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A route optimization model based on building semantics, human factors, and user constraints to enable personalized travel in complex public facilities

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ABSTRACT

Entire routing planning is a prerequisite to ensuring the appropriate navigation, especially for pedestrians with visual impairments. This paper focuses on optimizing the initial indoor route selection before micro-navigation. A new travel utility schema is defined to represent a user's travel confidence with regard to different types of obstacles and a user's acceptable level of travel difficulty. *The applicability of the model is evaluated using the layout data from a real bus terminal. The results show that the pedestrian doesn't always select the shortest path as assumed in existing papers, and will make detours to destinations to cut down the travel difficulties.* Although the current use case focused on people with visual impairment, the framework is generable to support other users such as users with wheel chairs and users with Autism Spectrum Disorder (ASD) to use public facilities independently.

1. Introduction

Independent travel in complex building facilities such as transportation hubs is tremendously problematic for people who are blind or have a visual impairment. Almost one-third of the whole population with visual impairment reports not being able to navigate within their community by themselves even with the help of guide dogs and/or a Hoover cane [4]. Currently, there exist assistive navigation technologies that make it possible to substitute the company of a "sighted guide" (i.e. sighted assistant) for pedestrians with visual impairment. This innovation will enhance their independence and community access. The navigation involves two key action components: mobility and orientation [18,34]. Mobility focuses primarily on micro-navigation to ensure safe movement through space without running into objects. It includes sensing the immediate environment and obstacle avoidance in the vicinity, based on the visual, auditory, location and olfactory stimuli identification [10]. While the second component, also labeled as macro-navigation, involves navigating the remote environment beyond that which is immediately perceptible. It consists of being oriented, route selection (or wayfinding), and executing routes to the destination. Micro-navigation has been thoroughly investigated in the existing literature such as detecting obstacles, locating, and correct heading in the near fields, while the studies on macroscopic routing planning for the entire travel are limited and still lag behind. This deficiency will degrade the performance of whole navigation applications because route planning is a prerequisite to travel orientation. Especially in the case of visual impairment, the absence of route selection optimization will cause an increase in travel difficulties and durations, which can enlarge the hurdles of independent movement, and augment the potential occurrence of injury. Additionally, every pedestrian has their particular criteria for route selection owing to their various levels of travel difficulty, independence, and confidence. It is not practical to generalize identical route selection rules for every pedestrian with visual impairment. Therefore, this paper will target entire route optimization for pedestrians with visual impairment to address the problematic issue of macro-navigation considering customized requirements. The route

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Table 1
Selected studies on the navigation for pedestrians with visual impairment.

Authors	Methods	Focuses	Navigation types
D'Atri et al. [6]	RFID and wireless technologies	Providing the environment information to assist the mobility of blind people	Micro-navigation
Kammoun et al. [16]	Geographical information system (GIS)	Improve the guidance process for better representation of the surroundings	Micro-navigation
Kaiser et al. [15]	Simultaneous localization and mapping from mobile robotics	Map and track the position of the pedestrian	Micro-navigation
Katz et al. [18]	Virtual augmented reality system	Route planning and guidance but missing the optimization of route selection	Micro- and Macro-navigation
Weyrer et al. [32]	OpenStreetMap (OSM)-based Data model	Developing the geospatial barrier catalog and a web-based prototype	Macro-navigation for intermodal door-to-door travel
Mancini et al. [20]	Sensors and mobile applications	Sensing the surrounding area for point-to-point navigation	Micro-navigation
Spiers and Dollar [27]	GPS	Haptic guidance for outdoor navigation	Micro-navigation
Buchs et al. [5]	EyeCane to translate distances from several angles to haptic and auditory cues	Avoiding the waist-up obstacles	Micro-navigation
Xu et al. [33]	BIM	Indoor path planning considering obstacles in the multi-floor buildings	Macro-navigation without optimization mechanism

selection is optimized herein based on the personalized criteria of every pedestrian with visual impairment, which enhances the opportunities for their community integration.

To date, a few studies on macro-navigation have been conducted and representative research topics have included positioning [17], spatial layout analysis (Rafian and Legge, 2017), and developing assistive orientation system [20,24]. However, the existing research focused primarily on the processes after the determination of the entire route selection, and they gave limited consideration to route planning optimization prior to orientation. Of these, Völkel and Weber [31] developed a client system for pedestrians with visual impairment to connect geographical data with route selection criteria. The multi-criteria routing was proposed according to the different requirements of pedestrians to achieve potentially conflicting objectives of minimum route length and risks. Kammoun et al. [16] proposed a route selection algorithm for blind pedestrians to choose an optimal pathway between an origin and a destination. A common point for these studies is that they selected the routes based on certain criteria, and gave little consideration to systematic route optimization. To summarize, the limitations of existing routing optimization compared with this study are presented as follows: (1) route planning was restricted to one destination, and the travel constraints were not considered such as the upper/lower time bound of activity, the acceptable level of travel difficulties and the constraints for the travel flow balance. Whereas in this paper, multiple activities with fixed and random sequences are both considered to formulate a systematic route selection optimization model subject to the aforementioned constraints. These constraints could ensure that the optimal solution of the optimization model is more suitable in practice and improve the applicability of the model. (2) The personalized requirements of different pedestrians were generally regarded as similar in previous studies, while this paper defines the customized travel utility to represent the individual time requirement, confidence, and the acceptable level of difficulty. (3) Most orientation research targeted outdoor activities. The route selections in existing studies of outdoor activities are optimized from the macroscopic view, giving very little, if not none, consideration on the mobility aspects (micro-navigation to ensure safe movement through space without running into objects). In addition, a single optimization objective such as the shortest path is pursued in existing studies. While the indoor route selection in this paper is more microscopic with comprehensive considerations of multiple travel obstacles in divided segments, such as escalator, lobby, corner, and sloped walkway. By comparison, this study concentrates on the public indoor travel of people with visual impairments, which is more conducive for large public places such as subway stations and the hospital.

The remainder of this paper is organized as follows. Section 2 is the literature review. Section 3 defines the personalized travel utility of pedestrians with visual impairment. Section 4 formulates the route planning optimization model under two scenarios of activities with fixed and random sequences. The empirical validation and discussions are presented in Section 5. Conclusions are provided in Section 6.

2. Literature review

The travel aids and assistive methods for pedestrians with visual impairment have been extensively investigated since the 1980s with the primary focus on basic obstacle avoidance [20,26] and navigation systems design [31]. By comparison, less efforts were devoted to route selection. Table 1 summarizes existing studies in this domain to indicate the research gaps. Most studies on indoor route planning focused on the micro-navigation to assist mobility, while the entire route planning of macro-navigation was scarcely considered. The route selection optimization is a prerequisite to travel navigation. Although a few researchers mentioned the guidance of the entire path [18,32], the optimization of routing was not emphasized. For example, Katz et al. [18] primarily relied on an adapted GIS database to access an overview of the path to follow. Weyrer et al. [32] tried to develop the geospatial barrier catalog and a web-based prototype to select the barrier-free path. However, the detailed routing optimization model was missing and the limitations would augment the difficulty in route selection especially when multiple alternatives can be chosen. Additionally, although the existing studies have also considered travel obstacles [8,29], few of them has integrated individual user preferences into route planning, and the criterion of route selection was limited to single objectives. Hoogendoorn and Bovy [12] proposed the cost-minimizing approach to organize the navigation path within an airport. The selection of human is always led by less tangible factors including the confidence, desire and independence level. Kurose et al. [35] assumed that pedestrians would take the shortest path between individual destinations. While, the shortest-path route was not always followed in practice because safety is the most basic requirement for visual impaired people and they try to avoid noisy and crowded cross-ways to accept a longer but safer route [30]. To address these limitations, a travel utility is defined in this paper to represent each pedestrian's individual preferences in time requirement, confidence, and the acceptable level of difficulty. On this basis, the personalized travel requirements can be satisfied to the most extent compared to the generalized optimization goals in the previous studies.

Building information modeling (BIM) contains detailed geometric and semantic information about buildings including their indoor environment [9], and it is widely regarded as one major technological advance in deriving information appropriate for navigation [3]. Among many other capabilities, it can enable spatial queries about locations and navigation paths through spaces [13,21,28]. For example, Isikdag et al. [13] proposed a BIM-based model dedicated to facilitating indoor navigation by providing detailed semantic information along with 3D geometries. Rueppel and Stuebbe [25] developed a BIM-based indoor emergency navigation system to provide for routing within a public

Table 2
Difficulties of different segments for each path during indoor travel.

Segment type no.	Obstacle	Personalized difficulty score
O_1	Escalator	S_1
O_2	Lobby	S_2
O_3	Obstacle in the way	S_3
O_4	Corner/Intersection	S_4
O_5	Sloped walkway	S_5
O_6	Normal walkway	S_6
O_7	Elevator	S_7

building and provided travelers with important information in their particular spatial context when the emergency happened. Xu et al. (2017) used BIM as the input data to enable efficient indoor path planning considering obstacles in the multi-floor buildings. In these studies, however, the optimization mechanism was not considered in routing, the methods proposed in these studies can hardly satisfy various travelers with different travel requirements and preferences. In this paper, we design a route selection optimization model that can use building semantics information such as locations of indoor pathways and staircases, walkway slopes, building functional layouts, and travel obstacles (furniture, trash cans, etc.) as well as personal travel preference and schedules to recommend optimized travel choices for blind users.

The route selection optimization with multiple destinations, in this paper, can be formulated as an operation research problem for which mathematical formulations were developed to derive the optimal or near optimum solution to support blind users' decision-making on route choices. The traveling salesman problem (TSP) is a typical route optimization question in other domains [1,7], and the traveler will visit each one of multiple locations and then return home. The route with the lowest cost was pursued in the interest of route selection optimization [11]. Algorithms have also been proposed to find solutions for the extremely large TSP [2,14,19]. In this paper, the pedestrian needs to make a single visit to each activity location. This similarity with the TSP makes the modeling method feasible in the domain of pedestrian route optimization. However, the routing problem in this paper has its unique characteristics: (1) the visual impaired traveler will not return back to the start location; and (2) the optimal objective is more complicated when considering the personal requirements of travelers, the total travel time, and travel difficulties. Additionally, two scenarios exist in practice in terms of the activity sequence including the fixed and random orders. On this basis, a novel route planning optimization model for pedestrians with visual impairment was proposed in this paper to facilitate macro-navigation for indoor travel.

3. Personalized travel utility of blind pedestrians

Route planning is the first step during the course of navigation for pedestrians with visual impairment. The route selection can facilitate users to preview the upcoming journey before travel, to access an overview of the path to follow. Additionally, different pedestrians have various travel requirements and acceptable levels of difficulty, and hence the route selection criteria should be customized. The independent and confident travelers generally prefer the shortest routes even if it maybe involve difficulties. While other conservative pedestrians

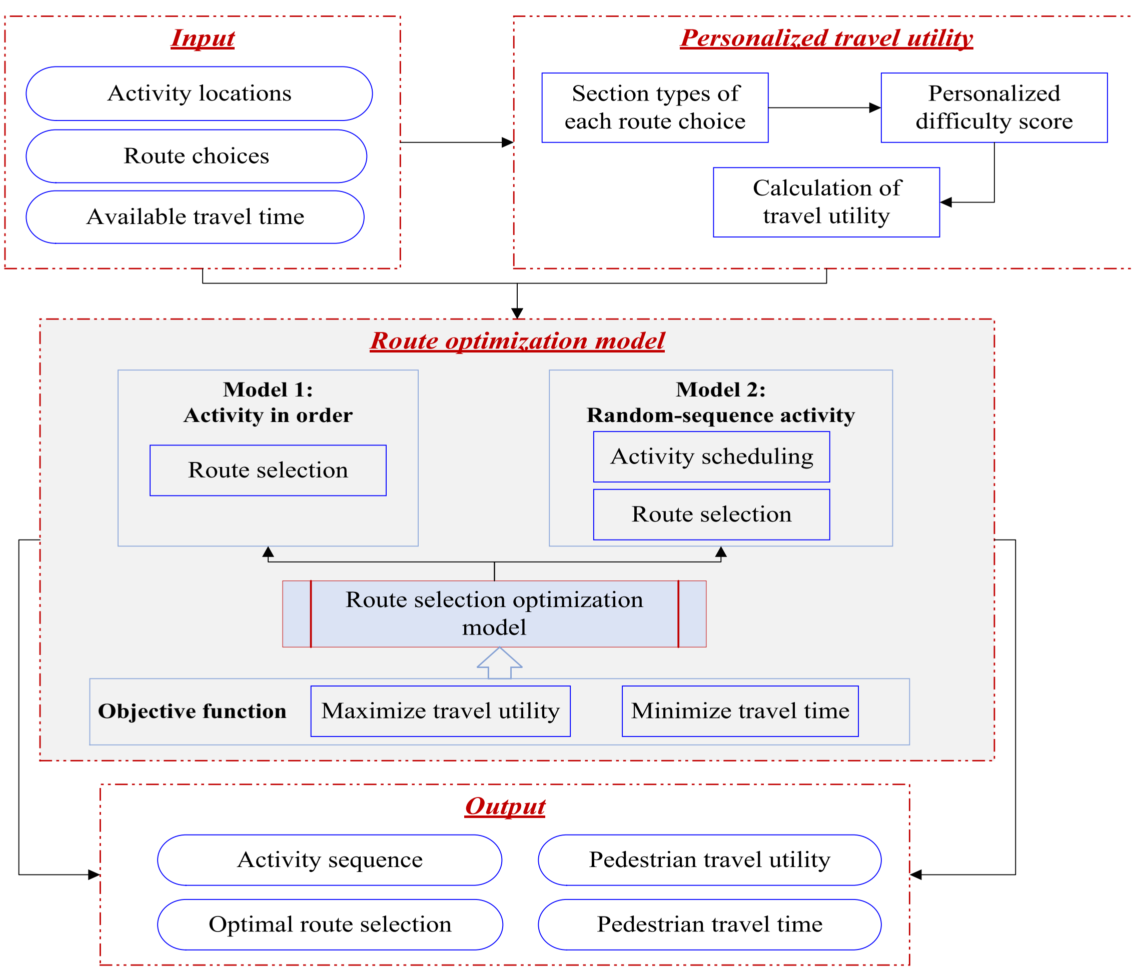

Fig. 1. Framework of route selection optimization model.

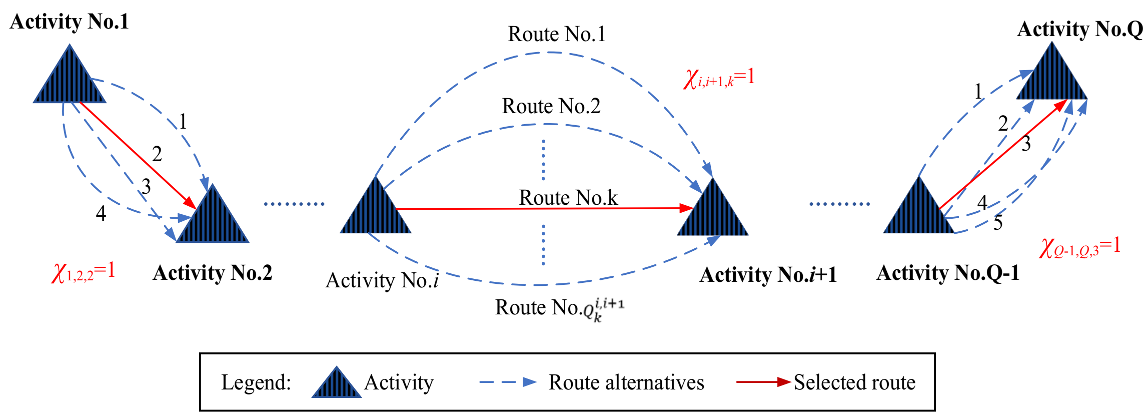

Fig. 2. Route selection optimization model for fixed-order activities.

would pursue a more prudent path which is longer but easier to follow.

Each travel path can be divided into several segments with different types of transit obstacles. The typical obstacles during the indoor travel are tabulated in Table 2, which represents different travel difficulties for the blind pedestrian. The "Obstacle in the way" means objects such as trash cans and other furniture items in the travel paths which can impede the straight movement of a blind pedestrian. The "corner/intersection" refers to the corners of interior building structures (i.e. walls) or the intersection of interior pathways. Generally, straight, wider and uncrowded walkways are preferable route elements, and blind people prefer the shorter and easier routes especially when the time is a chosen consideration. In this regard, the blind pedestrian hopes to avoid the elements such as the stairs, narrow sidewalk, large open areas, and intersections [18]. Additionally, different blind people can accept various difficulty levels during travel if these obstacles cannot be avoided. A travel utility is defined in this paper to represent the degree to which a given travel path choice for a blind pedestrian is better than other travel path choices in terms of travel difficulty. It is basically the difference in travel difficulty between a given path and the path with the maximum difficulty. It is a more mobility related parameter considering the unique travel challenges for blind pedestrians. In other words, the travel utility represents the personalized preferences over different route selections. The higher travel utility indicates that the selected route is much safer and this pedestrian has more confidence to pass it. A blind pedestrian will first grade the travel difficulty for different types of route segments using a scale from 1 to 5 based on their own criteria of the acceptable level of transit difficulty and confidence. On this basis, the travel difficulty of k route for the blind pedestrian is equivalent to the total difficulty scores of all obstacle segments in k route, which can be represented by Eq. (1). The travel utility for the selected route, denoted by μ, is equal to the difference between the maximum difficulty and the actual undergoing difficulty of the selected route μ as shown in Eq. (2).

$$D(k) = \sum\nolimits_{m}^{Q_m} S_m \times R_{mk}, \forall k = 1, 2, \dots, Q_k \tag{1}$$

$$U(\mu) = Max\{D(k)\} - D(\mu), \forall k = 1, 2, \dots, Q_k \tag{2}$$

Where m ($m = 1, 2, \dots, Q_m$) is the serial number of obstacles during indoor travel, and Q_m denotes the number of obstacle types. Q_k is the quantity of potential path to be selected. $D(k)$ and $U(k)$ are the personalized difficulty score and the travel utility of the blind pedestrian with k route selection, respectively. S_m denotes the personalized difficulty score of m obstacle for the blind pedestrian. R_{mk} represents the quantity of the m-type difficulty segments in the k path.

The customized travel utility of each route alternative can be calculated for every blind pedestrian using Eq. (2), which denotes the satisfaction level for the travel difficulty to go through. A larger utility value represents a lower level of travel difficulties. The pedestrian will optimize their route selection to maximize their travel utility if the time is not limited. Otherwise, they may reduce the utility to pursue a shorter travel duration if the activity is urgent. This paper tries to achieve the trade-off between the travel utility and the travel time to pursue a customized route selection for blind pedestrians with various transit requirements.

4. Route planning optimization modeling

A systematic route selection optimization model is proposed in this paper considering the personalized acceptable level of travel difficulties for various pedestrians. The framework of the model is illustrated as shown in Fig. 1. First, the locations of the activity to be conducted, potential route choices between every two activities and the allowable travel time are input into the model. The blind pedestrian will grade different types of obstacles in Table 2 according to their acceptable level of difficulties. On this basis, the travel utility of this pedestrian will be calculated, which is individualized and varies with his or her previous practice, confidence and personality. Subsequently, the travel routes will be optimized using a route selection optimization model to pursue the maximum travel utility and minimum travel time. The optimization is divided into two categories according to the activity sequences. If the event has to be conducted in a fixed order, only the route selection between every two events will be optimized. Sometimes, the activity has no direct relations and their sequences are random. The sequence of activities will first be scheduled in this scenario, followed by the optimization of route selection between every two activities. Finally, the optimal travel plan can be provided including the event sequence, route selection, travel time and the utility. This optimization model could support the decision makings on the navigation of blind pedestrians from the whole view. The navigation system will customize the travel route for each blind pedestrian with the input of the activities to do and their acceptable level for difficulties. Note that the route optimization in this paper is in pursuit of providing overall route planning information during the course of navigation, while the detailed guidance for each step is not considered.

4.1. Route optimization for fixed-order activities

The travel will be incurred when the pedestrians with visual impairment needs to conduct series of activities. The activity sometimes has inherent sequential orders owing to their correlations between each other, and hence these events have to be finished in a fixed sequence. For example, the pedestrian has to buy the tickets (activity 1) first before boarding the train or airplane (activity 2). In this situation, just the travel routes between different activities need to be optimized. Let μ be an arbitrary route selection plan, and the optimization objectives of route optimization are to maximize the travel utility and minimize the

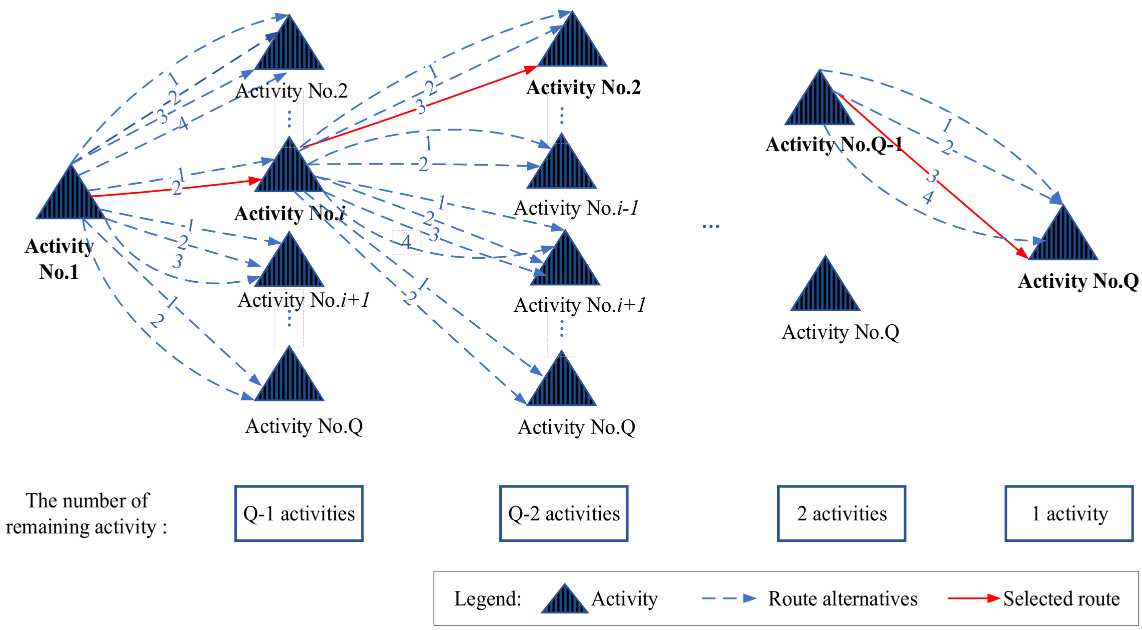

Fig. 3. Route selection optimization model for random-sequence activities.

travel time, as deduced by Eq. (3). Eq. (4) formulates the total travel difficulty score of the selected routes connecting all activities, and the travel difficulty score of k route connecting i and $i+1$ activities is calculated by Eq. (5). The travel utility of the selected route can be calculated by Eq. (6) which is defined as the difficulty differences between the one that the blind pedestrian goes through during this travel and the maximum value. Fig. 2 illustrates the diagram of the optimization model in this scenario of fixed-order activity, and the routes marked red are selected in this travel.

$$f(\mu) = Max\left[W^U \times U(\mu) - W^T \times C^T(\mu)\right] \tag{3}$$

$$D(\mu) = \sum_{i=1}^{Q}\sum_{k=1}^{Q_k^{i,i+1}}\sum_{m=1}^{Q_m} S_m \times R_{mk} \times x_{i,i+1,k} \tag{4}$$

$$D(i,k) = \sum_{m=1}^{Q_m} S_m \times R_{mk}, \forall k = 1,2,\dots,Q_k^{i,i+1}, \forall i = 1,2,\dots,Q \tag{5}$$

$$U(\mu) = \sum_{i=1}^{Q} Max\{D(i,k)\} - D(\mu), \forall k = 1,2,\dots,Q_k^{i,i+1} \tag{6}$$

$$x_{i,i+1,k} = \begin{Bmatrix} 1 \ \textit{if traveling from activity } i \textit{ to } i+1 \textit{ through } k \textit{ path} \\ 0 \ \textit{otherwise} \end{Bmatrix} \tag{7}$$

Where, U denotes the travel utility of the pedestrian and C^T is the travel time. W^U and W^T represent the weight values of the two sub-objectives, respectively. i (i = 1, 2, …, Q)is the series number of activities in this travel; m ($m = 1,2,\dots,Q_m$) represents the obstacles type as shown in Table 2; k (k = 1, 2, …, $Q_k^{i,\ i+1}$) denotes the serial number of potential routes connecting i and (i + 1) activity; $x_{i,\ i+1,\ k}$ equals one when the k path connecting the No. i and No. (i + 1) activity is selected for travel, otherwise, the value will be zero; R_{mk} is the quantity of the m-type difficulty segments in the k path, and S_m is the difficult score of this segment type graded by the blind pedestrian.

Additionally, the total travel time is equivalent to the completion time of final activities (see Eq. (8)). Let C_i^T be the completion time of No. i activity, and $T_{i-1,\ i}$ be the travel time from No. (i − 1) to No. i activity. P_i is the average duration time to conduct i activity for a blind pedestrian. Therefore, the completion time of i activity is equivalent to the completion time of (i − 1) activity plus the sum of the duration time of i activity and the travel time between these two events locations as shown in Eq. (9). The travel time between every two contiguous activities is defined in Eq. (12). Where T_{mk} is the general travel time of m-type segment in the k route. Eq. (11) enforces the under and upper time constraints to conduct the activity. L_i and T_i denote the earliest time to start executing the i activity and the time by which the i activity needs to be completed.

$$C^T(\mu) = C_Q^T(\mu) \tag{8}$$

$$C_i^T = C_{i-1}^T + T_{i-1,i} + P_i, \forall i = 1,2,\dots,Q \tag{9}$$

$$C_0^T = 0 \tag{10}$$

$$L_i \le C_i^T \le T_i, \forall i = 1,2,\dots,Q \tag{11}$$

$$T_{i,i+1} = \sum_{k=1}^{Q_k^{i,i+1}}\sum_{m=1}^{Q_m} x_{i,i+1,k} \times T_{mk} \times R_{mk}, \forall i = 1,2,\dots,Q \tag{12}$$

Further, the constraints for travel requirements are defined to ensure the feasibility of solutions as shown in Eqs. (13)–(14). Formula (13) implies that all activities will be visited and only be conducted once, besides just one route will be selected when traveling from No.i to No.(i + 1) activity. The sub-tour is eliminated with the constraints of Formula (14).

$$\sum_{k=1}^{Q_k^{i,i+1}} x_{i,i+1,k} = 1, \forall i = 1,2,\dots,Q \tag{13}$$

$$\sum_{i=1}^{Q} x_{i,i+1,k} \le Q-1, \forall k = 1,2,\dots,Q_k^{i,i+1} \tag{14}$$

4.2. Route optimization for random-sequence activities

On the other hand, the sequential order of the activities may be random during the tour. The route optimization can be divided into two steps in this scenario, including (1) activity sequence scheduling and (2) routing optimization. As shown in Fig. 3, the next activity needs to be selected every time from the remaining activities and the route alternatives connecting these two activities will also be optimized. This paper proposes the random-sequence-activity route optimization model to address these problems on the basis of Section 4.1. The model can be summarized as the multiple optimization objectives in Eq. (3) subject to the constraints of formulas (8)–(11) and (15)–(25).

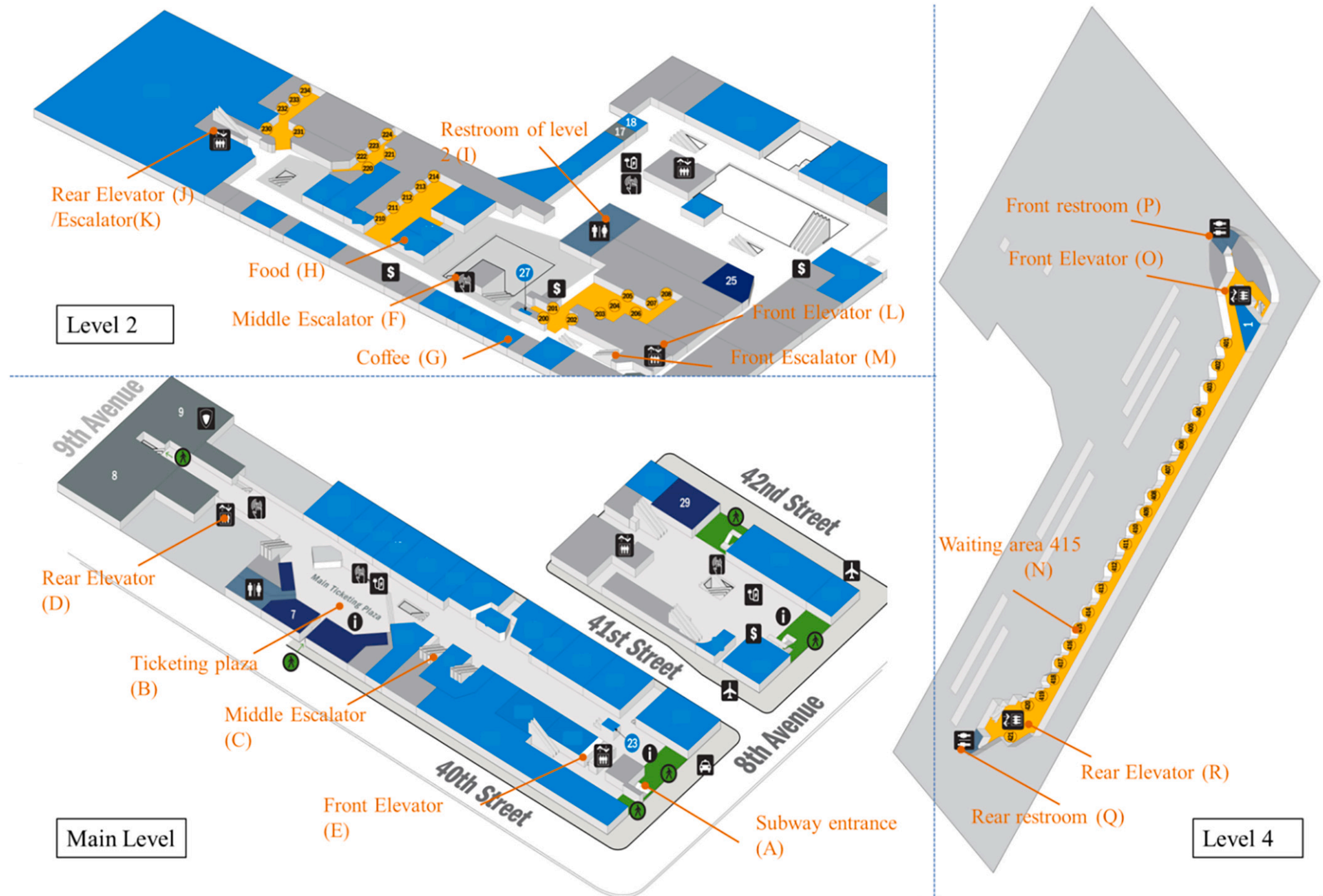

Fig. 4. Map of the port authority bus terminal in New York.

$$x_{ijk} = \left\{ \begin{matrix} 1 \text{ if traveling from activity } i \text{ to } j \text{ through } k \text{ path} \\ 0 \text{ otherwise} \end{matrix} \right\} \quad (15)$$

$$\delta_{ij} = \left\{ \begin{matrix} 1 \text{ if activity } j \text{ will be conducted after finishing activity } i \\ 0 \text{ otherwise} \end{matrix} \right\} \quad (16)$$

$$\sum_{k}^{Q_k^{i,i+1}} x_{ijk} = \delta_{ij}, \forall i, j = 1, 2, \dots, Q \quad (17)$$

$$D(\mu) = \sum_{i=1}^{Q} \sum_{j=1}^{Q} \sum_{k=1}^{Q_k^{i,i+1}} \sum_{m}^{Q_m} S_m \times R_{mk} \times x_{ijk} \times \delta_{ij} \quad (18)$$

$$D(i,k) = \sum_{m=1}^{Q_m} S_m \times R_{mk}, \forall k = 1, 2, \dots, Q_k^{i,i+1}, \forall i = 1, 2, \dots, Q \quad (19)$$

$$U(\mu) = \sum_{i=1}^{Q} Max\{D(i,k)\} - D(\mu), \forall k = 1, 2, \dots, Q_k^{i,i+1} \quad (20)$$

$$T_{ij} = \sum_{k=1}^{Q_k^{i,i+1}} \sum_{m=1}^{Q_m} x_{ijk} \times \delta_{ij} \times T_m \times R_{mk}, \forall i, j = 1, 2, \dots, Q \quad (21)$$

$$\sum_{i=1}^{Q} x_{ijk} \times \delta_{ij} = 1, \forall j = 1, 2, \dots, Q \quad (22)$$

$$\sum_{j=1}^{Q} x_{ijk} \times \delta_{ij} = 1, \forall i = 1, 2, \dots, Q \quad (23)$$

$$\sum_{k=1}^{Q_k^{i,i+1}} x_{i,j,k} \times \delta_{ij} = 1, \forall i, j = 1, 2, \dots, Q \quad (24)$$

$$\sum_{i=1}^{Q} \sum_{j=1}^{Q} \delta_{ij} \leq Q - 1 \quad (25)$$

An additional zero-one parameter δ_{ij} is defined in this model to imply whether activity j is conducted after the finish of activity i as shown in Eq. (16). Formula (17) ensures the balanced flow from and out of each activity location. If activity j is scheduled to be conducted after finishing activity i, it must exist one path k to be selected to visit j activity. Similarly, Eqs. (18) and (19) can calculate the travel difficulty scores of the selected route connecting all activities and the route k connecting i and i+1 activity, respectively. Eq. (20) defines the travel utility and Eq. (21) is the travel time between different activity locations. Formulas (22) and (23) enforce that each activity location will be visited by the pedestrians with visual impairment only once. Eq. (24) defines that only one route will be selected when traveling from activity i to $(i + 1)$. Eq. (25) is to eliminate the situation of sub-tour and all activities locations will be visited during one travel.

5. Case study

5.1. Data collection and model initialization

The Port Authority Bus Terminal is the central hub for interstate buses in New York City, featuring four levels and a wide array of shops, restaurants and services. This terminal is selected in this paper to verify the performance of the proposed model. All the detailed information about the terminal was obtained from the point cloud, BIM model, and publically available information. The point cloud and BIM data are outcomes of a large-scale Scan-to-BIM project which was conducted in 2016. Assume the pedestrians with visual impairment will take the bus from the New York City to New Brunswick, New Jersey, and two scenarios are designed herein to optimize the route selection. (1) The pedestrian enters the bus terminal from the subway exit at the Subway Level, to buy the tickets at the ticking plaza of Main Level and gets on the

Table 3
Walkway information of the possible route segments.

Level no.	Travel route	Distance (meters)	Whether it is a slope (Y or N)	Whether exist a barrier in the way (Y or N)
Main level	Subway entrance→ ticketing plaza (A → B)	129.0	Y	Y
	Ticketing plaza→ middle escalator (B → C)	61.8	Y	Y
	Ticket plaza → front elevator (B → E)	100.5	Y	Y
	Ticket plaza→ rear elevator (B → D)	93.9	Y	Y
Level 2	Middle escalator→ front escalator (F → M)	54.0	N	Y
	Middle escalator→ front elevator (F → L)	83.1	N	Y
	Middle escalator→ rear escalator (F → K)	101.1	Y	N
	Middle escalator→ rear elevator (F → J)	101.1	Y	N
	Rear elevator→ coffee (J → G)	134.4	Y	N
	Front elevator→ coffee (L → G)	23.7	N	Y
	Coffee→ food (G → H)	48.3	Y	N
	Food→ rear elevator (H → J)	86.1	Y	N
	Food→ front elevator (H → L)	72.0	N	Y
	Coffee→ restroom of Level 2 (G → I)	63.9	N	N
	Restroom of Level 2 → front elevator (I → L)	87.6	N	Y
	Restroom of Level 2 → rear elevator (I → J)	148.2	Y	N
	Food→ restroom of Level 2 (H → I)	47.4	N	N
Level 4	Front elevator → gate 415 (O → N)	156.6	Y	N
	Rear elevator → gate 415 (R → N)	46.2	Y	N
	Waiting area 415 → rear restroom (N → Q)	53.7	Y	N
	Rear restroom → rear elevator (Q → R)	21.6	N	N
	Waiting area 415 → front restroom (N → P)	153.3	Y	N
	Front restroom→ front elevator (P → O)	18.9	N	N

bus at gate 415 in Level 4. Hence, the fixed-order sequence of activity is: subway exit→ ticking plaza→ Bus gate 415. (2) Several random-order activities are designed in the second scenario including grabbing a coffee, buying food, and going to the restroom. The coffee and food store located at Level 2. The restroom at Level 2 and Level 4 can both be selected as illustrated in Fig. 4.

The walkway information of route segments at different levels is tabulated in Table 3. On this basis, the distance and the difficulty level of possible routes in each scenario can be deduced as shown in Tables 4 and 5. With respect to the first scenario of fixed-order activity, the pedestrian can take the elevator or escalator from the subway exit to arrive at the ticking plaza (Main level) as shown in Table 4. Additionally, there are six alternatives for the route from the ticking plaza to the bus gate 415 at Level 4. The pedestrian can arrive at Level 4 directly using the front or rear elevator which is far away from the ticking plaza, or take the near middle escalator at the Main level to arrive at Level 4 via Level 2. On the other hand, the three activities in Scenario 2 have no fixed order, and hence the route selection can be divided into six categories: Restroom→Coffee→Food, Restroom→Food→Coffee, Food→Coffee→Restroom, Coffee→ Food→Restroom, Coffee→Restroom→Food, and Food→Restroom→Coffee. Each category has 4 alternatives and three typical groups of alternatives are detailed in Table 5. The difficulty score S_m for each type of segments O_m in Tables 4 and 5 is graded by the pedestrian to represent the difficulty level for him to pass through. The values are assumed and illustrated in Table 6 based on the literature review [18]. The proposed model can serve other pedestrians with visual impairment by adjusting the personalized difficulty score S_i.

In this case study, the general travel time of the m-type segment T_{mk} is denoted by the inverse of the travel speed in this segment type V_{mk}, and we assume that the travel speed of the same segment type is same in different routes for simplification. The average travel speed of blind pedestrian in the normal walkway (m=6) is set as V_6=1.22 m/s [23], and the walk speed in other segment types is assumed to be equal to the walk speed in the normal walkway multiplying the ratio of the difficult scores between the normal walkway and segment type m as formulated in Eq. (26). Besides, the activities in this case study don't have the fixed upper bound, and thus L_i is set zero, which can be modified in other situations if there are special requirements.

$$V_m = V_6 \times \frac{S_6}{S_m}, m = 1, 2, 3, 4, 5, 7 \tag{26}$$

5.2. Results and discussions

The normalization of the two objective functions U and C^T is conducted owing to their different magnitudes and measures. The minimum ($f_{Min,\ i}$*) and maximum function values ($f_{Max,\ i}$*) in scenario i ($i = 1, 2$) are computed individually based on the constraints of Eqs. (4)–(25): $f_{Min,\ 1}{}^T = 32.26, f_{Max,\ 1}{}^T = 40.44, f_{Min,\ 2}{}^T = 13.92, f_{Max,\ 2}{}^T = 29.52, f_{Min,\ 1}{}^U = 0, f_{Max,\ 1}{}^U = 6.3, f_{Min,\ 2}{}^U = 0, f_{Max,\ 2}{}^U = 37.62$. Hence, the previous objective function can be converted into:

$$Maxf = Max\left(W^U * f_{B,i}^U - W^T * f_{B,i}^T\right) \tag{26}$$

Where

$$f_{B,i}^T = \left(f^T - f_{Min,i}^T\right) \Big/ \left(f_{Max,i}^T - f_{Min,i}^T\right)$$

$$f_{B,i}^U = \left(f^U - f_{Min,i}^U\right) \Big/ \left(f_{Max,i}^U - f_{Min,i}^U\right)$$

This proposed model is solved using Lingo 11.0, the software widely applied in formulating diverse optimization problems. The values of W^T and W^U, more importantly the ratio between them imply how a blind pedestrian values available time for travel against travel utility (indicating how travelable a path is considering his/her own mobility challenges). The weight value can be modified in practice according to the actual preferences of different pedestrians, and the pedestrian can provide their own ratio of these two objectives according to their own travel situations. To examine the validity of the proposed model under various extreme objectives and conditions, six scenarios with different weight distributions of objective functions are considered. Their optimal objective values are tabulated in Table 7. First, assuming that the weights of two objective functions W^T and W^U both equal 1/2. This indicates the time and the travel utility of difficulty level matter similarly to the pedestrians with visual impairment. Second, the single objective situation is individually considered in the case of fixed-order and

Table 4
Possible travel routes for fixed-order activities.

Activity sequence	Route no.	Route plan	Quantities of different segments in each route							Distance (m)
			O_1	O_2	O_3	O_4	O_5	O_6	O_7	
Subway exit→ Ticketing plaza	1	Subway exit→ escalator→ B	1	1	1	1	1	1	0	298
	2	Subway exit→ elevator→ B	0	1	1	1	1	1	1	430
Ticketing plaza → Boarding gate 415	1	B → C → Level 2 → M → Level 4 → N	2	1	1	2	0	2	0	908
	2	B → C → Level 2 → L → Level 4 → N	1	1	1	3	0	3	1	1005
	3	B → C → Level 2 → K → Level 4 → N	2	2	0	3	0	3	0	697
	4	B → F → Level 2 → J → Level 4 → N	1	2	0	3	0	3	1	697
	5	B → L → Level 4 → N	0	1	1	3	2	3	1	857
	6	B → J → Level 4 → N	0	1	1	3	2	3	1	599

Note: O_i represents the obstacle type of the route: O_1= Escalator, O_2= Lobby, O_3=Obstacle in way, O_4=Corner/Intersection, O_5=Sloped walkway, O_6=Normal walkway, and O_7=Elevator.

Table 5
Possible travel routes for random-sequence activities.

Activity sequence	Route no.	Route plan	Quantities of different segments in each route							Distance (m)
			O_1	O_2	O_3	O_4	O_5	O_6	O_7	
Restroom→ Coffee→ Food	1	N → Q → R → Level 2 → G → H → J → N	0	1	0	2	5	6	2	390.3
	2	N → Q → R → Level 2 → G → H → L → N	0	0	1	1	3	6	2	486.6
	3	N → P → O → Level 2 → G → H → L → N	0	0	2	3	3	6	2	472.8
	4	N → P → O → Level 2 → G → H → J → N	0	1	1	4	4	6	2	376.5
Food→ Coffee → Restroom	5	N → R → Level 2 → H → G → I → L → N	0	2	1	4	4	6	2	488.7
	6	N → R → Level 2 → H → G → I → J → N	0	3	0	5	5	6	2	438.9
	7	N → O → Level 2 → H → G → I → L → N	0	2	1	5	4	6	2	585.0
	8	N → O → Level 2 → H → G → I → J → N	0	3	1	6	4	6	2	535.2
Coffee→ Restroom→ Food	9	N → R → Level 2 → G → I → H → L → N	0	3	1	7	3	6	2	520.5
	10	N → R → Level 2 → G → I → H → J → N	0	4	0	7	4	6	2	424.2
	11	N → O → Level 2 → G → I → H → L → N	0	2	2	7	2	6	2	520.2
	12	N → O → Level 2 → G → I → H → J → N	0	3	1	7	3	6	2	423.9

Table 6
Difficult score of each obstacle type [18].

Segment type no.	Obstacle	Average difficulty score (S_i)
O_1	Escalator	4.47
O_2	Lobby	4.33
O_3	Obstacle in way	3.33
O_4	Corner/Intersection	2.83
O_5	Sloped walkway	2.65
O_6	Normal walkway	2.17
O_7	Elevator	2.00

random-sequence activities. Scenarios 1 and 4 with even weight distributions serve as the reference scenario to compare the effects of different goals on the solutions. On this basis, the increments of objective values compared to the reference scenarios are illustrated in Fig. 5 and each optimal solution for $f^T$and f^U is also marked.

The comparison of travel utility with different route selections is conducted to investigate the impacts of travel utility on the route selection. Take the fixed-order activities for example (Scenarios 1–3), the difference of travel utility between each route alternative and the optimal selected route in each scenario is calculated as shown in Fig. 6. For simplification, the potential six routes of "Subway exit→Escalator→Ticketing plaza→ Boarding gate 415" in Table 4 are defined as routes No.1–6, and the other six routes of "Subway exit→Elevator→Ticketing plaza→ Boarding gate 415" are marked as routes No.7–12. Note that the route number with red color represents the selected route in each scenario, and the travel utility of this route is set as a reference value. For example, the difference of travel utility in the No.1 route is −1.28, which represents the travel utility of the No.1 route is smaller than that of selected route No.12 (utility = 5.11). Similarly, the difference of travel utility in the scenario of random-sequence activities is illustrated in Fig. 7. The results in Figs. 5–7 and Table 7 are discussed below, and the following observations can be made.

(1) Table 7 and Fig. 5 reveal that a 23.29% increase of the travel utility occurs when it is the sole objective during route selection compared to the reference case in the fixed-order scenario

Table 7
Optimal objective values in different scenarios.

Scenarios no.		Weight values	Travel time (f^T)		Travel utility (f^U)		Route selection
			Objective (min)	Increment	Objective	Increment	
Fixed order	1	$W^T = 1/2, W^U = 1/2$	53.28	0%	5.11	0%	Route No.12 (Subway exit→ Elevator → B → J → Level 4 → N)
	2	$W^T = 0, W^U = 1$	57.66	8.22%	6.30	23.29%	Route No.7 (Subway exit→ Elevator → B → C → Level 2 → M → Level 4 → N)
	3	$W^T = 1, W^U = 0$	52.26	−1.91%	2.64	−48.34%	Route No.6 (Subway exit→ Escalator → B → J → Level 4 → N)
Random sequence	4	$W^T = 1/2, W^U = 1/2$	96.95	0%	41.96	0%	Route No.14 (N → Q → R → Level 2 → H → G → L → N)
	5	$W^T = 0, W^U = 1$	96.95	0%	41.96	0%	Route No.14 (N → Q → R → Level 2 → H → G → L → N)
	6	$W^T = 1, W^U = 0$	96.92	−0.03%	37.62	−10.34%	Route No.2 (N → Q → R → Level 2 → G → H → L → N)

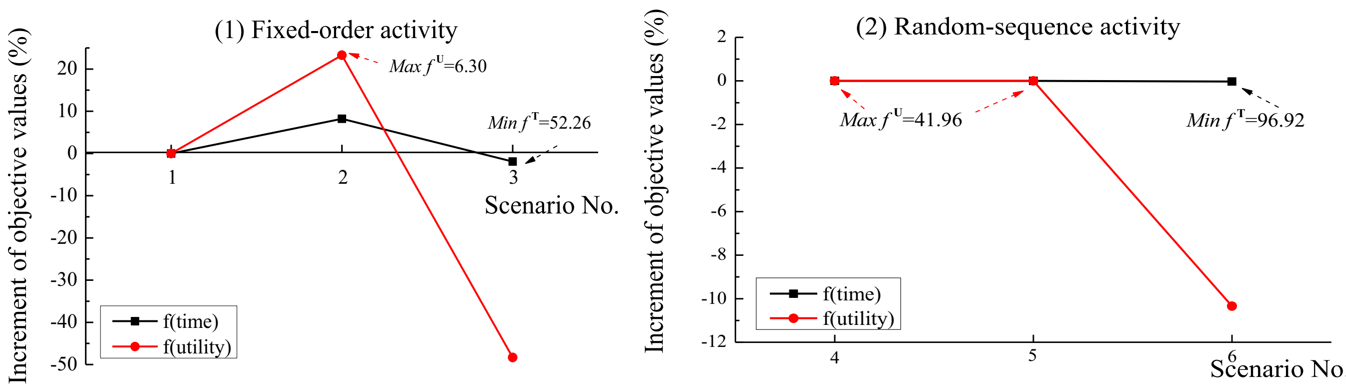

Fig. 5. Increment of optimal objective values in different scenarios.

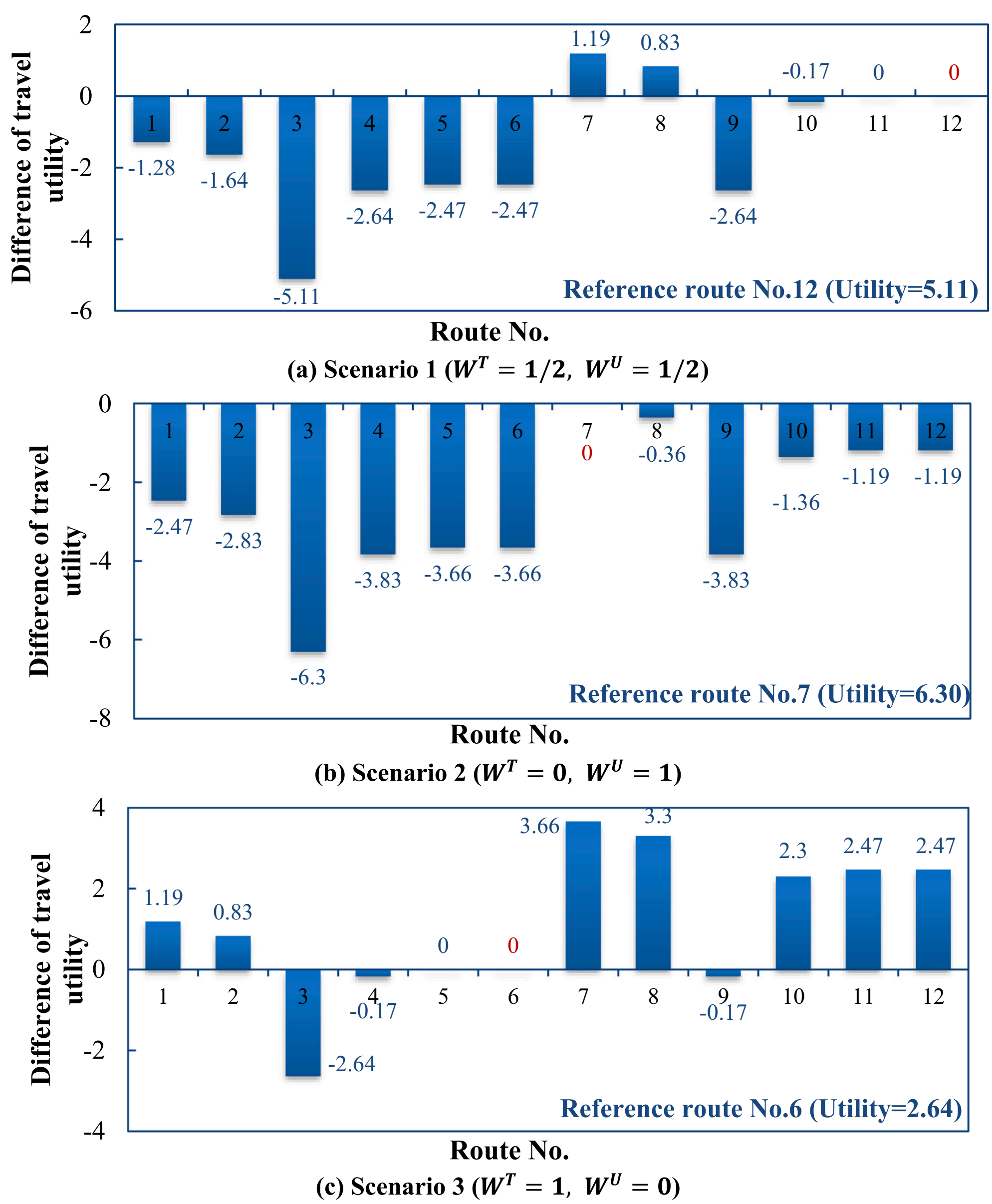

Fig. 6. Difference of travel utility compared with the selected route in the scenarios of fixed-order activities.

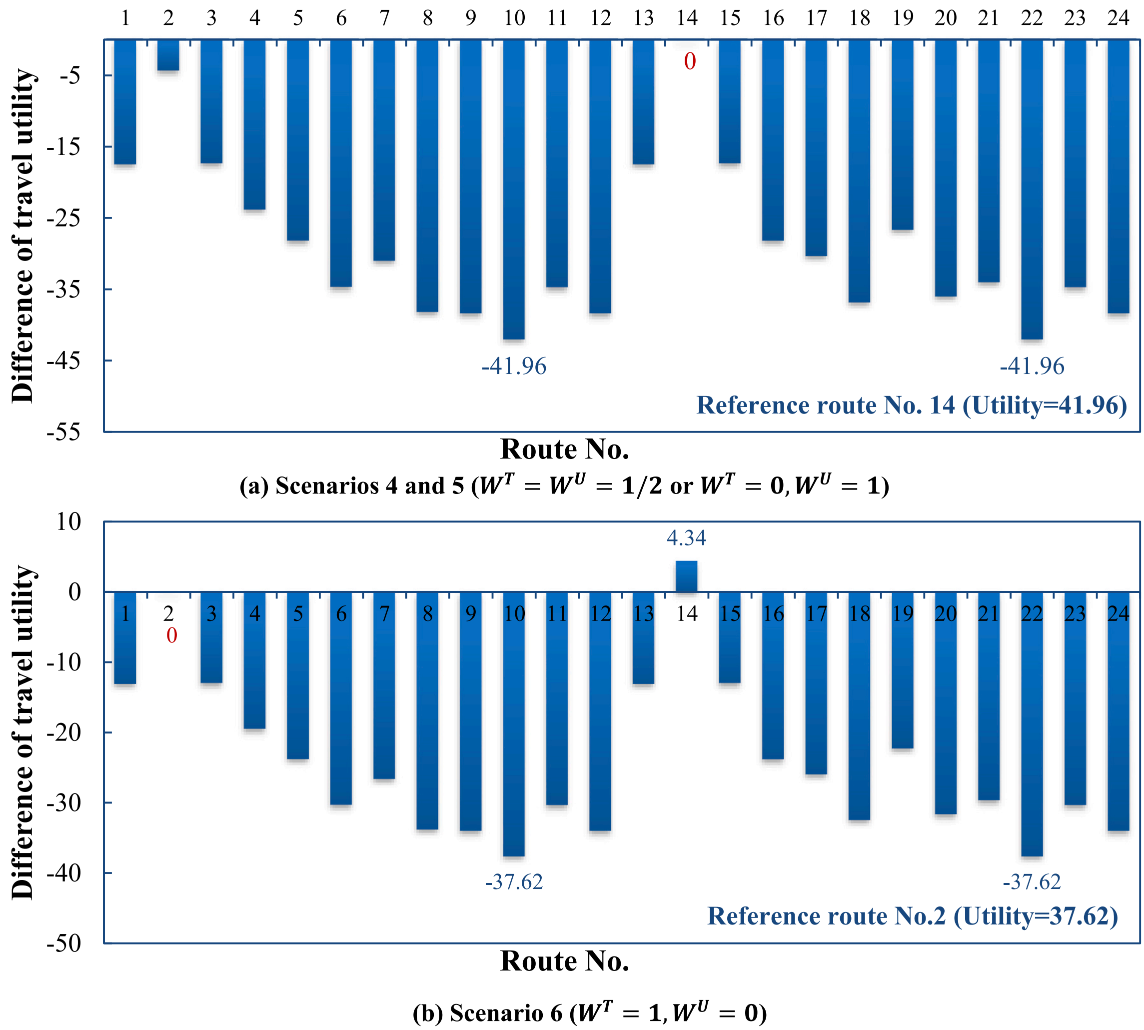

Fig. 7. Difference of travel utility compared with the selected route in the scenarios of random-sequence activities.

(Scenario 1). However, the utility will be reduced by 48.34% when the travel time goal is individually pursued. The diminishing trend also appears in the random-sequence scenario when the travel time is minimized (Scenario 6). Fig. 6(c) also suggests that the travel utility of the optimal route when minimizing the travel time is mostly lower than that of other alternatives. In this paper, the travel utility defines the satisfaction for the travel difficulty that the pedestrian will go through if the route is selected. Hence, it can be concluded that the goals of travel time and the travel difficulty level may conflict with each other, in particular in situations like the shorter paths have high travel difficulty for blind users. In this situation, the unconfident pedestrians with visual impairment can make a detour to the destination to cut down the travel difficulty level if the time is sufficient, and this proposed optimization model can facilitate the route selection to achieve the trade-off between travel utility and travel time. This also calls for a more inclusive design in indoor travels for people with visual impairments as the current designs give limited considerations to these vulnerable populations.

(2) It can be shown in Table 7 that the priority of the objective function impacts the final route selection. With respect to the fixed-order scenario, two alternatives of routes can be chosen from the Main level to Level 4. The shortest route directly from the Main level to Level 4 is selected when considering the travel time (Scenarios 1 and 3). Whereas, the pedestrian is suggested to make a detour via Level 2 to arrive at Level 4 to avoid the sloped walkway when the maximum travel utility is pursued (Scenario 2). This result indicates that the pedestrian doesn't always follow the shortest path as assumed in the previous literature because the travel difficulty and safety is the basic requirement for visual impaired people. They would prefer a longer but easier and safer route to avoid crowded intersections or difficult segments. These findings can enlighten the navigation design for visual impaired people to consider the personalized travel requirements.

(3) Figs. 6 and 7 illustrate the difference of travel utility in each route in the scenario of fixed-order and random-sequence activity, respectively. The figure shows route No.3 (B → C → Level 2 → K → Level 4 → N) has the lowest travel utility when the sequence of activity is fixed. It is owing to the additional lobby and corner when taking the rear escalator K at Level 2. In the scenario of random-sequence activity, route No.14 (N → Q → R → Level 2 → H → G → L → N) outperforms other alternatives with respect to the travel utility because its quantity of lobby and corner segments is smallest. While route No.10 (N → R → Level 2 → G → I → H → J → N) is most difficult to pass due to the detour to the restroom of Level 2 and the additional lobby to take the rear elevator of Level 2. We thus conclude that the pedestrians with visual impairment should avoid the lobby, corner and intersections to reduce the travel difficulty when selecting the routes. These results are consistent with the personalized requirements designed in this case study.

Table 8
Numerical results of sensitivity analysis.

Parameters	Increment	Scenario no.1 ($W^T = W^U = 1/2$)			Scenario no.2 ($W^T = 0$, $W^U = 1$)			Scenario no.3 ($W^T = 1$, $W^U = 0$)		
		f^T	f^U	Route No.	f^T	f^U	Route No.	f^T	f^U	Route no.
T_Q	0%	53.28	5.11	No.12	57.66	6.3	No.7	52.26	2.64	No.6
	+6%	53.28	5.11	No.12	57.66	6.3	No.7	52.26	2.64	No.6
	+12%	53.28	5.11	No.12	57.66	6.3	No.7	52.26	2.64	No.6
	−6%	53.28	5.11	No.12	53.28	5.11	No.12	52.26	2.64	No.6
	−12%	52.26	2.64	No.6	52.26	2.64	No.6	52.26	2.64	No.6

5.3. Sensitivity analysis

A sensitivity analysis of parameters in the case of fixed-order activity is conducted to verify the reliability of the proposed model. In this paper, the last activity of getting on the bus has a time limitation, and hence the pedestrian has to arrive at the Boarding gate 415 before the bus leaves. The upper bound of the time T_Q is selected in this section to investigate the relations between the changes of the parameter and the optimal solutions. The upper bound is set as $T_Q = 60$ min in the previous case study. Changes of −6%, −12%, 6%, and 12% are applied to this base value to compare the changes of objective values f^T and f^U in different scenarios. The results are shown in Table 8.

The table suggests that the reduction of time bound T_Q can affect the optimal selection of routes in Scenarios 1 and 2, while the objective values and optimal solutions remain the same in Scenario 3. It is because the time needed to pass the selected route in Scenario 3 of the reference case ($T_Q + 0\,\%$) is 52.26, which is much smaller than the time limitation when reducing T_Q by 6% and 12%. Whereas, the selected routes will consume 53.28 min and 57.66 min in Scenarios 1 and 2 of the reference case, respectively. Hence, these optimal routes cannot be selected owing to the time exceeds the limitation when T_Q is decreased by 6% or 12%. On the other hand, the objective values and optimal selection will not change when T_Q is increased gradually because the augment of the upper bound allows for more time to select the far route but with a low level of travel difficulty.

6. Conclusions

A systematic routing optimization model is proposed in this paper to address two questions: (1) optimizing the entire route selection for pedestrians with visual impairment before travel navigation; and (2) addressing the problematic issue of macro-navigation considering personalized travel requirements. Two cases of fixed-order and random-sequence activities are investigated to improve the applicability of the proposed model. Finally, the applicability of the model is evaluated using a bus terminal model with six scenarios with different priorities in objectives. To summarize, the contributions of this study can be shown in the following.

- A travel utility function is defined in this paper to represent the personalized requirements of travel satisfaction considering the travel confidence, the types of route segments, and the acceptable level of travel difficulty.
- Practical travel considerations including multiple destinations, the sequence of activities, various difficult levels of different route segments, and the time-bound of each task are investigated in the proposed model. This addresses the limited considerations of the real-world navigation environment in previous studies.
- The routing optimization model of indoor travel in this paper targeted the stage of entire route planning prior to the orientation. In contrast, existing studies primarily focused on the process after the determination of routes selection as well as supporting the decisions for the outdoor micro-navigation. Hence, this paper fills the research gaps on the initial route selection of indoor macro-navigation.

In summary, the proposed model builds a foundational model for supporting navigation decision makings for pedestrians with visual impairment in complex indoor environments. In our future work, the optimization model will further evaluate whether the sequence of travel obstacles impacts disabled users' route choices and if so how can we represent it in the route optimization model. Our future work also includes implementing the optimization model into an App service and test it with human subjects in real-time navigation with the ultimate purpose of evaluating user experience and further refining the model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Albayrak, N. Allahverdi, Development a new mutation operator to solve the traveling salesman problem by aid of genetic algorithms, Expert Syst. Appl. 38 (3) (2011) 1313–1320, https://doi.org/10.1016/j.eswa.2010.07.006.
[2] D. Applegate, R.E. Bixby, V. Chvátal, W. Cook, The Traveling Salesman Problem: A Computational Study, Princeton University Press, Princeton, 2006. ISBN:978-0-691-12993-8.
[3] T. Becker, C. Nagel, T.H. Kolbe, A multilayered space-event model for navigation in indoor spaces, in: J. Lee, S. Zlatanova (Eds.), 3D Geo-Information Sciences Lecture Notes in Geoinformation and Cartography, Springer Verlag, 2009, pp. 61–77. ISBN: 978-3-540-87395-2.
[4] A. Brilhault, S. Kammoun, O. Gutierrez, P. Truillet, C. Jouffrais, Fusion of artificial vision and GPS to improve blind pedestrian positioning, in: 2011 4th IFIP International Conference on New Technologies, Mobility and Security (NTMS), IEEE, 2011, pp. 1–5, https://doi.org/10.1109/NTMS.2011.5721061.
[5] G. Buchs, N. Simon, S. Maidenbaum, A. Amedi, Waist-up protection for blind individuals using the EyeCane as a primary and secondary mobility aid, Restor. Neurol. Neurosci. 35 (2) (2017) 225–235, https://doi.org/10.3233/RNN-160686.
[6] E. D'Atri, C.M. Medaglia, A. Serbanati, U.B. Ceipidor, E. Panizzi, A. D'Atri, A system to aid blind people in the mobility: a usability test and its results, in: Second International Conference on Systems (ICONS'07), IEEE, 2007, p. 35, https://doi.org/10.1109/ICONS.2007.7.
[7] M. Dorigo, L.M. Gambardella, Ant colonies for the travelling salesman problem, biosystems 43 (2) (1997) 73–81, https://doi.org/10.1016/S0303-2647(97)01708-5.
[8] N. Fernando, D.A. McMeekin, I. Murray, Route planning methods in indoor navigation tools for vision impaired persons: a systematic review, Disabil. Rehabil. Assist. Technol. (2021) 1–20, https://doi.org/10.1080/17483107.2021.1922522.
[9] R. Fosu, K. Suprabhas, Z. Rathore, C. Cory, Integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS)–a literature review and future needs, in: Proceedings of the 32nd CIB W78 Conference, Eindhoven, The Netherlands, 2015, pp. 27–29. https://itc.scix.net/pdfs/w78-2015-paper-020.pdf, 2021/5/20.
[10] J.M. Loomis, R.G. Golledge, R.L. Klatzky, J.R. Marston, Assisting wayfinding in visually impaired travelers, in: Applied Spatial Cognition, Psychology Press, 2020, pp. 179–202. ISBN:9781003064350.
[11] K.L. Hoffman, M. Padberg, G. Rinaldi, Traveling salesman problem, Encycl. Oper. Res. Manag. Sci. 1 (2013) 1573–1578, https://doi.org/10.1007/1-4020-0611-X_1068.
[12] S.P. Hoogendoorn, P.H. Bovy, Pedestrian route-choice and activity scheduling theory and models, Transp. Res. B Methodol. 38 (2) (2004) 169–190, https://doi.org/10.1016/S0191-2615(03)00007-9.

[13] U. Isikdag, S. Zlatanova, J. Underwood, A BIM-Oriented Model for supporting indoor navigation requirements, Comput. Environ. Urban. Syst. 41 (2013) 112–123, https://doi.org/10.1016/j.compenvurbsys.2013.05.001.

[14] M. Jünger, G. Reinelt, G. Rinaldi, The traveling salesman problem, in: M. Ball, T. Magnanti, C. Monma, G. Nemhauser (Eds.), Handbook on Operations Research and the Management Sciences, North Holland, Amsterdam, 1994, pp. 225–330, https://doi.org/10.1287/opre.4.1.61.

[15] E.B. Kaiser, M. Lawo, Wearable navigation system for the visually impaired and blind people, in: 2012 IEEE/ACIS 11th International Conference on Computer and Information Science (ICIS), IEEE, 2012, May, pp. 230–233, https://doi.org/10.1109/ICIS.2012.118.

[16] S. Kammoun, F. Dramas, B. Oriolaand, C. Jouffrais, Route selection algorithm for blind pedestrian, in: ICCAS 2010, IEEE, 2010, October, pp. 2223–2228, https://doi.org/10.1109/ICCAS.2010.5669846.

[17] S. Kammoun, M.J.M. Macé, B. Oriola, C. Jouffrais, Towards a geographic information system facilitating navigation of visually impaired users, in: International Conference on Computers for Handicapped Persons, Springer, Berlin, Heidelberg, 2012, July, pp. 521–528. ISBN:978-3-642-31534-3.

[18] B.F. Katz, S. Kammoun, G. Parseihian, O. Gutierrez, A. Brilhault, M. Auvray, C. Jouffrais, NAVIG: augmented reality guidance system for the visually impaired, Virtual Real. 16 (4) (2012) 253–269, https://doi.org/10.1007/s10055-012-0213-6.

[19] M. Mahi, Ö.K. Baykan, H. Kodaz, A new hybrid method based on particle swarm optimization, ant colony optimization and 3-opt algorithms for traveling salesman problem, Appl. Soft Comput. 30 (2015) 484–490, https://doi.org/10.1016/j.asoc.2015.01.068.

[20] A. Mancini, E. Frontoni, P. Zingaretti, Embedded multisensor system for safe point-to-point navigation of impaired users, IEEE Trans. Intell. Transp. Syst. 16 (6) (2015) 3543–3555, https://doi.org/10.1109/TITS.2015.2489261.

[21] M. Nepal, S. Staub-French, R. Pottinger, A. Webster, Querying a building information model for construction-specific spatial information, Adv. Eng. Inform. 26 (4) (2012) 904–923, https://doi.org/10.1016/j.aei.2012.08.003.

[23] N. Rouphail, R. Hughes, K. Chae, Exploratory simulation of pedestrian crossings at roundabouts, J. Transp. Eng. 131 (3) (2005) 211–218, https://doi.org/10.1061/(ASCE)0733-947X(2005)131:3(211).

[24] L. Fanucci, R. Roncella, F. Iacopetti, M. Donati, N. Giannelli, A mobility aid system for visually impaired people on the historical walls of Lucca city, Tuscany, Italy, in: 22nd Mediterranean Conference on Control and Automation, IEEE, 2014, June, pp. 2–7, https://doi.org/10.1109/MED.2014.6961317.

[25] U. Rueppel, K.M. Stuebbe, BIM-based indoor-emergency-navigation-system for complex buildings, Tsinghua Sci. Technol. 13 (S1) (2008) 362–367, https://doi.org/10.1016/S1007-0214(08)70175-5.

[26] S. Shoval, J. Borenstein, Y. Koren, Mobile robot obstacle avoidance in a computerized travel aid for the blind, in: Proceedings of the 1994 IEEE International Conference on Robotics and Automation, IEEE, 1994, pp. 2023–2028, https://doi.org/10.1109/ROBOT.1994.351166.

[27] A.J. Spiers, A.M. Dollar, Outdoor pedestrian navigation assistance with a shape-changing haptic interface and comparison with a vibrotactile device, in: 2016 IEEE Haptics Symposium (HAPTICS), IEEE, 2016, April, pp. 34–40, https://doi.org/10.1109/HAPTICS.2016.7463152.

[28] H. Tashakkori, A. Rajabifard, M. Kalantari, A new 3D indoor/outdoor spatial model for indoor emergency response facilitation, Build. Environ. 89 (2015) 170–182, https://doi.org/10.1016/j.buildenv.2015.02.036.

[29] T.A. Teo, K.H. Cho, BIM-oriented indoor network model for indoor and outdoor combined route planning, Adv. Eng. Inform. 30 (3) (2016) 268–282, https://doi.org/10.1016/j.aei.2016.04.007.

[30] T. Völkel, R. Kühn, G. Weber, Mobility impaired pedestrians are not cars: Requirements for the annotation of geographical data, in: International Conference on Computers for Handicapped Persons, Springer, Berlin, Heidelberg, 2008, pp. 1085–1092, https://doi.org/10.1007/978-3-540-70540-6_163.

[31] T. Völkel, G. Weber, RouteCheckr: personalized multicriteria routing for mobility impaired pedestrians, in: Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility, 2008, pp. 185–192, https://doi.org/10.1145/1414471.1414506.

[32] T.N. Weyrer, H.H. Hochmair, G. Paulus, Intermodal door-to-door routing for people with physical impairments in a web-based, open-source platform, Transp. Res. Rec. 2469 (1) (2014) 108–119, https://doi.org/10.3141/2469-12.

[33] M. Xu, S. Wei, S. Zlatanova, R. Zhang, Bim-based indoor path planning considering obstacles, ISPRS Ann. Photogram. Remote Sens. Spat. Info. Sci. 4 (2017).

[34] P. Rafian, G.E. Legge, Remote sighted assistants for indoor location sensing of visually impaired pedestrians, ACM Transact. Appl. Percep. 14 (3) (2017) 1–14.

[35] S Kurose, A.W.J. Borgers, H.J.P. Timmermans, Classifying pedestrian shopping behaviour according to implied heuristic choice rules, Environ. Plann. B: Plann. Des. 28 (2001) 405–418.