Flow-Capturing Location Allocation Programming for More Effective and Robust Locations

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Abstract: In order to assure a high longitudinal accessibility for local public facilities, the effect of flexible use along commuting flows is analyzed in this paper. First, it is shown that the flexible use during the commuting trips can improve the accessibility to existing facilities, compared to the rigid use only by the neighboring inhabitants, and also assure the robustness of accessibility under a change of residential distribution and closure of a facility. Secondly, at the facility location planning stage, it is shown that a flow-capturing location allocation planning (FCLAP) minimizing the additional travel time for the facilities based on the commuting flows, can provide superior locations to the standard residence-based location allocation planning (RBLAP) minimizing the home-facility travel time, in terms of the average travel time and its robustness under the change of residential distribution and the decreased number of construction.

Keywords: local public facility, location planning, flexible use, robustness of accessibility

1. INTRODUCTION

Local public facilities are expected to be used for a few decades. However, changes in residential distribution, such as a new development of suburban housing, and closures of facilities, are likely to occur, which will alter relative accessibilities to these facilities for the rigid use only by the neighboring inhabitants, which is called residence-based-use (RBU) (Horiuchi *et al.,* 2008). Miyagawa (et al, 2004) and Ozaki and Ohsawa (2005) discussed the decrease of the RBU accessibility under a decreasing number of facilities. Furthermore, facility closure planning has considered accessibility and running costs (Otani *et al*, 2002; Kitamura, 2007).

Hodgson (1981) proposed that people can use a local facility, not by making a new trip, but by inserting the facility between the preset destinations. We call the flexible use during the commuting trips, as flow-based-use (FBU). Hodgson compared FBU with RBU in terms of the additional trip length to facilities, and showed that FBU is superior to RBU. Similar comparisons have been shown, for example, in Miyagawa and Ohsawa (2001). However, these comparisons of FBU and RBU are focused on how to wisely use the existing facilities in short point of view. This paper stands on a longer point of view and compares FBU and RBU, in terms of the robustness of travel time under a change of residential distribution and closure of a facility.

As for location planning for new facilities, Hodgson (1981), Berman (1997) and Suzuki (2002) presented a formulae for the flow-capturing location allocation planning process (FCLAP), which minimizes any additional travel time for the facilities based on the commuting flows. This is based on the p-median model. Hodgson (1981) pointed out that FCLAP estimates the accessibility of FBU to be higher than residence-based location allocation planning (RBLAP), which have been frequently used for local public facility location planning by minimizing the home-facility travel time. Suzuki (2002) analyzed properties of optimal facility locations by solving FCLAP and RBLAP. Concerning the robustness of the RBLAP solutions, there have been some studies that have analyzed the effect of inaccurate predictions of residential distribution (Kubota and Suzuki, 2004), and have formulated RBLAP under uncertainty of the number of additional facilities to be located (Berman and Drezner, 2008).

This paper is written to answer the following questions. How does FBU save the average travel time to the existing facilities, compared with RBU? What is the performance of FBU in terms of the robustness of average travel time under a change of residential distribution and a closure of a facility? Moreover, at the facility location planning stage, how does FCLAP provide superior locations than RBLAP in terms of the average travel time? Does FCLAP successfully provide more robust locations than RBLAP under a change of residential distribution and a decreased number of facility constructions?

This paper is organized as follows. The method of evaluating accessibility to local public facilities is explained in section 2. In section 3 differences between flow-based-use (FBU) and residence-based-use (RBU) in terms of accessibility to the existing facilities are identified. The performance of flow-capturing location allocation planning (FCLAP) is compared to the more traditional residence based location allocation planning (RBLAP) in terms of accessibility to facilities for future FBU and its robustness are considered in Section 4. In section 5, the conclusions and suggestions for future research are presented.

2. ACCESSIBILITY MEASURE TO POINT FACILITIES

2.1 Facility use models

In this paper, an average travel time by car to local public facilities is used as an index that defines and evaluates accessibility to the facilities, although the literature points to many definitions of “accessibility”, see Guers and Ritsema van Eck (2001). The average travel time of residence-based-use (RBU) and that of flow-based-use (FBU) to the given facility locations can be calculated through the linear programming problems formulated below, neglecting capacity limitations. The problems are solved by a public-domain freeware for linear programming solver, called glpk (Ver.4.8).

The following definitions of subscripts, parameters and variables are used;

Subscripts: Residential zone (node): i, Employment zone (node): j, Facility candidate zone (node): k,

Parameters: Travel time from i to k: t_{ik}, Travel time from k to j : t_{kj}, Travel time from i to j : t_{ij},

Share of the commuters from i to j in year A: w_{ij}^A, The number of facilities to be located: p

Variables: $X_{ijk}(\geq 0)$: Allocation ratio of commuting users originating at residential zone i and terminating at office zone j to a facility in zone k,

$Y_k \in \{0,1\}$: Binary variables that stand for the existence of a facility in zone *k*.

Residence-Based-Use (RBU) model

This model minimizes the average travel time, *Z*, from home to the nearest facility chosen from the given facilities.

$$\min_{X_{ijk}} Z = \sum_{i,j,k} w_{ij}{}^{A} t_{ijk} X_{ijk} \tag{1}$$

$$s.t. \sum_{k} X_{ijk} = 1 \quad \forall i, j \tag{2}$$

$$X_{ijk} \le Y_k \quad \forall i, j, k \tag{3}$$

$t_{ijk} = 2 \times t_{ik} (\ge 0)$: Travel time of round trip to use facility in facility candidate zone *k* from residential zone *i*, which is irrespective to the employment zone *j,*

Flow-Based-Use (FBU) model

This model minimizes the average additional travel time *Z,* for given facilities based on the given commuting flows and obtains the most effective allocation of the users for the facilities.

$$\min_{X_{ijk}} Z = \sum_{i,j,k} w_{ij}{}^{A} t_{ijk} X_{ijk} \tag{4}$$

$$s.t. \sum_{k} X_{ijk} = 1 \quad \forall i, j \tag{5}$$

$$X_{ijk} \le Y_k \quad \forall i, j, k \tag{6}$$

$t_{ijk} = t_{ik} + t_{kj} - t_{ij} (\ge 0)$: Additional travel time to use facility in facility candidate zone *k* during the commuting trip from residential zone *i* to employment zone *j*（detour time）.

Equations (2) and (5) ensure that each commuter is assigned to exactly one facility. Equations (3) and (6) make sure that if there is no facility located at facility candidate zone *k*, none of commuters can be assigned to the zone *k*, and if there is a facility located at zone *k*, commuters can be assigned to it.

Taking into consideration that the RBU option is also permitted in the FBU, when the additional travel time to the facility nearest from the residence gives the shortest additional time along the commuting route, it is impossible that the average travel time of RBU becomes smaller than the average travel time of FBU for any given facility locations.

2.2 Case study

Child care facilities are taken up as targeted local public facilities in the case study. Improvement of accessibility of child care service is now considered as one of the most promising issues in Japan to expand the working opportunity of urban women (Miyazawa, 1998). The users of the facilities are regarded as the commuters who have (a) preschool children under the age of five. The case study area is set as the Northern quarter of Sendai Metropolitan Area, Miyagi prefecture, Japan, as shown Figure 1 (On this map the circle represents the center of the Sendai Metropolitan Area). This segment is chosen because there are many commuters with preschool children in Sendai City, so the results obtained are representative of the other three segments. The study area is divided into 43 zones according to the medium-sized traffic zones defined in the Person Trip Survey for the Sendai Metropolitan Area in

2002, after excluding those zones which do not include a center point of the statistical 500m mesh for the Population Census of the Statistics Bureau in Japan. This scale of zone definition is especially appropriate because there are very few zones where more than two child care facilities are located.

2.3 Data

The users of child care facilities are the commuters who have (a) preschool children under the age of five. It is assumed that one commuter decides one child care facility beforehand, and leaves one child there. Population under the age of five is provided by the Population Census in 2000. Commuting patterns (share of employment zones) of the residents in each residential zone are derived from the samples of the Person Trip Survey in 2002. Travel time is equal to average values of total travel time from residential zone to employment zone by car based on the Person Trip Survey, and Dijkstra method is applied to the travel time to fill the values for the missing OD pairs.

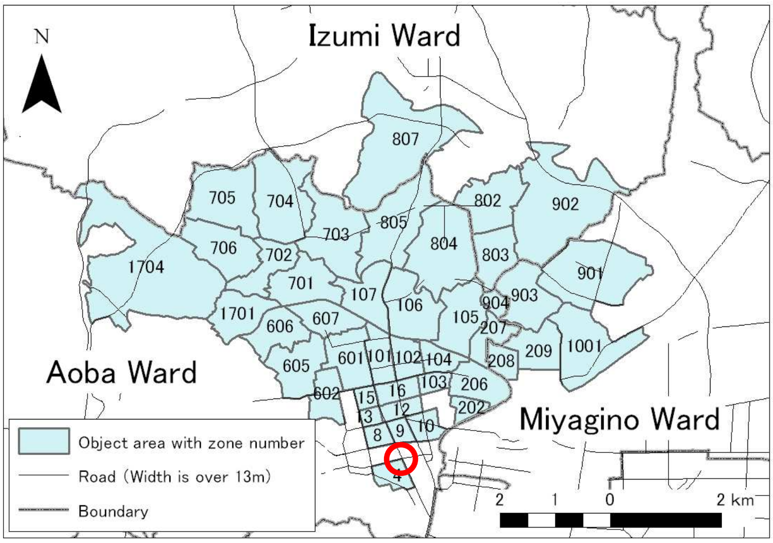

Figure 1 The study area and main road network in Sendai city, Japan

3. THE EFFICIENCY OF FLOW-BASED-USE (FBU)

3.1 The Assumption of an existing facility location

Section 3 assesses the efficiency of FBU compared with RBU for any given existing pattern of facility location. The results from this comparison definitely depend on the given existing facility location, but it is difficult to make comparisons for many variety of existing facility location patterns. Here, we calculate the performance of FBU and RBU, for the facility location most advantageous for the RBU. We assume the existing facilities locations designed by the following residence-based location allocation planning (RBLAP) that minimizes the residence-facility travel time. The solution of the model is called residence-based-location (RBL) in this paper.

Residence-based location allocation planning (RBLAP) model

This model minimizes the average residence-facility round trip travel time, Z, and determines the most convenient facility locations, Y_k, for RBU.

$$\min_{X_{ijk}, Y_k} Z = \sum_{i,j,k} w_{ij}{}^{A} t_{ijk} X_{ijk} \tag{7}$$

$$s.t. \quad \sum_{k} X_{ijk} = 1 \quad \forall i, j \tag{8}$$

$$X_{ijk} \leq Y_k \quad \forall i, j, k \tag{9}$$

$$\sum_{k} Y_k = p \tag{10}$$

$t_{ijk} = 2 \times t_{ik} (\geq 0)$: Travel time of round trip to use the facility in facility candidate zone k from residential zone i, which is irrespective to the employment zone j.,

Equation (10) ensures that the correct number of p facilities are located.

3.2 Comparison of the average travel time

Both the RBU model and the FBU model are applied to the RBL based on the survey w_{ij}^{2000}, then they are used to calculate the average travel time. The ratio in shown in the figures in this section 3 are the value of FBU divided by the value of RBU.

As shown in Figure 2, the average travel time of FBU is about half as long as the average travel time of RBU. Therefore, it is confirmed that the accessibility to facilities of FBU is substantially higher than that of RBU.

3.3 The increase of travel time under a change of residential distribution

There is a possibility that a change of a residential distribution increases the travel time to the existing local public facilities, while the facilities are in use. Here, we compare the RBU and FBU in term of the increase of average travel time under a change of a residential distribution.

First, we produce a set of 100 hypothetically-changed residential location pattern and

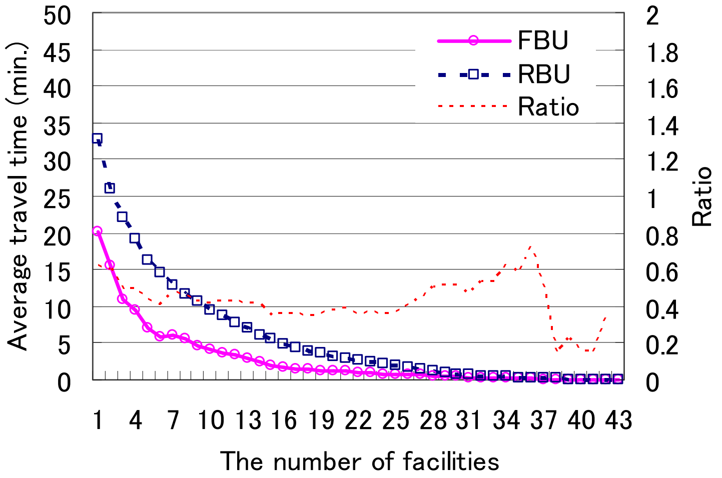

Figure 2 Comparison of average travel time for FBU and RBU

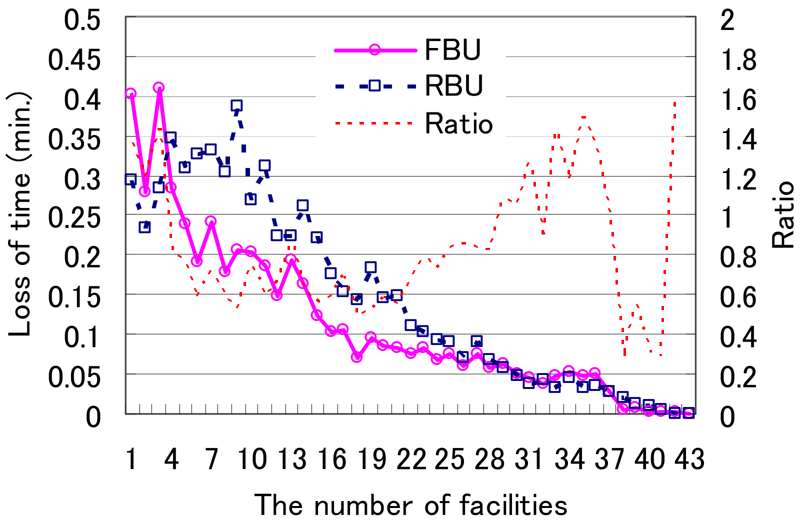

Figure 3 Comparison of loss of time under a change of a residential distribution

the corresponding share of commuters, w_{ij}^f, by applying equation (11).

$$w_{ij}^{\ f} = w_{ij}^{2000}(1+\sigma \cdot R) \qquad (11)$$

σ: Parameter representing the degree of a change of residential distribution. σ equals 0.3, because 0.3 is very large value on the condition that w_{ij}^f is positive.

R: Random numbers following normal distribution.

RBU model is applied for each case of the 100 residential distributions to obtain the corresponding average travel time to the facilities. These 100 numbers are arranged in numerical order, and the 95th shortest value is defined as "the average travel time in 95% probability", which is one service level of facilities to provide for users. The difference between the value from the original average travel time before the change of residential distribution is called "loss of time by RBU". Similarly, the FBU model is applied, and "loss of time by FBU" is calculated.

As shown in Figure 3, the "loss of time by FBU" is less than the "loss of time by RBU" at almost all facilities. This is because many commuters do not have to change their ways very much to work and are able to use the same facilities after a change of residential distribution in FBU case.

3.4 The increase of travel time under a closure of a facility

There is a possibility that a closure of facilities increases the travel time to the facilities, while the facilities are in use. Here, we compare RBU and FBU in term of the increase of average travel time under a closure of a facility. For each type of use; RBU and FBU, we allow a free choice of one facility to be closed out of the given RBL facilities, in order to reduce the effect of the closure. We can formulate such mathematical problem to find the facility of the least closure effect, but it is not shown because of space limitations. As a result we can calculate the increase of the average travel time due to the facility closure. They are called "loss of time by RBU" and "loss of time by FBU", respectively.

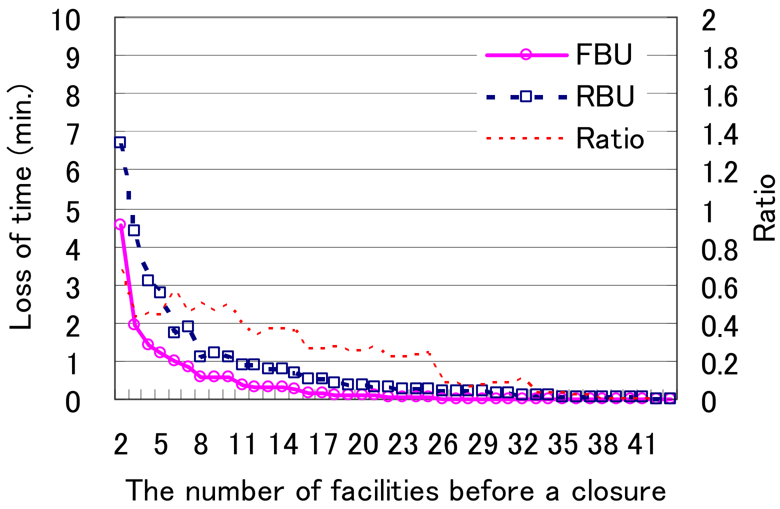

Figure 4 Comparison of loss of time under a closure of a facility

As shown in Figure 4, the "loss of time by FBU" is always smaller than the "loss of time by RBU". Therefore, even though a facility is closed, accessibility by FBU is kept relatively high because people are able to find another facility on their way to work more easily, compared with the case from their residence.

4. FLOW CAPTURING LOCATION ALLOCATION PLANNING (FCLAP)

4.1 Flow capturing location allocation planning (FCLAP)

In section 3, we have demonstrated the efficiency of FBU in terms of the average travel time and its robustness compared to RBU, even if the given facility location was designed as to optimize the RBU. If we consider FBU as a way of future facility use, we should change the location planning method into one of optimizing FBU. The performance of the location planning for local public facilities optimizing the accessibility by FBU is already suggested by several authors (Hodgson, 1981; Suzuki, 2002) with the name of "flow-capturing location allocation planning" (FCLAP) and formulated as follows. In this section, we call the solution to this problem as flow-capturing location (FCL).

Flow capturing location allocation planning (FCLAP) model

This model minimizes the aggregated additional travel time, Z, for the facilities, k, based on the given commuting flows from i to j, and solves the facility locations Y_k and corresponding FBU allocation X_{ijk}.

$$\min_{X_{ijk}, Y_k} Z = \sum_{i,j,k} w_{ij} {}^{A}t_{ijk} X_{ijk} \tag{12}$$

$$s.t. \quad \sum_{k} X_{ijk} = 1 \quad \forall i, j \tag{13}$$

$$X_{ijk} \leq Y_k \quad \forall i, j, k \tag{14}$$

$$\sum_{k} Y_k = p \tag{15}$$

$t_{ijk} = t_{ik} + t_{kj} - t_{ij} (\geq 0)$:

Additional travel time for FBU in facility candidate zone k during commuting trips from residential zone i to employment zone j （detour time）

Below, we compare the FBU performance for the FCL and for the traditional residence-based location (RBL).

4.2 The difference of average travel time for FBU

Because the FCLAP optimizes FBU accessibility, but FCLAP optimizes a different objective under the same feasibility conditions, FBU accessibility for the FCL dominates theoretically that for the RBL. In order to show the quantitative difference, we compare the FBU accessibilities for those two locations. The ratios in the figures in this section 4 are the value of the FBU average travel time for the FCL divided by that for the RBL.

As shown in Figure 5, the average travel time to the FCL is always shorter than that to the RBL. The ratio value is around 0.8, when the number of facilities is small as half the number of the zones. When the number of facilities becomes fairy large, the FCL locations capture most of the commuting flows, more successfully than the RBL: the ratio gradually drops with the increase of the number of facilities and approaches zero at around 37 facilities.

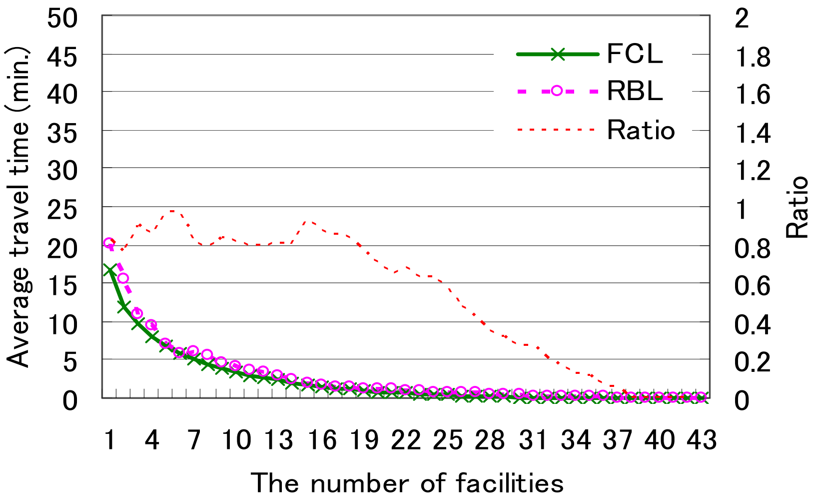

Figure 5 Comparison of the two locations in terms of the accessibility

4.3 The robustness of travel time under a change of residential distribution

As a change in the residential distribution might increase the average travel time to the FCL, as well as the RBL, we compare the robustness of the travel time to these two locations, when a change of residential distribution occurs.

As in section3.3, we produce a set of 100 hypothetically-changed residential location patterns and the corresponding share of commuters, w_{ij}^{f}, by applying equation (11). Both for the given FCL and RBL, the FBU model was applied for each case of the 100 residential distributions to obtain the travel time to the given facilities. These 100 numbers of the two locations are arranged in numeric order respectively. A value of

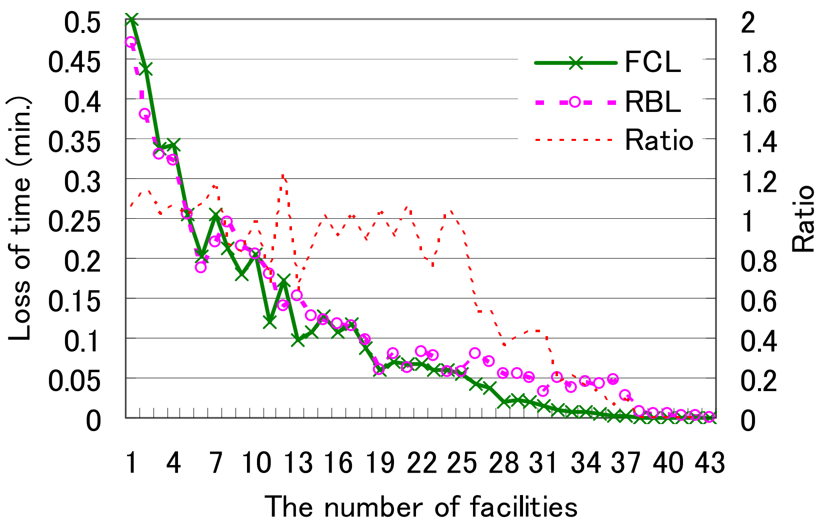

Figure 6 Comparison of the two locations in terms of the robustness of average travel time under a change of a residential distribution

the 95th number is called "average travel time in 95% probability". The difference between those values and the original average travel time before the change of a residential distribution for the two locations are called "loss of time to the RBL" and "loss of time to the FCL", respectively.

As shown in Figure 6, the "loss of time to the FCL" takes on similar values as the "loss of time to the RBL" for the smaller number of facilities up to 27, where the ratio suddenly drops because the number of facilities becomes large enough to capture all the commuting flows - even after the change of the residential location.

4.4 The robustness of travel time under a decreasing number of construction

It is difficult to predict the future number of users for public facilities. Sometimes, as a result of an over-estimation of demand at an early planning stage, cancelling the construction of a few facilities must be considered as a practical option. In such situations, however, stopping construction of a facility may be harmful for the travel time to those facilities which are already constructed. Here, we compare the robustness of the FCL and that of the RBL under a decreased number of facility constructions. For each location of the RBL and the FCL, we allow a free choice of one facility to stop the construction, out of the facilities originally located, in order to reduce the effect of the stopping of construction on the average travel time of FBU. We can also formulate a mathematical problem to find the least affecting facility, but we do not show the formulation, here. As a result, we can calculate the increases in the average travel time for FBU due to the stopping of construction from each initial location. They are called "loss of time to the RBL" and "loss of time to the FCL", respectively.

As shown in Figure 7, there is no large differences between "loss of time to the FCL" and "loss of time to the RBL" especially when the number of facilities before stopping construction is fewer than 15. " loss of time to the FCL" is larger than "loss of time to the RBL" when the number of facilities is larger than 15.

We further compare the average travel time after the stopping of construction for the two locations. Figure 8 shows that the ratio is kept under one for any number of facilities: Average travel time to the FCL is kept lower than that to the RBL, even after

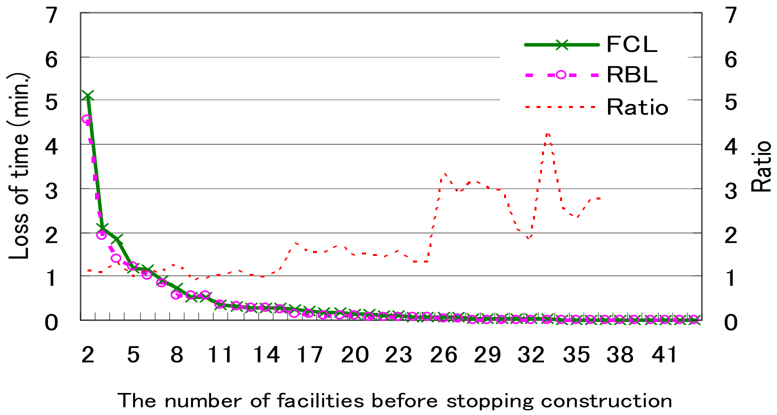

Figure 7　Comparison of the two locations in terms of the increase of average travel time under a stopping of construction

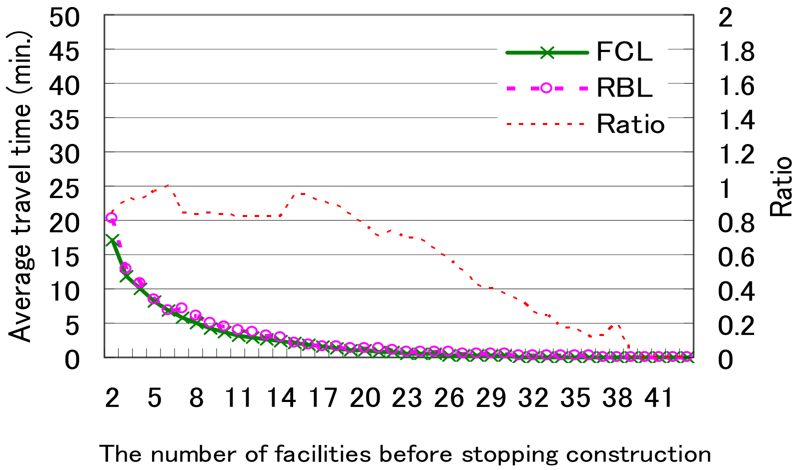

Figure 8　Comparison of the two locations in terms of the average travel time after stopping construction of a facility

the decrease in the constructed facilities. This is because the FCL as a whole concentrates in the middle of the objective area and locates several facilities along major roads, compared with the RBL. Thus, even if construction of a facility is stopped, people can find an alternative facility relatively close to the commuting route.

5. CONCLUSION

The effect of flow-based use (FBU) has been analyzed in this paper. First, it was shown that FBU can improve the accessibility to the existing facilities, compared with the traditional residence-based use (RBU), and also can assure the robustness of accessibility under a change of residential distribution and a closure of a facility. Therefore, in order to assure a high longitudinal accessibility for the existing facilities immediately, FBU should be permitted and promoted by the public agencies and local municipalities.　In a realistic metropolitan planning application, they must promote the wider announcements of the vacancy information of facilities and open the reservation system for the general citizens, as well as the neighborhood inhabitants.

Secondly, when a facility location plan is set up, we have demonstrated that the flow capturing location allocation planning method (FCLAP), or, in other words, location planning method minimizing the additional travel time for FBU, can provide superior locations to the traditional residence-based location allocation planning (RBLAP) method that minimizes the home-facility travel time, in terms of the average travel time and its robustness under a change of residential distribution and a decreased number of construction. Therefore, to assure a high accessibility to new facilities, their location should be planned using the FCLAP model. This conclusion seems to provide one theoretical underpinning when planning transit oriented developments (TOD) where mixed uses and employment are advocated in and around rail stations.

We must also discuss several reservations for the conclusion of this study. It seems that not all facilities should be flow-based; some of those services are really residential or neighborhood or community based rather than "flow-based." Secondly, our results owe much on the long time stability of trip patterns in city over the life-time of local facilities; large scale urban development projects or new transit corridor installations sometimes dramatically alter the trip pattern. Thirdly, we have not yet consider the travel mode into account. Severe congestions of transit service in peak hour actually prohibit us to accompany small children.

There are several research issues to consider. First, it is desirable that the generality of our conclusions is confirmed by applying models to other areas and public facilities other than child care centers. Secondly, it is necessary to improve the objective function by introducing more practical travel costs than included in this analysis: infants, school children, and some elderly people cannot drive by themselves, for example. Thirdly, it is also desirable that constraints are made more realistic by introducing the capacity of individual facilities, and specifying an upper limit of travel time, and so on.

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