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# Inventory routing problem for building members to shorten the period of damaged building restoration

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## *Abstract*

In recent years, natural disasters have frequently occurred in Japan, and it is necessary to support the disaster areas and strengthen their resilience. However, restoration of damaged buildings has been prolonged, and reconstruction activities of damaged buildings after the 2011 Great East Japan Earthquake have continued for eight years now. From the above, there is a need for rapid recovery of damaged buildings.

There are three major processes in the recovery of damaged buildings: Post-earthquake damage evaluation, Damage evaluation, and delivery of building members [1] [2]. In the first process, the damage status of buildings is classified into three categories: unsafe, limited entry, and inspected. In the second process, the detailed damage level of the building is determined, and the building members necessary for restoration are identified. The third process is needed for restoration of the damaged buildings and restoration work. The building members are delivered based on the demand identified in Damage evaluation process and the restoration work plan to be performed thereafter. At present, in Japan, these three guidelines are independently constructed, so the entire process does not advance to the next stage until the previous stage is completed, and the timing of the demand for building members is concentrated. In addition, in an emergency such as an earthquake, the supply and delivery capacities for restoration are limited compared to normal times. For these reasons, due to the shortage in supply capacity to demand, building members delivery delays occur. This is one of the factors that prolong the recovery period.

On the other hand, in the field of industrial management, the inventory routing problem has been proposed as a method of reducing the delivery cost and shortening the delivery period by simultaneously considering both the inventory plan and the routing plan [3]. It is possible to construct a delivery plan for reducing shortage and delivery delays, which equalizes the daily delivery volume in consideration of limited supply and delivery capacities for restoration. Furthermore, this method can lead to a more optimal plan by using demand forecasts and temporary inventory for the uncertain demand. In addition, it has been suggested that the results of Post-earthquake damage evaluation may predict the results of Damage evaluation. It is expected that a rough demand forecast of building members can be obtained from the results of Post-earthquake damage evaluation without waiting for the results of Damage evaluation.

This study proposes a model that integrates Damage evaluation plan and the delivery plan of building members for the purpose of shortening the restoration period. This model focuses on the period from the end of Post-earthquake damage evaluation to the completion of the delivery of building members, among the restoration period of the damaged buildings; a delivery planning model of building members constructed using the inventory routing problem. Demand forecasting is performed based on Post-earthquake damage evaluation results with reference to the past results of Damage evaluation. Demand is updated each period by Damage evaluation. Finally, the delivery plan is implemented ahead of time in parallel with Damage evaluation, and planned based on the forecast demand and the fixed demand.

*Keywords: Building restoration, Post-earthquake damage evaluation, Damage evaluation, Inventory routing problem*

## 1. Introduction

Natural disasters are frequent, with 20% of all earthquakes, of magnitude 6 or more occurring in the world, occurring in Japan [4]. Large-scale earthquake disasters cause not only human damage but also damage to infrastructure and houses. Therefore, there is a need for early support and restoration of the affected areas and enhancement of resilience. However, the restoration of affected houses has been prolonged, and social problems such as serious population outflow, industrial decline, and regional polarization have occurred. In fact, the restoration activities of the houses affected by the Great East Japan Earthquake in 2011 have continued even beyond eight years. From the above, early restoration of damaged houses has become an issue [5] [6].

Restoration of damaged buildings is divided into three stages. The first is Post-earthquake damage evaluation, which evaluates the safety of a building after a disaster occurs. In this process, the damage status of buildings is classified to prevent a secondary disaster caused by the collapse of buildings, falling objects, or falling objects due to the earthquake. Classification is performed in three stages: unsafe, limited entry, and inspected. The second process is Damage evaluation, in which a detailed damage level of a damaged building and building members necessary for restoration are investigated. The third process is delivery of building members for the restoration of the damaged building. Building members required for restoration are delivered based on the demand identified by Damage evaluation [1] [2] [7]. At present, in Japan, each of these processes requires a different professional and is usually performed independently from the other. These independent processes are designed based on information obtained from previous processes. Therefore, the next process cannot be advanced until the previous processes are completed, which leads to the concentration of demand for building members. Generally, when demand concentration occurs, the supply capacity becomes insufficient and the planning is delayed. Emergency logistics, such as during an earthquake, supply and delivery capabilities are often limited compared to normal logistics. Thus, due to a shortage in supply capacity to demand, building members delivery delays occur. This is one of the factors that prolong the restoration period [8].

In recent years, it has been suggested that the results of Post-earthquake damage evaluation can predict the results of Damage evaluation. For example, with the development of technologies such as data mining, drones, and image recognition, it is expected that demand forecasting with higher accuracy will be possible in the future [9][10]. Therefore, it is expected that the demand for members for the restoration of damaged buildings can be obtained from the results of Post-earthquake damage evaluation without waiting for the results of Damage evaluation. However, no model has been proposed to plan the delivery of building members for restoration based on more accurate forecast demand data. In this study, assuming that more accurate forecast demand data is available, we propose a model that integrates Damage evaluation and delivery of building members for shortening the restoration period.

On the other hand, in the field of industrial management, emergency logistics is attracting attention. Emergency logistics are classified into three types according to response timing: the preparatory phase, the response phase, and the restoration phase. In the preparatory phase, risk reduction before disasters is performed, such as strengthening infrastructure and pre-positioning inventory. In the response phase, rescue operations are carried out immediately after the disaster. These include facility locations, distribution of relief supplies, mass evacuation, and casualty care. In the restoration phase, the damaged system is restored through activities such as repairing and rebuilding infrastructure and delivering members [11]. This study focuses on the delivery plan of building members in the restoration phase.

Research on emergency logistics has been studied for various purposes, such as length of planning period, satisfaction of demand, high cost, and long distance of delivery. The purpose of Yi and Ozdamar (2007) is fairness of demand satisfaction. They used healthcare facilities' location and delivery plans for prioritized demand to minimize delays in providing each service [12]. The purpose of Balcik and Beamon (2008) is to minimize delivery costs. They looked at relief delivery plans and sought to maximize the benefits of helping recipients. Thus, the purpose of emergency logistics is wide-ranging, but the purpose of this study is to restore damaged buildings earlier. Therefore, this study focuses on reducing the length of the planning period [13].



In this study, the inventory routing problem is used as a method to reduce the delivery cost and shorten the delivery period by considering both the inventory plan and the routing plan at the same time. This method can create a delivery plan to reduce shortages and delivery delays. Also, the daily delivery volume can be equalized, taking into account the limited supply and delivery capacities for restoration.

In recent years, a method called planned transshipment has had attention. It has proven to be effective in reducing delivery costs in supply chains according to Coelho et al. (2012). Planned transshipment is a method of temporarily sharing warehouses by shops of a single decision maker, thereby shortening the transportation distance, and reducing the cost [3]. Peres et al. (2017) used this method with cases in Brazilian retail stores and showed that planned transshipment was effective in reducing the total cost in a multi-period, multi-product inventory routing problem. But, restoration of damaged buildings requires not only minimizing costs but also minimizing the restoration period. Using the planned transshipment model to minimize the delivery period has not been studied and its effects have not been investigated [14].

Therefore, this study proposes an inventory routing model that considers planned transshipment to shorten the delivery period for the purpose of shortening the restoration period, and verifies the effect. This model focuses on the period from the end of Post-earthquake damage evaluation to the completion of the delivery of building members, as part of the restoration periods of the damaged buildings. The proposed model shows vehicle routing and building members delivery planning to minimize delivery period. In the numerical experiment, the scenario is analyzed using the proposed model.

## 2. Model building

This section shows the preconditions of the proposed model, and Figure 1 illustrates its focus. The purpose of the proposed model is to shorten the delivery period, that is, the restoration period. Based on the demand information given by Post-earthquake damage evaluation and Damage evaluation, the proposed model seeks a delivery plan for building members.

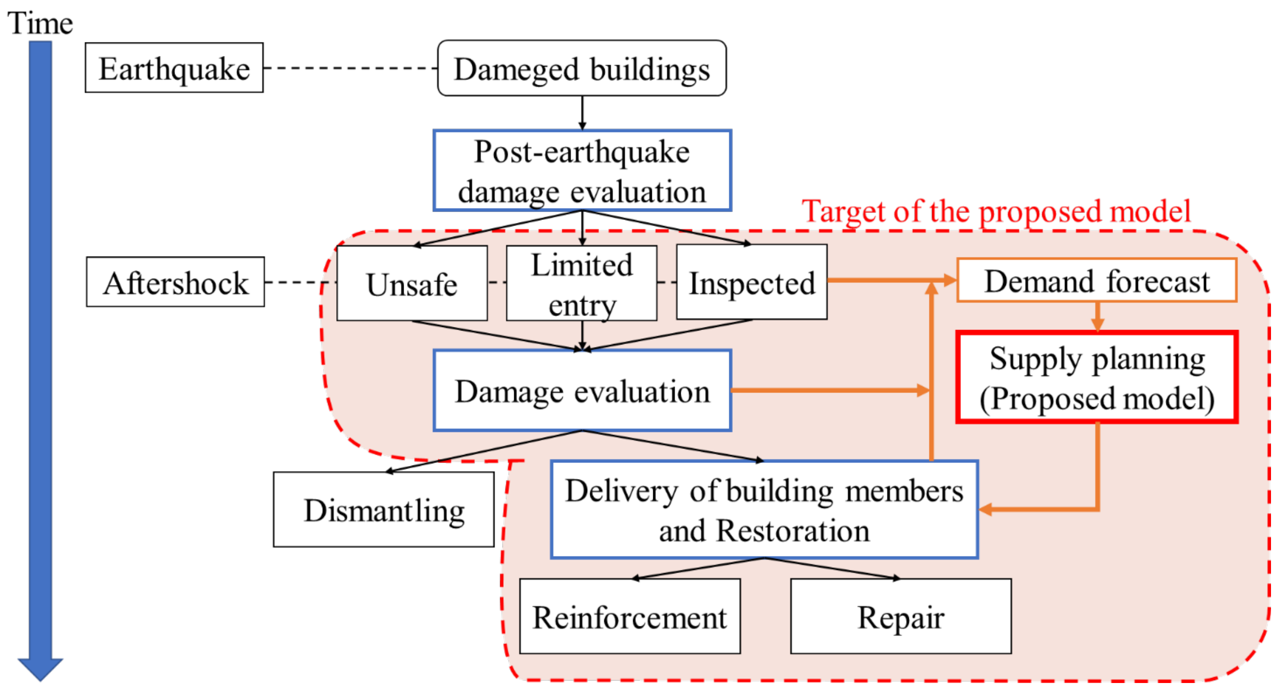



Fig. 1 – Target of proposed model



### 2.1 Precondition

The assumptions of the model in this study are as follows.

- The proposed model consists of one base and multiple demand points.
- The proposed model is represented by a complete graph.
- The planning period is a multi-period.
- The purpose is minimization of such period until the satisfaction of all demands.
- The base and each demand point have a limited inventory capacity.
- Each demand point faces a different demand for each period.
- The demand given for each demand point is based on very accurate forecasts.
- A single building member is considered to simplify the model.
- The building member has the same capacity and volume.
- Unsatisfied demands carry over to the next period.
- The base has a fixed number of vehicles.
- All vehicles are equal and have inventory capacity.
- A vehicle passes through a maximum of one route per period, and all vehicles depart from the base and return during that period. Vehicles not being used for deliveries remain at the base.
- Not all costs are considered.

### 2.2 Inventory routing problem with planned transshipment

This study used an inventory routing problem with planned transshipment (IRPT) as the basis of the proposed model. In the IRPT model, inventory management, delivery planning, and transshipment are considered simultaneously to derive a delivery plan. This study focuses on planned transshipment as proposed by Coelho et al. (2012) [3].

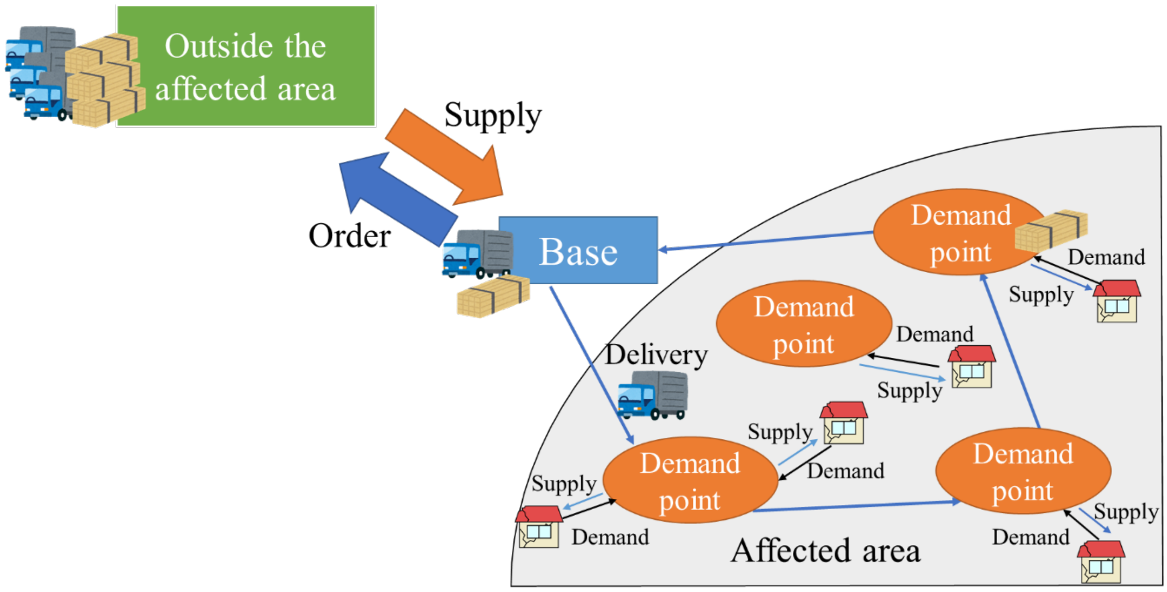



Fig. 2 – The proposed model (IRPT)



Fig. 2 shows a conceptual diagram of the proposed model. The demand point has different demands for each period. Demand points are assumed to be facilities that can process building members, such as home centers. The demand point orders the supply of the building material for each term to the base, and the base uses a vehicle to deliver the building members to the demand point. The base is assumed to be a large-scale warehouse. Building materials are supplied from outside the affected area to the bases in an amount corresponding to the capacity of the bases in each period.

Caunhye et al. (2016) proposed an emergency delivery model using lateral transshipment. In their model, to respond to uncertain demand in preparation for urgent deliveries, pre-placed inventory locations and subsequent delivery routing were performed. However, they limited inventory placement to warehouses, and transshipment was done only between warehouses. Therefore, a delivery plan between demand points was not considered [15].

In planned transshipment, the vehicles to be used are limited to normal delivery. Planned transshipment is a method of temporarily placing products to be delivered to a buyer in the future, in the warehouse of another buyer. Allowing temporary placement of other demand points of inventory will expand the delivery plan.

Rahbari et al. (2018) showed that planned transshipment is effective in reducing CO2 emissions and costs. They have shown that planned transshipments are effective in reducing transportation distances but have not shown them to be effective in reducing the planning period [16].

### 2.3 Formulation

The IRPT model proposed in this study uses the following notation:

**Sets**

| | |
|---|---|
| $V^d$ | Vendor (depot) |
| $V^c$ | A set of *n* buyers |
| $V$ | $V^d \cup V^c$ (A set of *n*+*1* nodes) |
| $K$ | A set of $k_{max}$ vehicles |
| $T$ | A set of $t_{max}$ periods |

**Parameters**

| | |
|---|---|
| $C_i$ | Maximum storage capacity of each buyer *i* |
| $C_{base}$ | Maximum storage capacity of the base |
| $d_{t,i}$ | Demand of each buyer during each time period *t* |
| $Z$ | Maximum capacity of vehicle |
| $r_{i,j}$ | Distance of the arc (*i*, *j*) |

**Decision variables**

| | |
|---|---|
| $t_{len}$ | Length of planning period |
| $Q_{t,i,k}$ | Quantity of product shipped from depot by vehicle *k* to buyer *i* in period *t* |
| $x_{t,i,j,k}$ | Decision to use or not use vehicle *k* in arc (*i*, *j*) in time period *t* |
| $y_{t,i,k}$ | Decision to arrive or not at buyer *i* vehicle *k* in time period *t* |
| $yy_{t,k}$ | Decision to use or not use vehicle *k* in time period *t* |
| $I_{t,i}$ | Inventory level of buyer *i* in period *t* |
| $QC_{t,i,k}$ | Inventory level in vehicle *k* shipped to buyer *i* in period *t* |
| $w_{t,i,j,k}$ | Transshipment amount by vehicle *k* from buyer *i* to buyer *j* in period *t* |



**Formulation**

Minimize $\quad t_{len}$ (1)

Subject to

$I_{t,i} - I_{t-1,i} = \sum_{k \in K} Q_{t,i,k} - d_{t,i} + \sum_{j \in V^c} \sum_{k \in K} w_{t,j,i,k} - \sum_{j \in V^c} \sum_{k \in K} w_{t,i,j,k}, \forall t \in T, \forall i \in V^c$ (2)

$I_{t,i} \leq C_i \; \forall t \in T, \forall i \in V^c$ (3)

$Q_{t,i,k} \leq y_{t,i,k} \times C_i, \forall t \in T, \forall i \in V^c, \forall k \in K$ (4)

$\sum_{i \in V^c} Q_{t,i,k} \leq yy_{t,i} \times Z, \forall t \in T, \forall k \in K$ (5)

$\sum_{i \in V^c} x_{t,i,j,k} = \sum_{i \in V^c} x_{t,j,i,k} = y_{t,n,k},, \forall t \in T, \forall j \in V^c, \forall k \in K$ (6)

$\sum_{i \in V^c} x_{t,0,i,k} = \sum_{i \in V^c} x_{t,i,0,k} = yy_{t,k},, \forall t \in T, \; \forall k \in K$ (7)

$y_{t,i,k} \leq yy_{t,k}, \forall t \in T, \forall i \in V^c, \forall k \in K$ (8)

$\sum_{k \in K} yy_{t,k} = 0, \; \forall t \in \{t_{len} + 1, \; t_{len} + 2, \dots, t_{max}\}$ (9)

$\sum_{i \in V} \sum_{j \in V} x_{t,i,j,k} = 0, \forall t \in T, \forall k \in K, i = j$ (10)

$\sum_{i \in S} \sum_{j \in S} x_{t,i,j,k} \leq |S| - 1, \forall S \subset V, \forall t \in T, \forall k \in K, |S| \leq 2$ (11)

$w_{t,i,j,k} \leq y_{t,i,k} \times y_{t,j,k} \times I_{t-1,i}, \; \forall t \in T, \; \forall i \in V^c, \; \forall k \in K$ (12)

$w_{t,i,j,k} \leq y_{t,i,k} \times y_{t,j,k} \times C_j, \forall t \in T, \; \forall i \in V^c, \; \forall k \in K$ (13)

$QC_{t,0,k} = \sum_{i \in V^c} Q_{t,i,k}, \; \forall t \in T, \forall k \in K$ (14)

$QC_{t,i,k} = \sum_{n \in V} x_{t,n,i,k} \times QC_{t,n,k} - Q_{t,i,k} + \sum_{j \in V^c} (w_{t,i,j,k} - w_{t,j,i,k}), \; \forall t \in T, \; \forall i \in V^c, \; \forall k \in K$ (15)

$Z \geq QC_{t,0,k} \geq 0, \; \forall t \in T, \; \forall i \in V^c, \; \forall k \in K$ (16)

$\sum_{i \in V^c} \sum_{k \in K} Q_{t,i,k} \leq C_{base}, \forall t \in T$ (17)

$x_{t,i,j,k}, y_{t,i,k}, yy_{t,k} \in 0{,}1, \forall t \in T, \forall i \in V, \forall j \in V, \forall k \in K$ (18)

$Q_{t,i,k} \geq 0, \forall t \in T, \forall i \in V, \forall j \in V, \forall k \in K$ (19)

$w_{t,i,j,k} \geq 0, \forall t \in T, \; \forall i \in V^c, \; \forall k \in K$ (20)

The proposed model minimizes the planning period. The objective function (1) minimizes the planning period length. The left side shows the difference in inventory between the end of period t and the end of period t-1, and the right side shows the amount of delivery and demand, including transshipments, in period *t*. Constraint (3) ensures that, during each time period and for each buyer, the inventory level complies with the storage capacity of the buyer. Constraint (4) ensures the amount of product delivered to node *i* by vehicle *k* in period *t*. Constraint (5) ensures that vehicle *k* complies with its capacity of vehicle *k* at each time period *t*.



Constraint (6) ensures the conservation of vehicle flow for each buyer, so that every vehicle $k$ arriving at a node $i$ coming from any buyer $j$ must leave the buyer $j$ going to any node $i$. Constraint (7) ensures that only vehicles carrying a product can leave the factory and that every vehicle must return to the factory. Constraint (8) ensures that vehicles not leaving the depot will not visit any buyer $i$. Constraint (9) ensures the length of the planning period. Constraint (10) prevents the existence of arcs ($i$, $j$), where $i$ equals $j$. Constraint (11) prevents the occurrence of sub routes. Equations (12) and (13) ensure that the constraints on the amount of inventory and the amount of transshipment due to vehicle loading constraints, respectively, are upheld. Equation (24) confirms the inventory level when the vehicle leaves the vendor. Equations (15) and (16) ensure that the inventory level in the vehicle follows the loading constraint when the vehicle leaves each buyer. Constraint (17) ensures that the members delivered from the base in each period do not exceed the stock capacity of the base. Finally, Constraints (18), (19), and (20) define the domain of the respective variables.

## 3. Scenario analysis

Numerical experiments are conducted to investigate the effectiveness of the proposed model.

### 3.1 Numerical example

The following numerical example is used to investigate the effect of the proposed model. There is one base, four demand points ($n$ is 4), a single building member, $k_{max}$ is 2, and $T_{max}$ is 10. The coordination of the vendor and buyers are shown in Table 1.

Table 1 – Coordination of the base and the demand points

| | x | y |
|---|---|---|
| 0 | 139.06 | 36.39 |
| 1 | 139.64 | 35.45 |
| 2 | 139.65 | 35.85 |
| 3 | 140.12 | 35.6 |
| 4 | 139.88 | 36.57 |

The distance between each vendor and buyer was calculated as a straight line. The dataset for this node is clustered in problem sets.

- Demand for each demand point is known throughout the period and is set as follows. 1: Demand for 35 in period 1; 2: Demand for 28 in period 2; 3: Demand for 15 in period 3; 4: Demand for 72 in period 4.
- Limit on inventory of the base is 40 (units), limit on inventory of the vehicles is 30 (units), and limit on inventory of each demand point is 20 (units).

The proposed model decides upon the delivery amount, use of transshipment, and the delivery route. The purpose of the proposed model is to minimize the planning period. In the scenario analysis, it is compared with the delivery distance minimization model. The delivery distance minimizing model is generated by replacing equation (1) with equation (21).

Minimize $$\sum_{i\in V}\sum_{j\in V}\sum_{t\in T}\sum_{k\in K} r_{i,j}\times x_{t,i,j,k} \quad (21)$$

Calculations were made using a personal computer (OS: Windows 7 professional 32 bit) with Intel® Core ™ 2 Duo CPU E8600 @ 3.33 GHz CPU and 4 GB RAM on Python 2.7.15. The mathematical planning solver used was Gurobi Optimizer Version 6.0.3. The results of the numerical experiments conducted under the above environment are shown below.

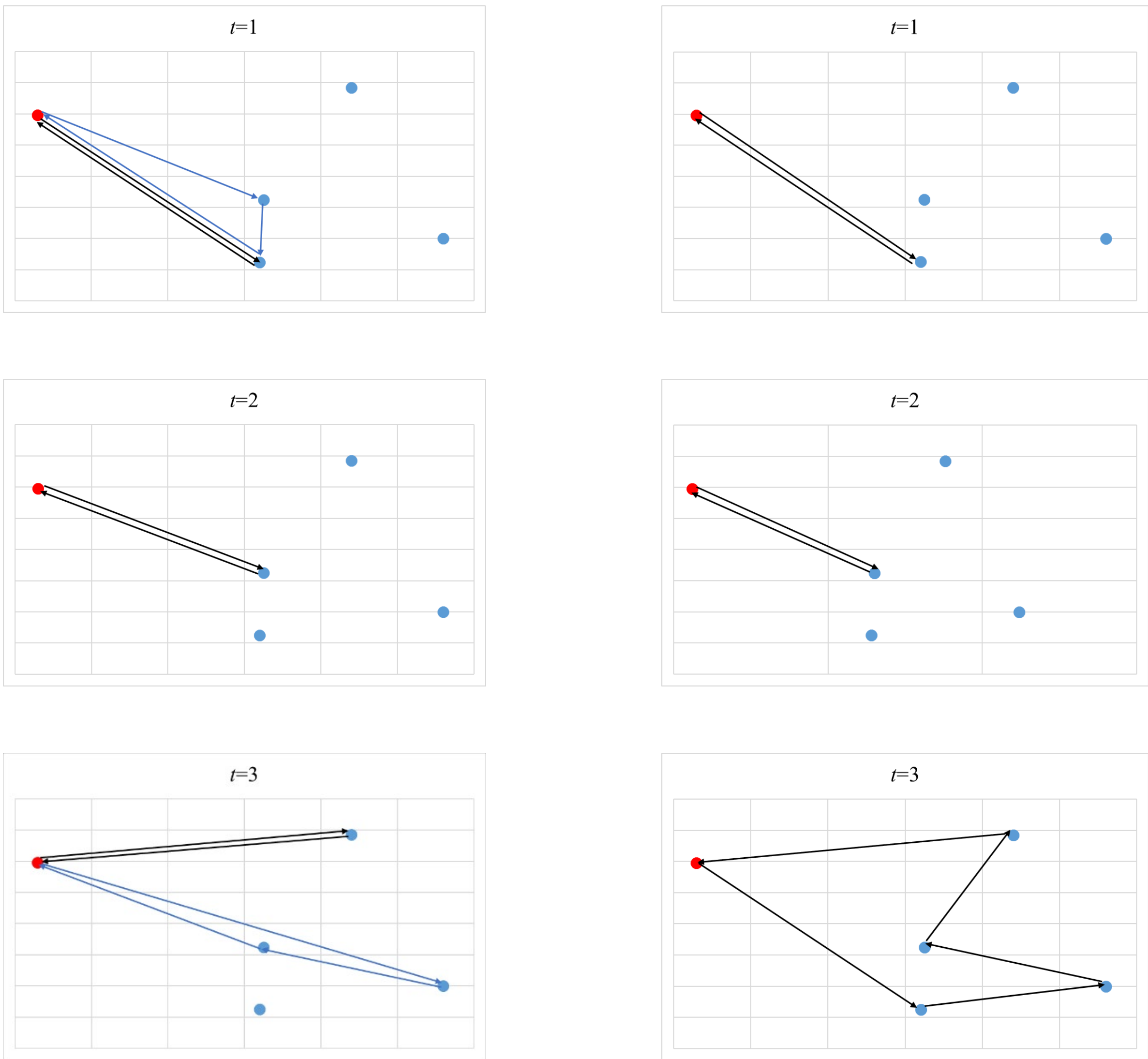

 

### 3.2 Comparison of the planning period

The IRPT model for minimizing the planning period and the IRPT model for minimizing the delivery distance were compared in terms of the delivery route established by each (Fig. 3)

The red dots show the base and the blue dots show demand points. The path of the vehicle is indicated by black and blue lines. As shown in Fig. 3, the delivery route differs between the period minimization and the distance minimization. In the former, a circuit is likely to be created, but in the latter, the piston traveling increases. In addition, it can be seen that the model for minimizing the planning period uses many vehicles, and the number of times of visiting each demand point is large.

Minimizing the planning period | Minimizing the delivery distance





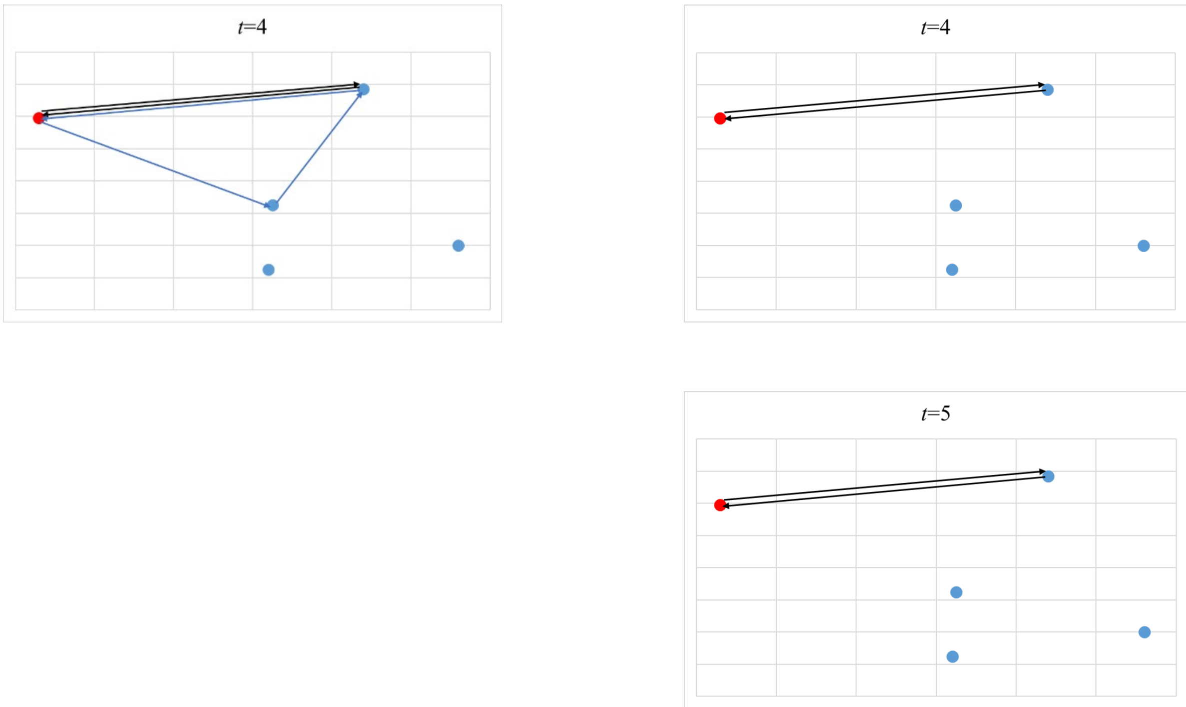



Fig. 3 – Comparing delivery routes by purpose

Fig. 4 is a graph comparing the period and the delivery distance. From this result, it can be seen that the short delivery distance is not proportional to the short planning period. Rather, the delivery distance is longer due to the minimization of the planning period, and a trade-off relationship can be seen. Therefore, it is shown that the proposed model is effective for minimizing the planning period in emergency logistics without considering cost.

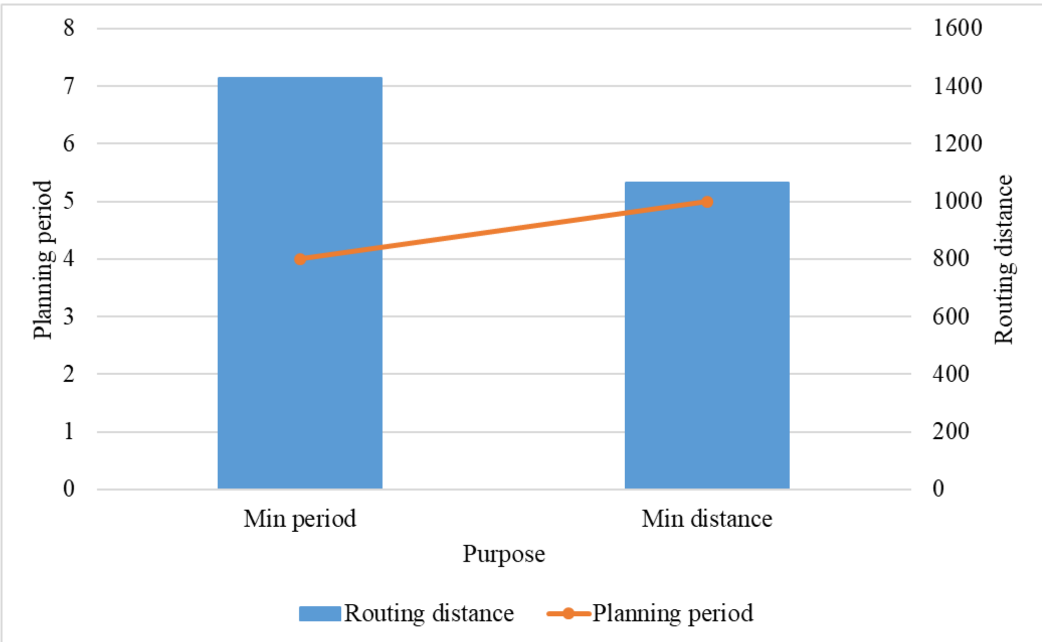



Fig. 4 – Comparing planning period and routing distance by purpose

## 4. Conclusion

This study models the inventory routing problem with planned transshipment of building members to shorten the restoration period. The proposed model is based on the assumption that accurate demand forecast data is available for the period from the end of Post-earthquake damage evaluation to the completion of building members delivery. In the proposed model, planned transshipment was used in the presence of supply resource constraints (vehicle and inventory constraints) to shorten the delivery period. Scenario analysis shows that IRPT is effective in shortening the delivery period. The results of numerical experiments show that the delivery distance is not always proportional to the delivery period length.

The proposed model enables quick decision support in the turmoil immediately after a disaster. When making decisions, two types of models are needed: a model that looks at the future considering complex elements from a lot of information, and a model that shows what can be done now that takes into account simple elements from a small amount of information. However, in an emergency such as an earthquake, a simpler and more flexible model is required than a model that carefully represents reality. The proposed model in this study is useful in this regard.

Future prospects include analysis in scenarios based on past disaster data and proposals for models incorporating updated demand. Furthermore, a model combining the demand forecasting phase and the delivery phase may be considered. In addition, the proposed model is static, and we would like to work on a dynamic model in future research.

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