
| C1: S1 realization | 100             | 100                   | 100                   | 100             | 100                   | 100                   | 18,135     |
| C1: S2 realization | 88.89           | 83.33                 | 100                   | 88.89           | 100                   | 66.67                 | 18,475     |
| C1: S3 realization | 53.34           | 55.56                 | 50                    | 80              | 100                   | 50                    | 28,415     |
| C2: S1 realization | 100             | 100                   | 100                   | 100             | 100                   | 100                   | 10,305     |
| C2: S2 realization | 38.89           | 50                    | 16.67                 | 88.89           | 100                   | 66.67                 | 20,445     |
| C2: S3 realization | 23.33           | 33.33                 | 8.3                   | 80              | 100                   | 50                    | 32,385     |

D.F.: demand fulfillment; R.F.: recovery fulfillment.
We assumed $w_1 = 0$, $w_2 = 0$, $w_3 = 1$ and set the value of sustainable factors of new $p1$ pallets as $[0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 12]$. The results are shown in Table 8. We found out that as the sustainable factors of new $p1$ pallets increase, the less new $p1$ pallets are used. The same conclusions could be drawn from Figure 2. It means for those high sustainable factor pallets, managers of a pallet pool should relatively reduce the usage of them.

2. The important effects of customer priority factors on decision making

Let $w_1 = 0$, $w_2 = 0$, $w_3 = 1$ and the value of the customer priority of $c$ as $[0.2 \ 0.5 \ 0.8 \ 1 \ 1.2]$. The results are shown in Table 9. According to the results, the higher the customer priority, the higher the customers’ recovery fulfillment. As shown in Figure 3, we can obtain the same conclusions. It suggests that managers of a pallet pool should first satisfy the needs of high priority customers.

### Conclusion

In this article, we present a model that can provide an optimal pallet allocation scheme over a pallet pool when some uncertain parameters can be estimated through historical data, while some others cannot be. The objective of this model is to minimize the expected total pallet allocation cost. This model’s constraints include supply capacity, transportation capacity, loading and unloading capacity, and so on. Additionally, sustainable factors and customer priority factors are studied in this article. It is apparently shown by our experimental tests that our work is of great help for the pallet pool managers make right decision under uncertain environment. We also found that sustainable factors and customer priority factors are quite important in decision making: (1) managers should use less high sustainable factor pallets and (2) managers should preferentially fulfill the demands of those customers with high priority.

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