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How to Move Automatic Pallets to Improve the Time Efficiency of Exiting in Automated Valet Parking

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Multistory car parking system garages were introduced to increase the capacity of parking garages. However, the systems have problems, such as accidents (intrapark movement and theft), searching for parking spaces, awkward boarding/deboarding at narrow designated places, and difficulties in their use by beginners and elderly people. Several studies have been conducted to address these issues. One was a proposal to introduce automatic and electric pallets for transporting vehicles, and to realize automated valet parking for entering and exiting. An electric pallet was equipped with its own sensor, which made it easier to move and realize a more effective use of space in a parking lot. However, evaluations of the capacity of the parking lot and the time efficiency of exiting demonstrated that the method was insufficient. We propose herein a method of moving automatic pallets that improves the time required for exiting in automated valet parking. Specifically, we propose to reduce the exit distance (distance to the exit) by changing how automatic pallets are moved. In this study, various sensors were introduced to move automatic pallets accurately. In addition, considering the material as the detection target of the sensor, we selected the parking lot and the passage in the multistory car park as options.

1. Introduction

Cars are used for movement and transportation, and are indispensable items for modern and convenient life. Cars require parking lots at two places: the starting point and the destination. A parking lot at the destination may be shared by an unspecified number of users, and it is difficult to design a parking lot that satisfies all users.

Land prices are particularly high in business districts and downtown areas, making it difficult to construct profitable parking lots. In such places, from the viewpoint of profitability, a multistory parking lot with a higher capacity is often built. It is possible to increase the number of parking spaces per unit area of the site by increasing the number of floors. However, because the cost of installing vehicle elevators and floor-to-floor ramps increases the overall cost of the

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garage, maximizing the number of parking spaces per floor is an important factor. Funase *et al.*[1] proposed a multistory car park to maximize space utilization in a confined area. The expansion of the scale that improves the profitability of multistory parking lots could worsen user experiences. For example, problems such as accidents (intrapark movement and theft), searching for parking lots spaces, difficult boarding/deboarding at narrow designated places, and difficulties in the use of parking lots by beginners and elderly people arise. If these problems are not solved, even if the accommodation rate improves, the utilization rate may decline, leading to a decrease in profitability.

In this study, we focus on automated valet parking and propose to improve the accommodation rate and prevent the deterioration of convenience. Previous studies[2–4] have pointed out that the accuracy of research on automated driving[5–9] is insufficient. Reasons for the low accuracy include that vehicles using parking lots are diverse and differ in performance and shape, and that entrance/exit procedures by automated driving based on instructions from mobile phones have not yet reached the stage of practical use. To improve accuracy, Funase *et al.*[10] proposed an automated valet parking system with high-precision automated driving by limiting the target of automated driving to automatic pallets for transporting vehicles. The authors also proposed a method of determining parking locations in automated valet parking to improve the time efficiency of the exit procedure. However, because there is still room for improvement in the time efficiency of the exit procedure, we propose a new automatic pallet transfer method to further improve the time required for exiting the garage. In addition, in this research, we propose a method of improving the exit efficiency of automated valet parking using automatic pallets. Each automatic pallet is equipped with a number of sensors, which enable the accurate movement of the automatic pallet and the determination and guidance of exit passages. The material used is another key factor that should be considered as a sensor detection target. In this case, the material can be a parking space or a passage in a multistory car park.

2. System of Multistory Car Parking

2.1 Automatic pallet

Funase *et al.*[10] proposed an automatic pallet, which was an autonomous vehicle that can load one car and carry it from the entrance to a parking location or from the location to the exit.

This automatic pallet was an improvement of a previous device proposed by Funase *et al.* [4] that makes it easier to park and exit at a desired location. Specifically, they added two sets of wheels (left and right, and front and rear) to the original model, so that the pallet could move in four directions without changing the position of the loaded vehicle. When one set of wheels was deployed, the other set was retracted. The wheels were made smaller than those of a car to improve the stability of the automatic pallet.

The improved automatic pallet also had nine built-in sensors that could read the unique numbers of eight neighboring spaces as well as that of the space on which the pallet was parked. These sensors allowed the pallet to move through a passage smoothly and to determine the types of neighboring space and the presence/absence of parking nearby.

The automatic pallet had front and rear wheel stoppers to secure the vehicle loaded on it. When not in use, the wheel stoppers retracted into the pallet. When in use, they deployed from the pallet. By shortening the distance between the front and rear wheel stoppers, the vehicle on the pallet could be securely retained.

2.2 Multistory car parking

The parking lot in our model has multiple floors from the first basement floor to the *m*th highest floor and uses automatic pallets on which cars are parked. The surface of each floor is treated so that pallet wheels do not slip. Two elevators are installed for pallet transport, each connected to the entrance and exit of the floor. Every automatic pallet is assigned a unique serial number with which entrance and exit procedures are managed. A unit space is a space slightly larger than an automatic pallet, which can accommodate one automatic pallet. Each unit space is also given a unique serial number. Each floor is divided into unit spaces. The unit space that the automatic pallet can access directly from the passage is called the basic unit space (No. *j*). The unit space whose four sides do not face the passage is called the complex unit space (No. *k*). By configuring the layout of unit spaces and passages as shown by the two types of complex unit space in Fig. 1, even if all the basic unit spaces neighboring a complex unit are blocked by pallets with cars on them, moving two of any of the occupied pallet*s* allows a passage to be created from the complex unit space.

Each floor has a passage connecting the entrance and exit elevators. Passage unit spaces have embedded markers pointing to the exit and cannot accept automatic pallets with cars. Ideally, a passage should be a tree-like structure with the exit elevator as the root node, because creating a closed-circuit passage reduces the number of parking spaces available for the automatic pallet. A passage with this structure has only one route from any unit space on the passage to the exit, so the distance to the exit is the shortest. Although there are dead ends in the branch passages, the passages are set to minimize the number of complex unit spaces. The passages on each floor are located in the same place [Figs. 2(a) to 2(c)]. The number of floors can be determined from the unique number of unit spaces per floor, and the type of unit space (basic, complex, or passage) can be determined from the floor plan of the parking structure.

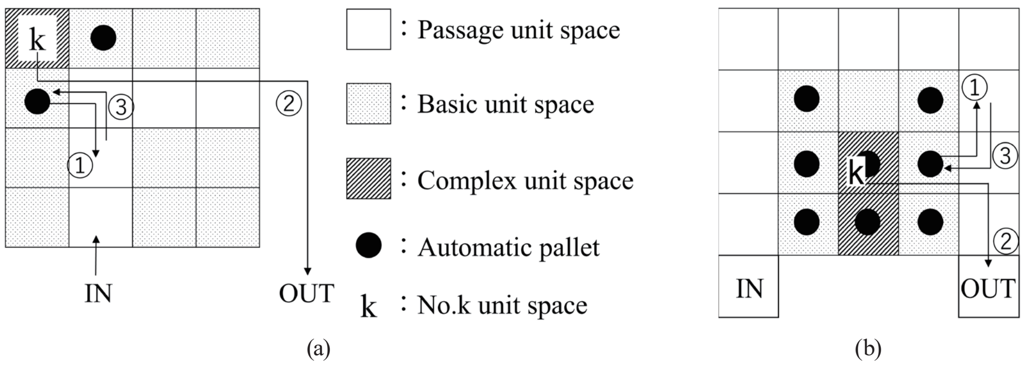

Fig. 1. Procedure for creating a passage from a complex unit space (No. *k*) to the exit. (a) Type 1 (the complex unit in the corner). (b) Type 2 (the complex unit blocked by pallets with cars).

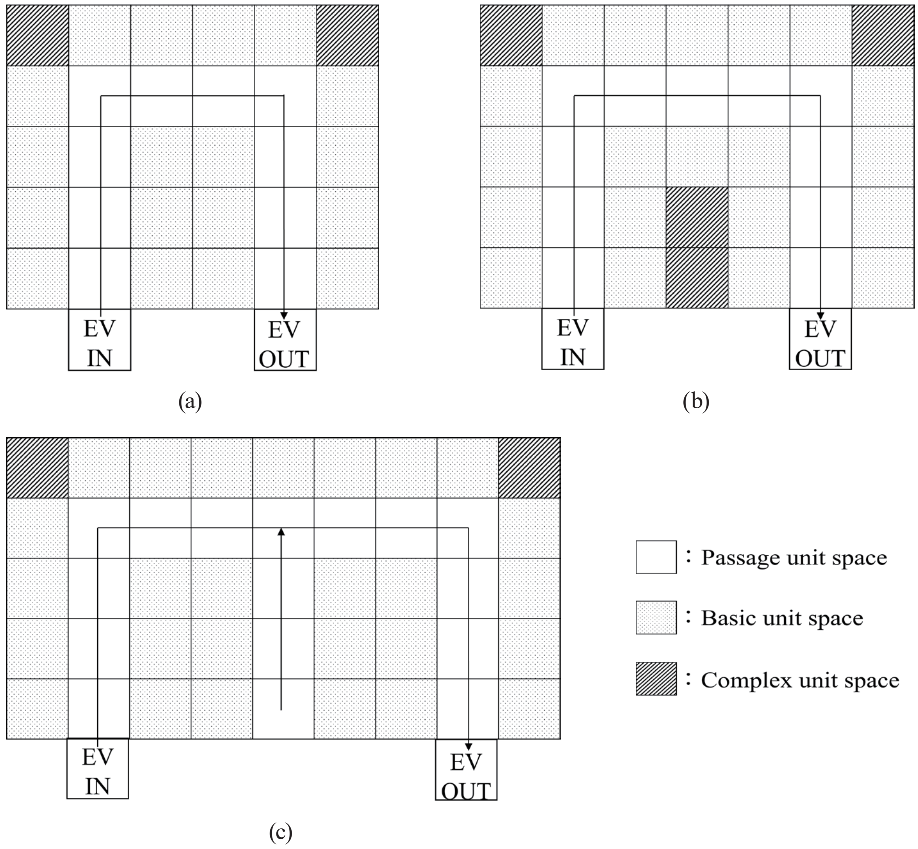

Fig. 2. Floor plans of a multistory car park. (a) 5 × 6 unit spaces/floor. (b) 5 × 7 unit spaces/floor. (c) 5 × 9 unit spaces/floor.

The number of unit spaces on the shortest passage from the No. j basic unit space to the exit elevator (counting the space of the elevator as 1) is the distance to the exit from the No. j basic unit space. The distance $E(j)$ is expressed as

$$E(j) = \text{shortest distance } \{(\text{No. } j), \text{the exit elevator}\}. \tag{1}$$

The term $E(k)$ is the distance from the complex unit space No. k to the exit as expressed by Eq. (2). The constant 1 in the equation is the number of steps from the complex unit space to the neighboring basic unit space.

$$E(k) = \min\{ U(j_1), U(j_2), \ldots, U(j_e)\} + 1 \tag{2}$$

The term $U(j_t)$ shows the shortest distance from the distances between the exit and each basic unit space {No. j_1, No. j_2, … No. j_e} adjacent to the complex unit space (No. k). In short, the term $U(j_t)$ represents the shortest distance in basic unit spaces neighboring the No. k complex unit space. When a basic unit space is occupied by the automatic pallet, the number 4 is added to $E(k)$. As shown in Fig. 1, two steps of neighboring basic unit space's car are necessary to move the blocked No. k complex unit space's car and two additional steps are necessary to move the basic unit space's car back to its original position.

2.3 Automated valet parking system

In this study, the automated valet parking system proposed by Funase *et al.*[10] is used. A new method of determining the parking location is proposed.

An automated valet parking system fully automates the following two tasks which are performed by staff in conventional valet parking systems:
(1) Finding a parking place and moving a car to that place.
(2) Moving a car to the exit when asked by the user.

Other studies have proposed various automated valet parking systems, but they are all based on a system in which cars are automatically guided in the parking lot. Cars vary widely in shape and performance, which makes it difficult to guide them automatically.

Our system employs pallet guidance, which limits the target of automatic guidance to one type of vehicle. This results in a higher accuracy of the guidance in the system.

2.3.1 Automatic entrance procedure

Cars arriving at the entrance of the parking lot are parked in the designated section of a turntable in which an automatic pallet is embedded. If the car is not properly parked in the section, an alarm prompts the driver to park the car correctly within the section. When the driver has parked the car properly as instructed by the system, the driver gets off and locks the car and registers his/her face with an authentication camera. The registered facial image is associated with information such as the date and time of entrance and the unique number of the assigned automatic pallet, which is printed on paper and handed to the user. The printed paper is only a record for the user and may be used when problems arise, and is not required for ordinally exit.

When the car is parked properly, the retracted front and rear wheel stoppers are deployed. The front wheel stopper moves backward and the rear wheel stopper moves forward to securely retain the front and rear wheels of the car. After securing the car, the automatic pallet loaded with the car is lowered into the basement by an elevator. From the basement, it is guided to the multistory car park through an underground passageway. The facial image and the unique numbers of the automatic pallet and unit space are associated in a database. A new automatic pallet is then set on the turntable. These operations are performed automatically.

2.3.2 Automatic exit procedure

The exit procedure is conducted in the opposite direction of the entrance procedure. Drivers and users go to the boarding area and have the registered face confirmed by a facial authentication camera. After this authentication procedure, the automatic pallet associated with the facial image is automatically guided from the unit space to the boarding area.

If the parking lot uses a toll system, when the fee based on the parking time is paid, the front and rear wheel stoppers are released. If the parking lot is free of charge, the wheel stoppers are released as soon as the automatic pallet arrives at the boarding area. After the wheel stoppers are released, the user can drive the car out of the parking lot. The usage information is recorded for each authenticated face image.

3. Automatic Entrance Procedure

3.1 Main preparation

(1) When the exit distances of unit spaces on the ith floor are arranged in ascending order, $N_i(t)$ represents the unit space with the shortest distance to the exit.
(2) For a floor number (i = 0, 1, 2, ..., m), the system creates a table containing (a) the ranks of exit distances (E_{ji}) sorted in ascending order for the unit space No. ji on the ith floor, (b) the unique numbers of the unit spaces, and (c) the distances to the exit. This table is called the exit distance table. However, the floor number i of 0 means the first basement floor. The exit distance means the number of units to the exit.
(3) The position of a unit space in this multistory car park is represented by three-dimensional coordinates (x, y, z). The terms x and y show the longitudinal and lateral distances from the origin, respectively. The term z is the number of floors. The origin is the front row at the left end next to the entrance elevator on each floor. The coordinates (x, y, z) of the unit space *No.* j are assigned to $Cx(j)$, $Cy(j)$, and $Cz(j)$, respectively.
(4) When the position of the three-dimensional coordinates (x, y, z) defines the unit space No. j, the location is represented by $P(x, y, z) = j$. When the unit space No. j is occupied by the automatic pallet No. t, it is represented by $Q(j) = t$.
(5) When the automatic pallet No. t is parked in the unit space No. j, it is represented by $A(t) = j$.

Table 1 shows the exit distance table for the first basement floor in Fig. 2(a). Figure 3 shows the unique numbers of the unit spaces.

3.2 Algorithm for determining the first parking location

For a floor number (i = 0, l, 2, ..., m), let p_i be the number of automatic pallets parked on the ith floor. The number of automatic pallets parked in the multistory car park is represented by p^*. When a car is loaded on the automatic pallet No. t, the initial parking place is the unit space on the floor where T in Eq. (6) is minimum. For example, if the second option $E(N_1(p_1 + 1))+2E'(T')$ is minimum, the car will be the unit space of No. $N_1(p_1 + 1)$ on the first floor. The three-dimensional coordinates (x, y, z) are assigned to $Cx(N_1(p_1 + 1))$, $Cy(N_1(p_1 + 1))$, and $Cz(N_1(p_1 + 1))$, respectively.

$$P(x, y, z) = N_1(p_1 + 1) \tag{3}$$

$$Q(P(x, y, z)) = t \tag{4}$$

Table 1
Exit distance table for the first basement floor in Fig. 2(a).

Order t	Unit space $N_0(t)$	Exit distance $E(N_0(t))$	Order t	Unit space $N_0(t)$	Exit distance $E(N_0(t))$
1	28	2	11	15	7
2	30	2	12	2	8
3	22	3	13	7	8
4	24	3	14	13	9
5	16	4	15	6	10
6	18	4	16	19	10
7	12	5	17	21	10
8	5	5	18	25	11
9	4	6	19	27	11
10	3	7	20	1	13

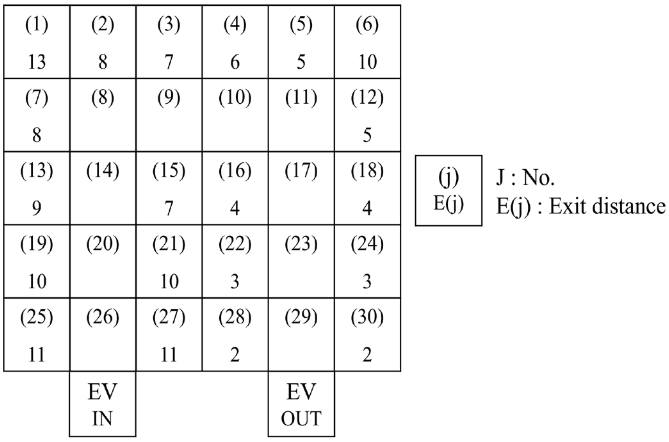

Fig. 3. Unique numbers and exit distances of unit spaces on the first basement floor in Fig. 2(a).

$$A(t) = N_1(p_1 + 1) \tag{5}$$

When p_i reaches the maximum number of cars that can be parked on the ith floor, the option that includes p_i is deleted from Eq. (6). Also, when p^* is the maximum number of cars that can be parked in the multistory car park, the entrance procedure is placed on hold until a vacant space becomes available.

$$T = Min\{E\left(N_0\left(p_0+1\right)\right), E\left(N_1\left(p_1+1\right)\right)+2E'\left(T'\right), E\left(N_2\left(p_2+1\right)\right) \\ +2E'\left(T'\right)\cdot 2, \cdots, E\left(N_m\left(p_m+1\right)\right)+2E'\left(T'\right)\cdot m\} \tag{6}$$

The term $E'(T')$ is the time required to move the elevator one floor, which is the same amount of time required to move one unit of distance to the exit.

The elevator is routinely stationed on the 1st basement floor. When the elevator goes up to the ith floor to accept an automatic pallet, it will return to the 1st basement floor again. This operation is represented in muptiplier of 2 in Eq. (6). The unit space selected by this algorithm is the parking location with the shortest exit time in the multistory car park. Funase *et al.*(4) provided a method of searching the parking position of a specified unit space No. j.

3.3 Algorithm for improving parking location

After a user orders his/her car to be delivered to the boarding area, the unit space No. j where the corresponding automatic pallet is parked becomes empty. The system moves the automatic pallet parked in the unit space on the same floor whose exit distance rank is larger by one than the unit space No. j into the newly emptied space. This operation is carried out for all the automatic pallets on the same floor. The operation is described in Algorithm 1.

[Algorithm 1]

(1) The equation $I = INT((j - 1)/k)$ finds the floor (ith floor) where the unit space No. j is located. The term k is the number of unit spaces per floor.

(2) From the exit distance table, the system finds the rank (r) of the exit distance of the unit space No. j.

(3) For $t = r, r + 1, r + 2, \ldots, p_i - 1$

- $Q(N_i(t)) \leftarrow Q(Ni(t + 1))$
- $A(Q(N_i(t)) \leftarrow Ni(t)$

p_i is the number of automatic pallets parked on the ith floor. When $r = p_i$, no improvement operation is performed. The initial value of $Q(t)(t = 1, 2, \ldots, e)$ is 0. The term e is the sum of the numbers of the basic and complex unit spaces per floor.

(4) $p_k \leftarrow p_{k-1}, \quad p^* \leftarrow p^* - 1$

If the next exit request (O) is made during the above movement, the pallet currently being operated is moved to the target unit space first, and the current operation is temporarily suspended. The information required for restarting the operation is pushed to the stack. Then, the exit request is accepted, and the pallet requested is guided to the exit. Once the exit order has been completed, the suspended operation is restarted.

3.4 Exit algorithm

The driver goes to the boarding area where his/her face is confirmed by a facial recognition camera. From the automatic pallet No. t corresponding to the facial image, the system finds the number of unit spaces, where the automatic pallet with the recognized driver's car is parked ($A(t) = j$).

The system simultaneously determines whether the unit space searched is a complex or basic unit space. If it is the former, the passage to the exit is guided by the operation shown in Fig. 1. If it is the latter, the passage to the exit is guided without additional procedures. After arriving at the exit, the system sets $A(t) = 0$ and $Q(j) = 0$.

The exit distance, the number of direction changes, and the number of floors the elevator descends are determined from the unit space where the car is parked. This information allows the system to calculate the time required for the exit procedure. For the guidance time of the pallet from the exit at the 1st basement floor to the boarding area, a previously investigated value is added as a constant to the above calculated time.

4. Optimization Plan That Determines Parking Location

Funase *et al.*[10] proposed to improve the efficiency of exiting. In this study, the exit distance was determined so that the number of frames moved until the target automatic pallet exited was minimized. A frame represented one unit space, and the movement of one unit space was represented by moving frames. The exit distance was the number of moving frames moved when passing through a passage as shown in Fig. 3.

However, even for basic unit spaces, it may be possible to reduce the number of moving frames using the procedure shown in Fig. 1 in the case of a complex unit space.

For example, in Fig. 3, No. 21, which is the basic unit space on the first basement floor, has an exit distance of 10. This is the number of moving frames when passing through the passage. However, in this case, the number of moving frames can be reduced using the procedure shown in Fig. 1. Specifically, the automatic pallet parked in the unit space No. 22 can be moved to No. 23 and then No. 17. As a result, the pallet in question can be moved to Nos. 23 and 29 through the now-empty unit space No. 22 and then to the exit. After that, the automatic pallet that is moved to No. 17 can be returned to its initial location. In this sequence, the total number of moving frames is eight, and the exit distance is reduced by 2.

In summary, algorithm 2 is proposed for obtaining an exit distance table that considers the case where the number of moving frames can be reduced.

[Algorithm 2]

(1) Obtain new exit distances for all unit spaces (basic and complex unit spaces) on the 1st floor. The new exit distance is the minimum number of moving frames on the route that can reach the exit using the automatic pallet movement method shown in Fig. 1.

(2) For $i = 0, 1, 2, \dots, m$, the following operations after (1) are repeated.

(3) Arrange the new exit distances obtained in (1) in ascending order to create an exit distance table for the ith floor.

This algorithm reduces the number of moving frames by moving the automatic pallet using the method shown in Fig. 1. The new and resulting improved exit distance tables show that the automatic pallets are now closer to the exit.

(Example 1) Table 2 shows the exit distances when Algorithm 2 is applied to the unit spaces on the first basement floor shown in Fig. 2(a). The ranking improves after the unit space No. 12. The improved number of moving frames is the total number of shortened exit distances and returned evacuated automatic pallets. Figure 4 shows the improved exit distances.

Table 2
Exit distance table on the first basement floor determined by algorithm 2.

Order t	Unit space $N_0(t)$	Exit distance $E(N_0(t))$	Total number of improved movement frames
1	28	2	—
2	30	2	—
3	22	3	—
4	24	3	—
5	16	4	—
6	18	4	—
7	12	5	—
8	5	5	—
9	4	6	—
10	3	7	—
11	15	7	—
12	27	7	improved(−1)
13	2	8	—
14	7	8	improved(−1)
15	21	8	improved(−2)
16	13	9	improved(−1)
17	6	10	—
18	19	10	improved(−1)
19	25	11	—
20	1	13	—

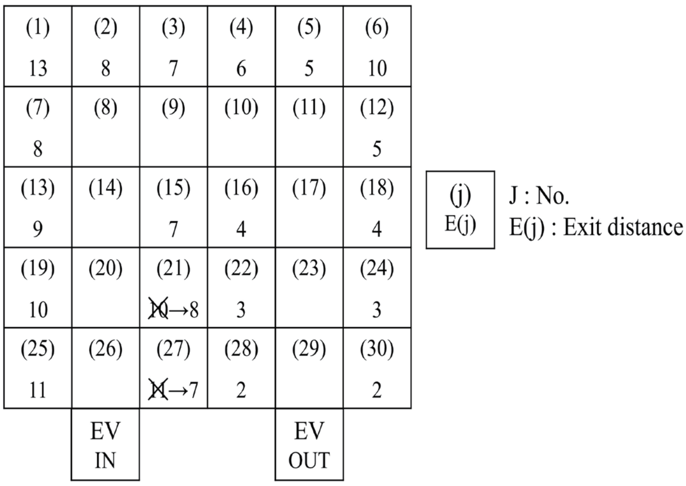

Fig. 4. Improved exit distances for unit spaces on the basement floor in Fig. 2(a).

5. Conclusions

In this study, we introduced various sensors to accurately move an automatic pallet and proposed a method of improving the exit efficiency of automated valet parking by considering the material as the detection target of the sensor. Specifically, we created a temporary shortcut instead of a conventional detour passage and used that shortcut to shorten the distance to the exit.

The multistory parking lot targeted in this study is a parking lot with a passage. We proposed a parking lot with good efficiency in its exit time using the mainstream automatic driving system. However, because there is not enough space in cities and other places where land prices are high, it is important to increase the number of parking spaces per unit floor area. In such places, valet parking without passages is used, but it is inefficient in terms of exiting the parking lot, and there are cases of accidents during entry and exit by the staff. For this reason, we are considering automated valet parking, but if there is a parking lot with a passage, automated driving is the mainstream, and we believe that the multilevel parking system proposed in this paper is ideal. Also, if there is no passage, we consider that a multilevel parking system such as that proposed by Funase *et al.*[1] is ideal. As a plan for optimization, we consider a system that temporarily uses the unit spaces dedicated to passages as parking spaces. These remain issues for future study.

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