APPLYING VEHICLE ROUTING PROBLEM WITH TIME WINDOWS TO DAY CARE COURTESY BUS SERVICE

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Abstract: In previous research, the authors' group has discussed both the development and prototype of the proposed courtesy bus scheduling system for a day care. The research found in this paper highlights the upgrades of the system. The arrival time of the buses and their allocation to the customers is explicitly considered. Then, the problem is formulated as a Vehicle Routing Problem with Time Window (VRP-TW). In addition, the characteristics of the formulated problem (VRP-TW) are discussed and a detailed investigation into the algorithms is carried out. Finally, the upgraded system is applied to the actual data set and the potential of this system is thoroughly examined.

Keywords: special transport, Vehicle Routing Problem with Time Windows (VRP-TW), algorithm, day care service

1. INTRODUCTION

Japan is an aging society. The total population of Japan is 127 million and the aging rate (ratio occupied by people aged 65 or older in the entire population) is 18.0% as of October 1, 2001 (Cabinet Office (2002)). The amount of elderly needing care is expected to increase throughout the country, from about 2 million (1993) to 2.8 million (2000), and to 3.9 million (2010) (Ministry of Health and Welfare (1999)). It is predicted that one out of three citizens will be aged 65 or older in approximately 2050.

There are several types of care services available to the elderly. These include home-visiting services, day care services, short-term residential care services, and long-term care at specialized nursing homes or health facilities. In order to supply the necessary care services at the various health facilities, the courtesy bus service is often required. It is a kind of special transport.

The authors' group carried out a preliminary survey and proposed a prototype of a computer aided system for supporting the courtesy bus scheduling and routing (Tsutsumi and Narimatsu (2001)). The study, which explores the application of the computer aided system in senior citizen care services, is only the initial step. There are, however, a number of issues that must be resolved. The aim of this paper is to demonstrate how an upgraded prototype will address most of these unresolved issues.

This paper is organized into seven chapters. Chapter 2 briefly describes the characteristics of the day care courtesy service and identifies the problems of the prototype. The methodology employed to solve the problems is discussed in Chapter 3. Chapters 4 and 5 formulates a Vehicle Routing Problem with Time Windows and discusses the algorithms employed in the study. In Chapter 6, the upgraded system is applied to the existing data set and its performance is examined. Finally, the entire study is summarized in Chapter 7.

2. FRAMING THE PROBLEM

In order to understand the issues addressed in this paper, an overview of the essence of the day care courtesy scheduling and routing, and the prototype to support solving them is necessary. Day care service typically begins with customer pick up service from the home to the service centre by courtesy bus, with the exception of those few customers who can arrive at the centre on foot. The mathematical problem of the routing and scheduling of the courtesy bus discussed in this paper is a version of Vehicle Routing Problem (VRP) (*e.g.* Taniguchi *et al.* (2001)). There are, however, many constraints to be considered during a customer pick up service. In densely built-up areas such as in Tokyo, some of the roads are too narrow for the bus to go through or to stop for customers. Other obstacles include one-way roads, cul-de-sacs and disabled users who are unable to cross the road or sit for long periods of time in buses. In addition, there are a limited number of off-the-shelf Geographic Information Systems (GIS) that can provide effective routing techniques which address these obstacles (*e.g.* Tarantilis and Kiranoudis (2002)). Therefore, the authors' group has started to develop a specialized courtesy bus scheduling and routing system for day care service based upon GIS, and upon employing the Vehicle Routing Problem (Tsutsumi and Narimatsu (2001)).

The prototype utilizes GIS software as the database management system (DMS) and as a display tool. However, the computer aided system is still considered patchwork because the interface of the system is thought to be poor for those who are unfamiliar with computers. Furthermore, the mathematical computation tool for scheduling, the database management tool and the display tool are not interlinked, and must therefore be managed individually by system users.

Moreover, this prototype does not resolve the issues regarding time demand. Although this prototype minimizes the total amount of travelling time and cost, it doesn't consider the arrival time for each customer explicitly. It cannot, therefore, fulfil the time demands of customers. This is a serious problem especially for those who may not be mobile without their families' assistance, or have the ability to sit on a bus for long periods of time. Another great effect on the scheduling, involving change of time and route could also mean a burden on the day care service staff who accompany or drive the buses. Since the demand for senior citizen care services exceeds the supply in urban areas, many of the elderly are on waiting lists for this service. Thus, a new customer frequently joins the service when another customer becomes ill, dies or stops the service. In addition, the introduction of the dynamic link cost in future also requires strong time consideration.

Another problem with the previous system is its consideration of only one bus type. In practice, however, efficient operation means microbus and medium-sized buses should be used simultaneously, and customers should be allocated to each more carefully.

Tsutsumi and Kato (2003) show that the upgraded system must aim to process a user-friendly interface, and construct an improved system based upon ArcView 8.1, which is the GIS software produced by ESRI. Calculation programs are made with Visual C++ and the interface is developed with Visual Basic. These two parts are linked by the Dynamic Link Library. Hence, this paper discusses the introduction of plural vehicles and the explicit time consideration.

3. METHODOLOGY

The characteristics of the prototype constructed by Tsutsumi and Narimatsu (2001) are as follows.

- It employs ArcView 3.2 as the database management system (DBMS).
- Scheduling is decided by minimizing the total travel time/cost.
- Detailed street/road network data is managed by GIS, which makes it possible to consider many problems regarding densely built-up areas.
- GIS is also used as the display tool.

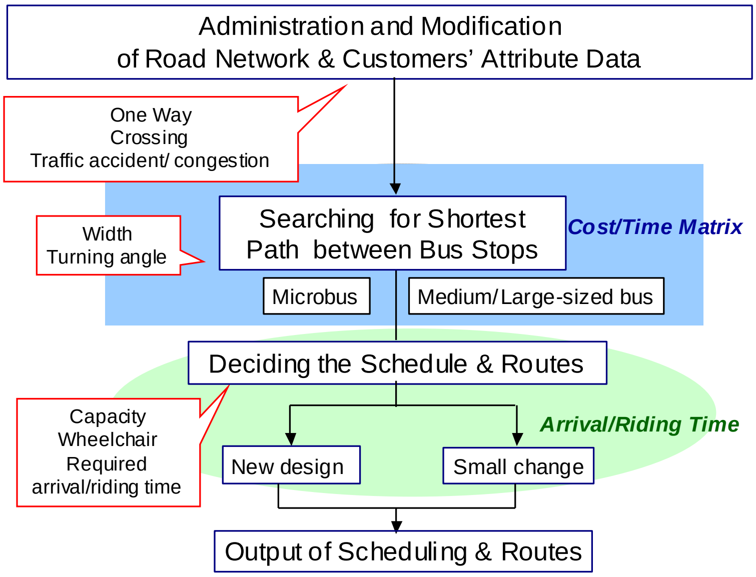


Figure 1 Outline of the Newly Developed System

This paper follows the methodology developed by Tsutsumi and Narimatsu (2001). Figure 1 outlines the newly developed procedures in the system. This system utilizes ArcView 8.1 and constructs the data upon it. The system implementation consists of three steps:
Step 1: The data of road network and users is built up.
Step 2: The search for the shortest path among each bus stop and estimation of the travel time/cost is completed.
Step 3: The scheduling of courtesy buses is computed and displayed.

First, the system user builds up the data of the road network and the customers of the day care service. Customers' data contain their name, age, sex, address, telephone number, day of needed service, contents of the service, ability to walk alone (wheelchair user or not), handicapped level and so on. Although the road network data is provided by municipalities, in many cases, it is not available without modification. Thus, the user modifies the road network data, considering if it is a street or a back road, and its conditions, such as illegitimate turns and one ways. The user then also decides upon the bus stops necessary for each customer and plots it with GIS. Secondly, the user searches for the shortest path between each bus stop and estimates the travel time/cost. For this purpose, each link contains the data of the time required. Thirdly, after having obtained the cost/time among bus stops, the user selects the order in which the courtesy bus picks up the customers to the centre and returns them home.

In most cases, road network data provided by municipalities are undirected graph. In order to consider the following problems, we construct the road data based on either directed or oriented graph lane in Step1. This makes it possible for the system user to specify the lane for picking up customers unable to cross the roads. The node of intersection, defined as two streets with two lanes crosses, is expanded to eight nodes and given different node numbers according to a conventional way. The expanded nodes are carefully numbered to ensure that multiple nodes do not use the same number. Using the coordinated data and the cosine rule, the crossed axis angle in the intersection is calculated and utilized to judge whether the bus can turn easily. Axis angle information is provided in order to avoid the U-turns in each path, which occurred in the previous system. For more detail, see Tsutsumi and Kato (2003).

Algorithms for the shortest paths problem have been studied for a long time and advances in the theory are still being made. A good description of their performances appears in Cherkassky *et al.* (1996). Since we neither dwell on them nor attempt a detailed study of efficiency, we choose Dijkstra algorithm in Step 2, which is most widely known to be efficient.

The system searches for the shortest path between each bus stop and gives a matrix of travel time/cost estimate. Then, the system selects the order in which the courtesy bus picks up the customers and drops them back home based upon the cost/time criteria in Step 3. U-turns at bus stops occurred in the previous system. Uchimura (2000) proposes three methods to avoid bus stop U-turns. The simplest proposal was adopted in this system, which requires the retrial of the shortest path search using temporal setting of no entry. See Tsutsumi and Kato (2003) for more detail.

The new system considers the arrival time of the buses and customer allocation. Multiple buses are explicitly considered and the problem is formulated as Vehicle Routing Problem with Time Window (VRP-TW). The following chapter discusses the details of formulation.

4. FORMULATION

Let x_{ijk} be a binary variable ($x_{ijk} \in \{1,0\} \left(\forall i, \forall j \in S, \forall k \in U\right)$), which indicates whether or not the courtesy bus numbered in k goes directly from bus stop i to j , that is,

$$x_{ijk} = \begin{cases} 1 & \text{: If the courtesy bus No. } k \text{ goes directly from } i \text{ to } j, \\ 0 & \text{: Otherwise.} \end{cases}$$

where S ={0,1,2,···, ···$\bar{I}$ } denotes the union of the set of bus stop, {1,2,···, ···$\bar{I}$ }, and the set of facility, {0}, and U ={1,2,···, ···$\bar{K}$ } denotes the union of the set of courtesy bus. We equate bus stop with customer. Consequently S-{0} also denotes the union of the set of customer, {1,2,···, ···$\bar{I}$ }. Let t_{ijk} be the corresponding cost, which is equivalent with time for simplicity hereafter. For simplicity, waiting time for customer is assumed to be zero. The objective functions are total time of the tour for each bus and total time of the tour for each customer. They are combined with the weight parameter α. Herewith, the problem of deciding the schedule and routes is formulated as follows:

$$\min_{x_{ijk}}. \quad C = \sum_{i \in S} \sum_{j \in S - \{i\}} \sum_{k \in U} x_{ijk} \left(t_{ijk} + f_i\right) + \alpha \sum_{i \in S - \{0\}} \sum_{k \in U} \left\{T_{0k} - y_{ik}\left(t_i + f_i\right)\right\} \tag{1}$$

subject to

$$\sum_{i \in S - \{j\}} x_{ijk} = y_{jk} \quad \left(\forall j \in S, \forall k \in U\right) \tag{2}$$

$$\sum_{j \in S - \{i\}} x_{ijk} = y_{ik} \quad \left(\forall j \in S, \forall k \in U\right) \tag{3}$$

$$\sum_{k \in U} y_{ik} = 1 \quad \left(\forall i \in S - \{0\}\right) \tag{4}$$

$$\sum_{k \in U} y_{ok} = \bar{K} \tag{5}$$

$$\sum_{i \in S - \{0\}} y_{ik} \leq p_k \quad \left(\forall k \in U\right) \tag{6}$$

$$\sum_{i \in S - \{0\}} y_{ik} w_i \leq w_k \quad \left(\forall k \in U\right) \tag{7}$$

$$t_j = t_i + t_{ijk} + f_i \quad \left(\forall (i, j, k) \in V = \left\{(i, j, k) \middle| x_{ijk} = 1, i \in S, j \in S, k \in U\right\}\right) \tag{8}$$

$$T_{ok} = t_{ok} + \sum_{i \in S} \sum_{j \in S - \{i\}} x_{ijk} \left(t_{ijk} + f_i\right) \quad \left(\forall k \in U\right) \tag{9}$$

$$e_i \le t_i \le l_i \quad (\forall i \in S) \tag{10}$$

$$t_0^k - t_i \le g_i \quad (\forall (i,k) \in V = \{(i,k) | y_{ik} = 1, i \in S, k \in U\}) \tag{11}$$

$$\sum_{i \in S-\{0\}} y_{ik} q_{ik} \le p_k \quad (\forall k \in U) \tag{12}$$

$$\sum_{i \in S-\{0\}} \sum_{k \in U} y_{ik} q_{ik} = \sum_{i \in S-\{0\}} \sum_{k \in U} q_{ik} \tag{13}$$

where y_{ik} is a 0-1 variable which indicates whether or not the courtesy bus visits bus stop *i* (equivalently pick up the customer *i*) , that is,

$$y_{ik} = \begin{cases} 1 & \text{: If the } k\text{th courtesy bus picks up customer } i, \\ 0 & \text{: Otherwise.} \end{cases}$$

Other variables are defined as shown below.
t_i : arrival time for customer *i*,
t_{ok} : departure time at the facility for bus *k*,
T_{ok} : arrival time at the facility for bus *k*,
f_i : required time for customer *i* to get on a courtesy bus
p_k : capacity of courtesy bus *k*,

$$w_i = \begin{cases} 1 & \text{: Customer in wheelchair,} \\ 0 & \text{: Otherwise,} \end{cases}$$

w_k : capacity for wheelchairs of courtesy bus *k*,
e_i : minimal time that customer *i* request to be picked up,
l_i : maximal time that customer *i* request to be picked up,
g_i : maximal time for customer *i* to be seated in a bus,

$$q_{ik} = \begin{cases} 1 & \text{: If user } i \text{ needs to be carried by bus } k, \\ 0 & \text{: Otherwise.} \end{cases}$$

Constraint set (2) to (4) states that each customer must be assigned to exactly one bus. Constraint set (5) states that each bus *k* leaves the centre (facility) once. Constraint set (6) prohibits a bus from servicing more customers than its capacity and constrain set (7) considers its capacity for wheelchairs. Constraint set (8) shows the relationship among departure time, arrival time, travel time and required time for picking up a customer, if the bus *k* travels from *i* to *j*. Constraint set (9) denotes the arriving time for the centre. Constraint set (10) ensures that all time windows requested by the customers are respected. Constraint set (11) states that all the times required in a tour are within an allowance. Constraint set (12) and (13) considers the customer’s request for the bus type.

Needless to say, employing a time window can help us to consider the customers’ demand. In addition, it strengthens the case of making small adjustments when there are only a few customers join or stops the service. In this case, it is better to make smaller modification to the departure/arrival time for existing customers. Since the prototype doesn’t consider time explicitly, it computes the scheduling similarly to a completely new design, often causing an unnecessary effect on scheduling. By utilizing the constraint set (10), a large change of scheduling can be avoided.

The constraint set (10) can be formulated as a penalty function for early arrival and delay, and included in the objective function as follows:

$$\min_{x_{ijk}}. \quad C = \sum_{i\in S}\sum_{j\in S-\{i\}}\sum_{k\in U} x_{ijk}\left(t_{ijk} + f_i\right) + \alpha\sum_{i\in S-\{0\}}\sum_{k\in U}\left\{T_{0k} - y_{ik}\left(t_i + f_i\right)\right\} + \beta\sum_{i\in S-\{0\}} h_i\left(t_i\right) \ , \tag{14}$$

where

$$h_i\left(t_i\right) = \begin{cases} 0 & \text{: for those who have no particular time demand,} \\ e_i - t_i & \text{: in case of early arrival,} \\ \delta\left(t_i - l_i\right) & \text{: in case of delay,} \end{cases} \qquad \left(\forall i \in S - \{0\}\right) \tag{15}$$

β, δ : weight parameters.

According to the authors' interview survey, the customers' explicit time demand is not so strong. However, once the schedule is operated, they prefer avoiding changes of time. These mean that in a case of completely new design, $h_i(t_i)$=0 holds for many customers, so that the consideration of time windows is not practically difficult. On the other hand, in the case of small adjustments, to solve the problem above formulated requires much power. However, there is a way to avoid such difficulty, which will be described in Chapter 4.

Although the travel time from i to j, t_{ijk} is assumed to be constant over time, it is possible to consider its time dependency such as in traffic congestion. The formulation of the time windows is potentially important for future dynamic modelling.

5. ALGORITHM

VRP belongs to the Combinatorial Problems known as NP-hard. Algorithms for NP-hard problems have been studied instigating important advances. In practice, approximate (or heuristic) algorithms are quite useful. The basic heuristic methods are *greedy method* and *local search* (LS). The latter is also known as the *hill climbing method* or the *neighborhood search*. Recently, metaheuristics, which combine such heuristics methods, are currently being developed. Among them are *random multi-start local search* (MLS), *genetic algorithm* (GA), *simulated annealing* (SA),and *tabu search* (TS).

Yagiura and Ibaraki (2001) give a comprehensive survey of the existing algorithms and compare their performance. They summarize their computational results as follows:

- The performance of GA is about the same as, or rather worse than the others.
- The performance of TS crucially depends on the problem structure and the neighbourhood.
- Algorithms *iterated local search* (ILS), g*enetic local search* (GLS), and SA (and its variants) improve the performance of MLS. The differences among them in the performance are small compared to the amounts of improvements from MLS.

Metaheuristic algorithms usually include program parameter to control the search, some of which must be carefully tuned to obtain sufficient performance. It is also reported that GA, SA and TS dominate in this point.

There are two outstanding characteristics in the VRP-TW formulation discussed in Chapter 4. First, there are more constraints to consider including not only the explicitly formulated ones but also the ones regarding road attributes, than the standard VRP-TW. Second, the number of customers which each vehicle visits is usually less than 20, which are fewer the standard VRP-TW. Although the former characteristic may indicate some unexpected results or require some investigation on the application of existing methods, the latter suggests that we need not be so nervous about the methods to adopt. We also need not dwell the optimal solution for the problem, because only a few minutes of difference in objective function does not matter. An operational algorithm is more preferable than the one which is theoretically sophisticated but difficult to handle with. What we aim at in this paper is not efficient solution but efficient operation or support for working.

Having investigated on the characteristics of the problems above mentioned, we choose MLS and ILS. In the MLS, LS is repeated from a number of initial solutions. In the ILS, the initial solutions are generated by slightly perturbing a good solution which is found during the past search. Once the routines are constructed for LS, most of them are available for MLS or ILS, which means that the programming for MLS or ILS is not so difficult. To be more precise, we basically employ the *2-opt procedure* (Lin (1965)) as LS. In combination with it, *Or-opt procedure* is also applied so that the search is able to escape from poor locally optimal solutions. (See *e.g.* Thangiah, Potvin and Sun (1996), Golden and Stewart (1985) for more information on these algorithms.)

Figure 2 presents how to search the optimal tour based upon the 2-opt Algorithm. The basic step of 2-opt is to delete two edges from the tour and reconnect the remaining fragments by adding two new edges. Correspondingly, in Figure2, the dashed lines in the left are replaced with the dashed lines in the right.

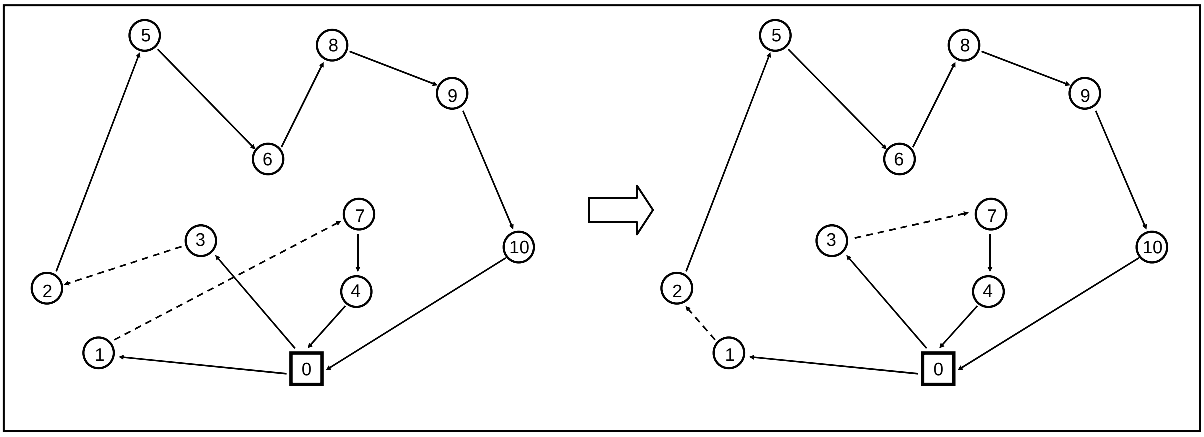


Figure 2 Schematic Representation of Searching based on the 2-opt Algorithm.

In the case of small adjustments regarding few customers mentioned in the previous chapter, changing the departure/arrival time for the existing customers as little as possible is the most effective solution. Explicit consideration of time has also been a contribution up to this point. Theoretically, by inputting the current departure/arrival time data into constraint set (10), equivalently the penalty function (14), our VRP-TW gives the appropriate solution. According to our experiments, however, the algorithm applied in the framework of MLS and ILS does not perform up to expectation. This may be due to the prevention of strong constraints searching for an escape from poor locally optimal solutions. In addition, much research has been developed for symmetric VRP where the travel time from i to j, t_{ijk} equals to the travel time from j to i, t_{jik} ($i \neq j$), should be taken into account. The problem, however, formulated in this paper is asymmetric VRP, where $t_{ijk} \neq t_{jik}$. As a result, the latter is more difficult to solve than the former, which may also burden the search. Consequently, a very simple algorithm for resolving this problem was developed in this system.

Figure 3 illustrates this new development in resolving the algorithm problem. In this example, the number 0 shows the centre, and the numbers 1 to 11 show each customer. Hypothetically, customer 6 stops the service instead of customer 11, due to illness. Customer 11, who has been on the waiting lists, starts the service. The procedure, therefore, eliminates the customer 6 and inserts customer 11 keeping the order of the other customers to find the solution. Naturally, customer 11 will be inserted between customer 5 and 8, or customer 1 and 7 who live near him/her in this case.

Let $\bar{I}$ be the number of customers in the current tour and $\bar{K}$ be the number of closed loops in the tour, which is assumed to be equivalent to the number of courtesy buses in this case. If

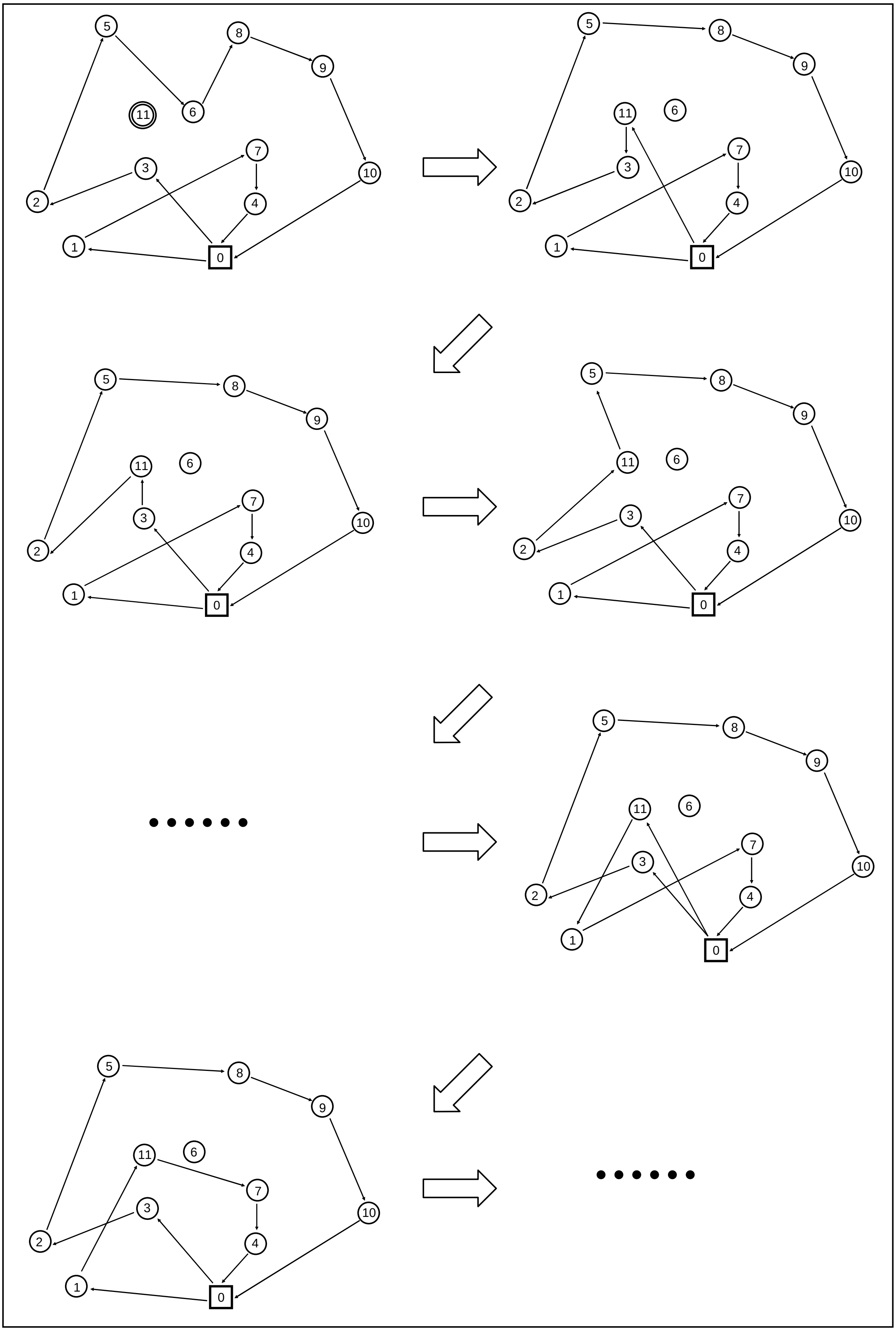


Figure 3 Outline of the Algorithm for Small Change

m customers leave the group and *n* new customers join the group, the number of possible solutions is given by the number of permutations of *n* things taken from a set of $(\bar{I}-m+n+\bar{K}-1)$ as follows:

$$ {}_{\bar{I}-m+n+\bar{K}-1}P_n = \frac{(\bar{I}-m+n+\bar{K}-1)!}{(\bar{I}-m+\bar{K}-1)!} \quad (16) $$

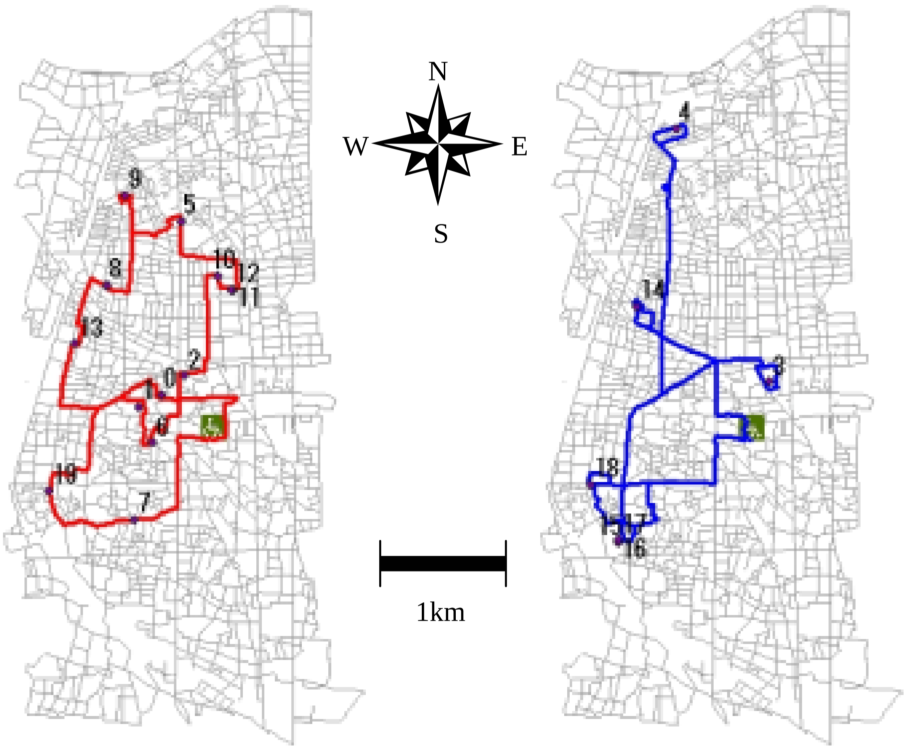
This is not a large number compared to the amount of possible solutions for a completely newly designed case, $(\bar{I}-m+n+\bar{K}-1)!$. For example, in the case of $\bar{I}$ =20, $\bar{K}$ =2, *m*=3 and *n*=3, the number is 7,980. It is rare that three customers would change simultaneously, so therefore, the number of possible solutions is far less. Thus, no further special techniques are required for the calculation based on this simple algorithm.

6. AN EMPIRICAL TEST

Our newly developed system employs ArcView 8.1 as the DBMS and user interface. The significant advantage of ArcView 8.X is that it can be customized by Visual Basic for Applications (VBA) macros (*e.g.* Zeiler (2001)). We customise the system with Visual C++ for calculation and Visual Basic for user interface. The calculation programs are made with Visual C++ to ensure the rapid calculation. These parts are linked by the dynamic the link library (DLL), which offers efficient potential for future customisation.

A case study was also conducted on the same day care centre to which Tsutsumi and Narimatsu (2000) applied their prototype. Figure 4 illustrates the outline of this densely built-up area. The number of customers is about a hundred. The customers are roughly grouped by weekdays. The first group visits the facility Mondays and Thursdays. The second group visits Tuesdays and Fridays, and the third group visits Wednesdays and Saturdays. Each group is divided into two sub-groups according to time of day, which begins at 9 and 10 a.m. Consequently, there are six groups and each of them has fifteen to twenty customers.

Figure 4 Outline of Case Study Area
(Rokugatsu, Seifu-Kai, Social Welfare Corporation, Adachi Ward, Tokyo)



(i) Microbus (ii) Medium-sized bus

Figure 5 A Result of Routing

~4m 4m~6m 6m~

Figure 6 Width of Street/Road in the Case Study Area

We chose two sub-groups, which belong to the same day of the week and time zone, and carried out calculations. Two different types of buses are considered. The number of seats is 7 for the microbus and 25 for the medium-sized bus. The capacity for wheelchairs is 3 and 4 respectively. The system operated smoothly. Figure 5 shows a result of computation where the medium-sized bus is used on wider roads and the microbus is used on narrower paths. This is easily recognized by comparing Figure 5 to Figure 6. Some members of the customer groups were changed, and the study found that the system gave reasonable solutions. As shown in Table 1, computation time is short, except during the case when a computer whose CPU operates at 1 GHz with 128 Mb memory was used. It is predicted, however, that these figures will change according to the data and parameter set.

Table 1 Assessment on Computation Time

CPU	1 GHz	1.9 GHz	1.8 GHz
Memory	128 Mb	512 Mb	1,048Mb
Shortest Path Search	180 sec.	30 sec.	30 sec.
Scheduling	300 sec.	90 sec.	80 sec.

7. CONCLUSIONS

In this paper, ways to improve the computer aided system for courtesy bus scheduling in day care service developed by the authors' group were presented. The arrival time of the buses and the allocation of each to the customers are explicitly considered, and the problem is formulated as a Vehicle Routing Problem with Time Window (VRP-TW). Having discussed the characteristics of the problem formulated in this study, Multiple randomly started Local Search (MLS) and Iterated Local Search (ILS) were chosen and applied for completely new scheduling. However, it turned out that the existing algorithms do not perform efficiently when only a small number of members need to change. Thus, a new algorithm was proposed and its performance was examined. The updated system was constructed upon ArcView 8.1 and applied to an actual data set. After obtaining the shortest path among customers, it took only several minutes to have a reasonable solution when an ordinary computer, which is efficient enough to support the scheduling and routing, was used.

In this system, the detailed street/road network data is managed by GIS. This makes it possible to consider the problems presented by densely built-up areas. As mentioned at the beginning of the paper, the target of the study can be regarded a kind of special transport. Indeed, the system contains the potential characteristics, which could be applied to other special transport in densely built-up areas. The assessment of the system by the day care service staff is strongly required, and must be considered in future research.

In this paper, the travel time is assumed to be constant over time. It is obvious that the introduction of the dynamic link cost to consider traffic congestion or road construction is also very important to upgrade the system and make it more practical. Since the formulation with time windows has developed a potential of such a dynamic modelling, data on the dynamic link cost in the road network is most expected.

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