

## PLANNING WORK CREW ASSIGNMENTS FOR PEDESTRIAN AREA RENOVATION TO IMPROVE ITS IMPACT ON THE PUBLIC

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**Abstract.** When renovating a pedestrian area, it is crucial to maintain as normal as possible an operation while the renovation activities are underway. Usually the area is divided into several zones to accommodate the renovation in sections. A zone closure forces the users to take an alternative route that could be longer or more congested. The impact of such re-routing must be minimized by properly planning the work crews. In this paper, the author proposed a model using simulation to estimate the impact of the extra walking distance on pedestrians, and ant colony optimization to search for the near-optimal work crew schedule. The author applied the model to the renovation of a public pedestrian area in a villa resort. It provides a near-optimal work schedule for a variety of work crews with minimal walking time delay for the pedestrians. This model takes into account total walking time delay, average delay per person, and total duration in order to evaluate all alternatives to allow both owner and contractor to decide the appropriate work schedule.

**Keywords:** renovation, public impact, work zone, simulation, ant colony optimization.

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### Introduction

Both maintenance and renovation has been emphasized in the operation of an infrastructure and is well represented in the literature. Tupenaite *et al.* (2010) proposed a multi-criteria assessment approach for the alternative evaluation of built and human environment renovation. Viteikienė and Zavadskas (2007) applied a multipurpose evaluation method to rank the sustainable development and renovation priorities of the residential areas in a city. These evaluation frameworks have also been applied to the alternatives for the regeneration of rural buildings (Zavadskas, Antucheviciene 2007), and to renovation projects in schools (Pikutis, Šeduikytė 2006). In addition, Lepkova *et al.* (2008) developed an integrated method for the modelling of facilities-management alternatives. For renovation and refurbishment projects, many approaches have been proposed in the literature. Kaklauskas *et al.* (2005) developed a multivariate design method applying multiple criteria to analyze the refurbishment of a building. Zavadskas and Vilutienė (2006) established a model for determining the selection criteria for evaluating a maintenance contractor. For more advanced support to planners, a building refurbishment knowledge-based decision support system was developed (Kaklauskas *et al.* 2008) and integrated with web-based technology for project collaboration (Zavadskas *et al.* 2004). Zavadskas *et al.* (2009) also proposed a multi-attribute assessment of the indoor environment, especially for the refurbishment

of dwellings. The above literature provides a good basis for follow-up research.

Pedestrian area renovation is one kind of the projects. There are a variety of outdoor pedestrian areas, such as pedestrian pathways, sidewalks, pedestrian-only streets, concourses, and plazas. These areas need to be renovated when damaged or worn out or because they simply have become outdated after many years of public use. These renovations impact the pedestrians that use these areas. If this impact is adequately controlled, then pedestrians are likely to accept the disturbance. For instance, most pedestrians will accept walking around a specific section of a pedestrian area, but may complain if the entire area is closed off. Therefore, in most pedestrian renovation projects a complete closure of the pedestrian area is usually avoided. Dividing the construction work in zones is a common solution.

If a renovation project is divided into several zones, the project manager must create work schedules for these different zones. S/he has to determine the number of crews to assign and to which zones. The number of crews to be deployed determines the number of work zones that can undergo renovation at the same time. It also affects the total duration of the renovation project. Generally speaking, the more work crews there are the faster the work zones can be completed. However, work in different zones may impact pedestrians in different ways, depending on the size and the location of the closure. Thus, it is important that the project manager comes up with a prop-

er work crew schedule that minimizes the impact of the renovation on the pedestrians while keeping the duration of the project as short as possible.

In this paper, we used the pedestrian walking time delay as a criterion for assessing and comparing the impact of the renovation on the pedestrians. We proposed a model integrating simulation and ant colony optimization (ACO) algorithms to produce the work schedule for the renovation project. We used simulation to estimate the walking impact, and ACO to search for a near-optimal work schedule for the different work zones. The proposed model was then applied to find the near-optimal assignment schedules for different numbers of work crews. These results help the project manager determine the number of work crews that must be assigned and help pedestrians save a considerable amount of walking time during the renovation project.

## 1. Pedestrian area renovation

### 1.1. Differences from new construction

Renovation projects differ in many ways from a new construction project. As far as renovating a pedestrian area is concerned, a renovation differs from new construction in three major aspects:

- 1) **Space conflict:** Unlike construction of a new pedestrian area, the renovation of a pedestrian area is to refurbish an existing facility in an existing already built-up environment. The renovation then takes place in the space originally used by the regular pedestrians as well as the occupants of the adjacent buildings. This results in a space conflict during the renovation (i.e. it is impossible to maintain smooth passage of pedestrians through a space that is being renovated). Thus, this space must be closed to pedestrians for a certain period of time for renovation. In addition, for occupants of nearby buildings, vacating and occupying the space that is being renovated needs to be considered so as to allow for entering and exiting these buildings.
- 2) **Impact on workers and pedestrians:** Compared to new construction work, renovation work imposes larger limitations on both workers and users (McKim *et al.* 2000). In order to maintain the normal functioning of a pedestrian area while adjacent renovation activity is underway (Krzek *et al.* 1996), the project manager cannot close the entire pedestrian area, and must schedule several work crews according to the principle of construction zoning. This usually results in extending the project duration. The impacts of renovation work on pedestrians are two-fold. First, an entire building may need to be closed off if the pedestrian area in front of it is under renovation. Second, pedestrians must take alternative routes to their destinations if their usual pedestrian area is under renovation. For project planners, it is imperative that they minimize the impact of the renovation on both workers and pedestrians.
- 3) **Coordinating the work schedule:** The planner for a new project usually only needs to take into considera-

tion those tasks that involve the actual construction of the project. For a renovation project, the planner must coordinate and accommodate the schedules of the users who will continue to operate and occupy the space (Whiteman, Irwig 1988). In the case of a pedestrian area renovation, the project planner must first familiarize him/herself with the pedestrians' activities, needs, and behaviours and take all of that into consideration when planning the work schedule for the crews, in order to minimize any impact on the pedestrians.

### 1.2. Zoning the renovation work

It is evident that it is usually not possible to close the entire area to accommodate a single-phase pedestrian area renovation project. Only a few zones in the entire area being renovated can be closed off during any given period of time, while the remaining zones must continue their normal function. An example of construction zoning is shown in Figure 1. It is a renovation project of several pedestrian streets. The entire construction area is divided into seven work zones. Based on the number of available work crews, only one or two work zones can be renovated at the same time.

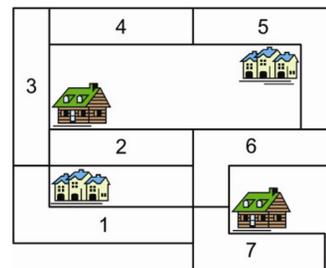


Fig. 1. Dividing the entire pedestrian area into several work zones

For pedestrians who use these streets on an everyday basis, it is important that the walking impact be minimized. To satisfy this requirement, the project planner has to come up with a work schedule for these work zones. Any work schedule that can effectively minimize the walking impact of the renovation work is based on two mechanisms: determining the number of work crews and planning their work schedule. We proposed an integrated model that applies simulation to estimate the walking impact of the renovation on pedestrians and an ACO algorithm to schedule the work crews for. A detailed explanation of these two mechanisms is provided as follows.

## 2. Estimating the walking impact by simulation

Even if the pedestrian area to be renovated is divided into several work zones, the renovation will still cause some changes in the pedestrians' walking behaviour. As shown in Figure 2 (the same project as shown in Fig. 1), if No. 6 work zone is closed for renovation, the pedestrians have to change their walking route and pass through work zones No. 5, 4, 3 and 1 to successfully arrive at their destination. The new route requires a much longer walking

distance than the original one. In addition, the pedestrian may encounter other pedestrians while travelling through zones 5, 4, 3, and 1. These encounters increase the density of pedestrians in these zones, resulting in a slowdown of the flow rate of pedestrians. The above changes as well as the chain effects on the surrounding streets as a result of the renovation work in zone No. 6 will delay the walking time of this pedestrian. In this paper we used the sum of walking time delays for each pedestrian over the duration of the project as an objective function to evaluate the walking impact and how to minimize it.

**2.1. Changes in walking behaviour**

Even if the pedestrian area to be renovated is divided into several work zones, the renovation will still cause some changes in the pedestrians' walking behaviour. As shown in Figure 2 (the same project as shown in Fig. 1), if No. 6 work zone is closed for renovation, the pedestrians have to change their walking route and pass through work zones No. 5, 4, 3 and 1 to successfully arrive at their destination. The new route requires a much longer walking distance than the original one. In addition, the pedestrian may encounter other pedestrians while travelling through zones 5, 4, 3, and 1. These encounters increase the density of pedestrians in these zones, resulting in a slowdown of the flow rate of pedestrians. The above changes as well as the chain effects on the surrounding streets as a result of the renovation work in zone No. 6 will delay the walking time of this pedestrian. In this paper we used the sum of walking time delays for each pedestrian over the duration of the project as an objective function to evaluate the walking impact and how to minimize it.

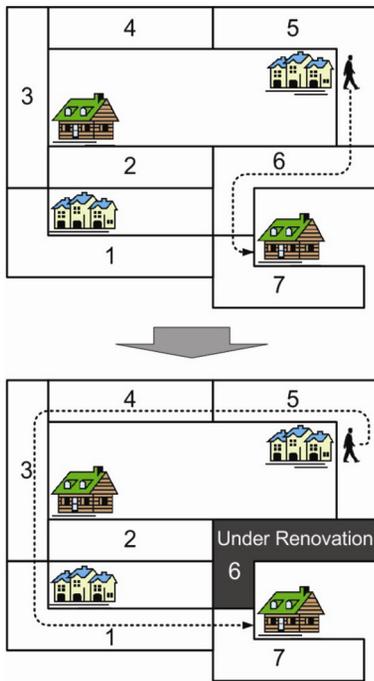


Fig. 2. An example of a change in walking behaviour

**2.2. Walking time delay**

To minimize the walking impact of the renovation on the pedestrians, the main goal of the work schedule was to minimize the walking time delay for the pedestrians (minimum *WTD*). The objective function is represented by the following Eqn (1):

$$WTD = \sum_{t=1}^T \sum_{m=1}^L \sum_{n=1}^L \sum_{p=1}^{P_{t,m,n}} \delta_{m,Close_t} \delta_{n,Close_t} (IW_p - NW_p), \quad (1)$$

where:

- WTD* = The total pedestrians' walking time delay caused by the renovation project;
- T* = The total scheduled duration of the renovation project;
- L* = The number of locations for the starting points and terminal points of the pedestrian walking routes;
- $P_{t,m,n}$  = The total number of pedestrians walking from the starting point at location *m* to the terminal point at location *n* in the *t*<sup>th</sup> day;
- Close<sub>t</sub>* = A set of work zones which are closed for renovation work on the *t*<sup>th</sup> day;
- $\delta_{m,Close_t}$  = 0 if the starting point *m* is at one of *Close<sub>t</sub>* on the *t*<sup>th</sup> day, otherwise it is equal to 1;
- $\delta_{n,Close_t}$  = 0 if the terminal point *n* is at one of *Close<sub>t</sub>* on the *t*<sup>th</sup> day, otherwise it is equal to 1;
- IW<sub>p</sub>* = The walking time of the *p*<sup>th</sup> pedestrian impacted by the closures of renovation work zones;
- NW<sub>p</sub>* = The normal walking time of the *p*<sup>th</sup> pedestrian prior to the start of the renovation project.

We used the above Eqn (1) to calculate the pedestrians' walking time delay (*WTD*) caused by the renovation project. The walking time is expressed in man-seconds. If a pedestrian's starting point or terminal point is at a work zone that is closed for renovation, then his or her walking activity has to be suspended. As a result, the number of pedestrians during a renovation project varies from day to day. Take Figure 3, for example. A shop has to be shut down when work zone No. 7 in front of the shop is being closed off for renovation. Thus, any pedestrians wanting to visit this shop must cancel their trip. This makes  $\delta_{n,Close_t}$  zero, the walking time will not be estimated in the objective function, and the number of pedestrians on the *t*<sup>th</sup> day will decrease.

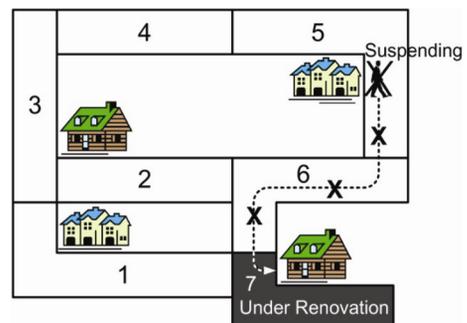


Fig. 3. The pedestrians' walking activities are suspended when work zone 7 is active

### 2.3. Pedestrian simulation

To estimate the walking time of the pedestrians we introduced the walking behaviour model into a microscopic simulation engine. The microscopic simulation considers the behaviour of individual pedestrians, and the simulation result will be very close to real-life. Several microscopic simulation software packages have been applied to simulate pedestrian behaviour. Compared with other software, VISSIM allows us to rewrite the coordinates to shift the location of the activities in the file and also control the simulation through the interface (Planung Transport Verkehr 2010). Thus, we applied VISSIM to assess the walking time of pedestrians during a renovation project under different work schedules.

The walking behaviour in VISSIM was simulated on the basis of the Social Force Model proposed by Helbing and Molnár (1995). The basic idea was to model the elementary impetus for motion with forces analogous to Newtonian mechanics. By summing up social, psychological, and physical forces, a force is created to be an entirely physical parameter for acceleration. The forces which influence a pedestrian's motion are due to the pedestrian's intention to reach his/her destination as well as the actions of other pedestrians and obstacles (Planung Transport Verkehr 2010). Computer simulations have shown that the Social Force Model is capable of very realistically describing the self-organization of several observed collective effects of walking behaviour (Helbing, Molnár 1995).

For coupling the ACO algorithm with the VISSIM, we compiled a program using MATLAB to automate both the simulation and the optimization. This program sets pedestrian routing diversions in VISSIM according to the work zone schedules derived from ant colony optimization. The program rewrites the closed work zones data in .inp file (the simulation data file of VISSIM) and controls the simulation through the COM interface of VISSIM. The component object model (COM) functionality supports Microsoft Automation and is designed for use with external programming environments, such as MATLAB and C++. This makes it available to automate certain tasks in VISSIM by executing COM commands from an external program (Planung Transport Verkehr AG 2010).

### 3. Assigning work crews by ant colony optimization

Although time-cost trade-off analysis has frequently been applied to scheduling optimization in previous research, this analysis method is not fully applicable to the issue addressed in this paper for the following reasons:

- 1) We can view the impact of a renovation on pedestrians as a kind of social cost and perform a time-cost trade-off analysis to find the most effective point where the impact is minimum. However, a time-cost trade-off analysis does not offer suggestions on the construction sequence of numerous work zones and the sequence of assigning work crews;
- 2) In most construction projects, the time-cost trade-off curve is a smile curve. In other words, the optimal solution with the minimum cost is easily obtained. However, the impact of a renovation project usually

increases with the shortening of the total duration (because more work zones have to be closed concurrently). In this case, the time-cost trade-off curve is a downward sloping curve rather than a smile curve. Therefore, it would be difficult finding an optimal solution to our research problem if we used a time-cost trade-off analysis.

For these two reasons we did not apply the time-cost trade-off analysis to solve the problem addressed in this paper. Instead, we adopted the ant colony optimization (ACO) to search for a near-optimal solution. The ACO algorithm uses the paths that ants travel to represent the sequence of work crew assignment and achieve optimization based on the ants' accumulation of pheromone. Through the ACO algorithm, we can obtain an optimal construction sequence for each work zone and an optimal work crew assignment schedule.

Since portfolios of work schedules for a renovation project are usually numerous, we used optimization algorithms to find the near-optimal solutions. To date, many methods have been proposed to solve project planning and scheduling problems, including genetic algorithms (GA) (Chen, Weng 2009), particle swarm optimization (PSO) (Zhang *et al.* 2006), case-based reasoning (CBR) (Dzeng, Lee 2004), and ant colony optimization (ACO). ACO is often applied to scheduling problems (e.g. Christodoulou 2009, 2010; Duan, Liao 2010; Lee 2011, 2012a). In the area of construction engineering and management, ACO algorithms have been used to address pipe routing (Christodoulou, Ellinas 2010), time-cost trade-off problems (Xiong, Kuang 2008; Ng, Zhang 2008), and site layouts (Lam *et al.* 2009; Ning *et al.* 2011). They have empirically proven to perform to a high level of accuracy in their search of near-optimal solutions. Therefore, we applied ACO in the scheduling of work crews to the various work zones.

The ACO algorithm, first introduced by Dorigo *et al.* (1996), is a branch of the swarm intelligence system. To search for food, ants follow pheromone paths made by other ants, and at the same time, deposit pheromones along the path they take. Most ants will habitually take the path on which more pheromones are deposited. The effect of this positive feedback leads ants to take the path with more pheromones deposited on it. The application of ACO in this research consists of converting the scheduling problem to ACO, determining the selection probability of the work zones, updating the pheromone count, and applying the ant team mechanism.

#### 3.1. Converting the problem to an ACO algorithm

We used the above-mentioned renovation project to explain the process of converting the work crew assignment to that of the ants' paths. As shown in Figure 4, the whole area is divided into seven work zones. In ACO, these seven work zones are connected by paths that ants can take, and each ant denotes a work crew consisting of several workers. An ant decides the selection probability for a work zone based on the amount of pheromone deposited on the available paths. When the ant travels from a work zone to the next work zone it denotes the completion of

the renovation in the former work zone. After the ant has traversed all the work zones (i.e. the renovation tasks in all work zones have been completed), then the path it took constitutes a work schedule for the crew. By converting the work schedule into the format of an ant path solution, we can use the optimization mechanisms of ACO to search for the near-optimal solutions through iterations.

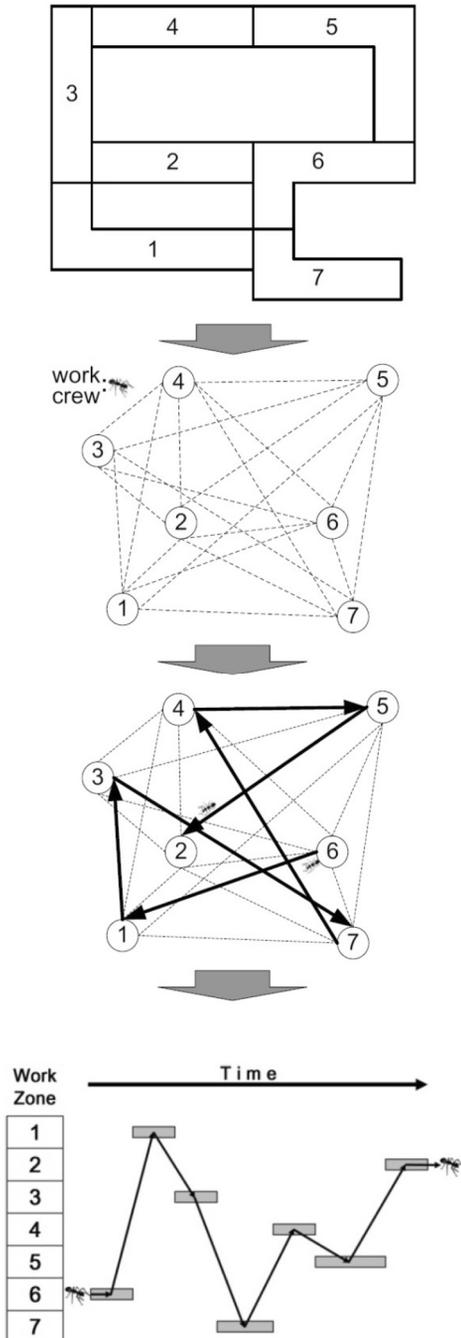


Fig. 4. Converting a work schedule to an ant's path

**3.2. Selection probability of the work zones**

Selection probability and pheromone updating are the two main optimization steps in ACO. As mentioned above, the whole pedestrian area is divided into several work zones, all of which can be renovated independently. We used

ACO to plan the work schedule. The selection of the sequence for the work zones is explained by the path selection of the ants. The selection of the next work zone depends on the amount of pheromones deposited on the paths between the work zones. In ACO, a solution is termed a path and is represented by a sequence of work zones that an ant has travelled. ACO operates by iteratively generating a population of solutions where each solution represents the path a single ant has taken (Afshar, Mariño 2006).

When ant  $k$  finishes work zone  $i$  and moves to work zone  $j$ , the selection probability used in ACO (Dorigo, Gambardella 1997) is as per Eqn (2):

$$p_{ij}^k = \begin{cases} \frac{\tau_{ij}^\alpha \cdot \eta_j^\beta}{\sum_{l \in allowed_k} \tau_{il}^\alpha \cdot \eta_l^\beta} & \text{if } j \in allowed_k \\ 0 & \text{otherwise} \end{cases}, \quad (2)$$

where:  $allowed_k$  is the list of work zones not yet selected;  $\tau_{ij}$  is the pheromone trail between work zone  $i$  and work zone  $j$ ;  $\eta_j$ , which is the heuristic value representing the desirability of selecting work zone  $j$ , is the inverse of the increase in  $WTD$  caused by the renovation of work zone  $j$ ;  $\alpha$  and  $\beta$  are parameters that determine the relative influence of the pheromone trail and the heuristic value.

**3.3. Pheromone update**

The above selection probability ( $p_{ij}^k$ ) varies with the number of ants walking through the work zones based on pheromone trail ( $\tau_{ij}$ ) which is constantly updated. When ants select or leave a work zone, they will deposit pheromones as a reference for other ants that follow them. This behaviour is called pheromone updating. The algorithm applied in our model is the Ant Colony System (ACS), one of the variants of ACO. There are two kinds of pheromone updates in ACS. One is the local update that all ants will perform, and the other is the global update that only the best ant will perform (Dorigo, Gambardella 1997):

- 1) The local update is performed each time and by all ants after selecting a work zone. The main goal of the local update is to diversify the search performed by subsequent ants during each iteration (Dorigo, Gambardella 1997). Each ant applies it only at the last work zone visited:

$$\tau_{ij} = (1 - \rho) \cdot \tau_{ij} + \rho \cdot \tau_0 \quad (3)$$

where:  $\rho \in (0,1)$  is the pheromone decay coefficient; and  $\tau_0$  is the initial value of the pheromone.

- 2) The global update is applied at the end of each iteration by only one ant (either the one that found the best solution in the iteration or the best-so-far solution) (Dorigo, Gambardella 1997). The global update formula is slightly different from the local update, and is expressed as Eqn (4):

$$\tau_{ij} \rightarrow \begin{cases} (1-\rho) \cdot \tau_{ij} + \rho \cdot \Delta\tau & \text{if work zone } j \text{ belongs} \\ & \text{to the solution of the best ant (4)} \\ \tau_{ij} & \text{otherwise} \end{cases}$$

where  $\Delta\tau$  is the inverse of the minimum *WTD* of the iteration.

Through these methods of pheromone updating, ants will deposit different amounts of pheromone based on the quality of the work schedule (the level of *WTD*). By increasing the number of iterations, lower-*WTD* solutions will gain more pheromone, and the near-optimal solution will be gradually discovered.

### 3.4. Ant team mechanism

In most applications of ACO, one ant’s path selection represents a solution. In a renovation project, more than one work crew may be assigned to share the project and complete their share of the work simultaneously. For optimizing the schedule, we can use one ant to represent one work crew and then group these ants into teams and let them (i.e. the work crews) finish their work zones respectively. The ant team mechanism has been used to solve other kinds of manpower scheduling problems in previous literature, and has demonstrated its strengths in framing both the problem and the optimization process (Lee 2012b; Lee *et al.* 2012). We therefore adopted this mechanism to construct the assignment tracks and the schedule solution for the work crews. For example, Figure 5 shows a schedule where two ants each finish the work in the seven work zones. For the next iterations, these two ants deposited pheromones on each route linking certain work zones.

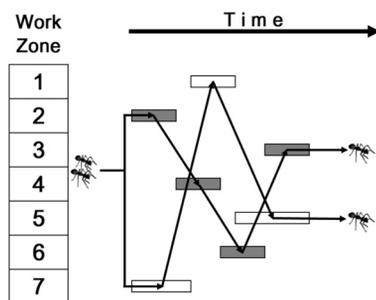


Fig. 5. Assignment schedule by an ant team

### 4. The integrated model

We integrated the simulation and the ant colony optimization described in the preceding sections into a model to support the work schedule for the renovation project. The flowchart of the model is presented in Figure 6, and the descriptions of the steps are as follows:

- 1) In the beginning we inputted all available data into the model. The data required for project planning include the number of work crews, the number of work zones the whole area must be divided into, and

the duration to complete the work in each zone. The data required for simulation and optimization include the walk activities of the pedestrians collected through onsite observations and video records, and the parameters of ant colony optimization (i.e. the number of ants and iterations,  $\alpha$  and  $\beta$ , which determine the relative influence of the pheromone trail and the heuristic value, respectively, the pheromone decay coefficient  $\rho$ , the initial pheromone value  $\tau_0$ , and the convergence conditions for the termination of the iterations).

- 2) The input of the pedestrian walk activities in the previous step are then modelled using the VISSIM simulation platform to form the activity network. This activity network consists of the starting point, terminal point, the start time of the walk, and the speed of each pedestrian. The model then simulates the activity network in VISSIM in order to estimate the walking time of each pedestrian.

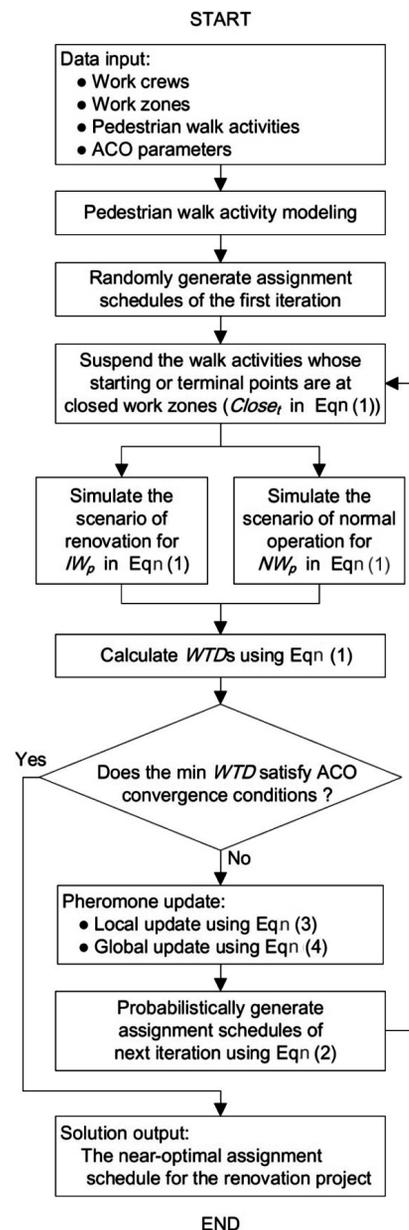


Fig. 6. Flowchart of the model

- 3) Since one ant represents a work crew, we randomly generated assignment schedules of the first iteration. The assignment schedules are shown in Figure 4. The ant path has become the sequence for assigning the work crews. Because no pheromone update has occurred yet, the probability of being selected by ants in the first iteration is the same for all paths between work zones.
- 4) In the estimation of the total pedestrian walking time of an assignment schedule generated in the previous step, the number of pedestrians varies each day. This is because the walk activity of the pedestrians whose starting point or terminal point is at one of the work zones closed for renovation on the same day should be suspended (i.e.  $Close_t$  in Eqn (1)). This calibration will also be performed in the scenario of normal operation without any work zone, so that the number of pedestrians used for estimating the total pedestrians' walking time delay ( $WTD$ ) is constant for both scenarios. The mathematical function is shown in Eqn (1).
- 5) After the calibration is completed, the model will simulate the total duration for each assignment schedule. The simulation is executed on a daily basis. In other words, the model will simulate the renovation scenario each day to estimate the total  $IW_p$  in Eqn (1) both the scenario under normal operation and with no renovation taking place each day (it should be noted that the number of pedestrians remains constant across the two scenarios) in order to estimate the total  $NW_p$  in Eqn (1). The difference between the total  $IW_p$  and the total  $NW_p$  for one day is the  $WTD$  caused by the renovation work on that day.
- 6) The simulation yields the total  $IW_p$  and the total  $NW_p$  on each day. Using Eqn (1), the objective function value and the  $WTD$  for each work schedule of this iteration is obtained.
- 7) Then we examine if the minimum  $WTD$  from the work schedules of this iteration satisfies the ACO convergence conditions. If the convergence conditions are met, the assignment schedule with the minimum  $WTD$  will be proposed by the model as a near-optimal solution. If not, the next iteration will be carried out to find a better solution.
- 8) Before entering the next iteration, the model will perform the pheromone update, including the local update shown in Eqn (3) and the global update shown in Eqn (4).
- 9) After the pheromone update, the model will generate the work schedules of the next iteration based on the selection probabilities obtained using Eqn (2) with an updated  $\tau_{ij}$ . For the new iteration, the model will repeat the steps of the last iteration, including the suspension calibration, simulations, calculating the  $WTDs$ , and examining if the convergence conditions are satisfactory.
- 10) The iteration terminates when the minimum  $WTD$  of the latest iteration satisfies the convergence conditions. In the meantime, the near-optimal solution will be obtained, and the steps end.

The proposed model can yield a suggested solution to help planners minimize the walking impact of the renovation. The planners can also run the proposed model multiple times to find the minimum  $WTD$  and the near-optimal assignment schedule given different numbers of work crews. These results can help them make their decision. In the next section, we used an example to explain the process of decision support and evaluate the feasibility of the model.

## 5. Application example

In this section, we used a renovation project of a public pedestrian area in a villa resort to evaluate the feasibility of the proposed model. This resort is located along a coastline and has been in service for 26 years. Because a large portion of the bricks used to pave the public pedestrian areas had become uneven or damaged, the president of the resort decided to renovate the pedestrian areas. The weather conditions in this region are stable and comfortable all year round. As a result the villa resort enjoys good business in all seasons. In other words, a considerable amount of business revenue is at stake if it has to be closed completely to accommodate the renovation. Therefore, the president has stipulated that the contractor must perform the renovation without affecting the normal operation of the villa resort. We applied the proposed model to this renovation project. The process and results are as follows.

### 5.1. Project introduction and data features

The layout of the villa resort is shown in Figure 7. There are four gates on the west side of the resort. Except for the restaurant and the green areas which are labelled, all the villas are available for lodgers. Each villa is fenced in with an exclusive garden and leisure facilities for each villa. All lodgers must enter/exit their villa grounds through the gates marked in Figure 7. The area outside the fencing is the public pedestrian area, which is the area to be renovated in this project.

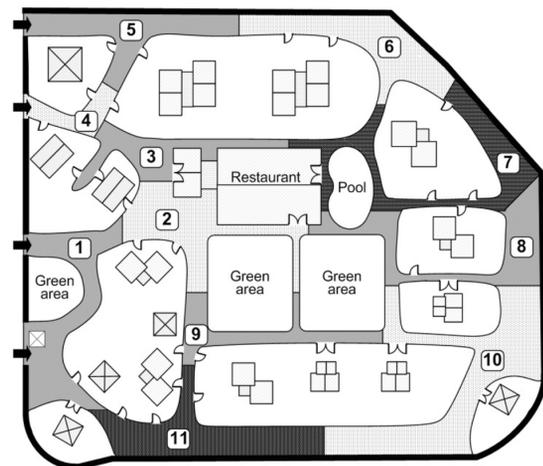


Fig. 7. Work zones in the pedestrian areas of the villa resort

In order to maintain the normal operation of the villa resort while the renovation activities are underway, the

contractor divided the public pedestrian area into eleven independent work zones, marked from No. 1 to No. 11 in Figure 7. A work zone must be completely closed if it is being renovated.

The maximum number of work crews that the contractor can assign is four. Assuming that the four crews have the same level of productivity and skills, the contractor can then estimate the duration of the renovation work in each work zone, as shown in Table 1. The contractor will then use the proposed model to determine the optimal number of work crews and schedule the work accordingly.

Table 1. Duration of the renovation in the work zones

Work zone	Duration (day)
1	16
2	13
3	13
4	7
5	12
6	12
7	18
8	15
9	7
10	16
11	12

On the condition that the resort continues its operations, the renovation work will certainly cause walking time delays for pedestrians. The data recorded over one week show that an average of 629 pedestrians used the public pedestrian area. Among them, 192 were lodgers, 341 were customers of the restaurant and other leisure services, as well as 96 resort staff. Their walk activities had different starting and/or terminal points, different starting times, and different walking speeds. Some approaches of survey and analyze the pedestrian walking was proposed in the literature (Ušpalytė-Vitkūnienė, Burinskienė 2006). In the case, we set up several cameras in the public pedestrian area to capture 24-hours of pedestrian walking activities. We then inputted the recorded data into the VISSIM simulation platform to form an activity network.

**5.2. Model processing**

After constructing the activity network, the proposed model followed the steps listed in Figure 6 to randomly generate work schedules of the first iteration for ACO. Then, the walking activities were suspended each day for those people whose starting point or terminal point was in one of the closed work zones (i.e.  $Close_i$  in Eqn (1)). The calibrated activity network for each work schedule was

then simulated to estimate the total  $IW_p$  and the total  $NW_p$  and calculate the  $WTD$  in Eqn (1).

The model then proceeded to the ACO algorithm in the next step. According to Dorigo and Gambardella (1997), it is better for the size of the ant colony to be equal to the total number of nodes (i.e. the work zones in this research). Therefore, in this example project, there were eleven ant teams in each iteration. To avoid missing good solutions, we reserved the best solution in each iteration for the next iteration. We referred to the ACO applications in other studies (Ning *et al.* 2010; Lee 2009) to set the optimization parameters, including  $\rho = 0.7$ ,  $\alpha = 1$ ,  $\beta = 3$ ,  $\tau_0 = 20$ . In addition, we set “the number of iterations with no better solutions in sequence to exceed 200” as a condition of stable convergence, and 1000 iterations as the range for observing convergence. In other words, the proposed near-optimal solution was the best solution that satisfied the condition of stable convergence within the 1000 iterations observed. When the convergence conditions were satisfied, the near-optimal work schedule was the one proposed by the model.

**5.3. Alternative evaluation**

The project planner applies the model to evaluate the four alternatives of the number of work crews (1–4 work crews) and finds the near-optimal assignment schedule for each alternative. A comparison of the four alternatives is shown in Table 2. The four alternatives have different  $WTD$ s, different average delays (i.e. the average walking time delay for a pedestrian using the area on a daily basis during the renovation, expressed in seconds/man-day), and the total duration for the renovation project.

As shown in Table 2, none of the alternatives are superior to each other in all three indexes. Thus, we cannot directly determine which alternative is the best suggested solution. Therefore, we build a three-attribute utility function based on the multi-attribute utility theory (MAUT). This function was then used to compare the utility of the four alternatives for the president of the resort (i.e. the project owner). This total utility function is defined in Eqn (5):

$$\text{Total Utility} = w_1 \cdot U_{WTD} + w_2 \cdot U_{avd} + w_3 \cdot U_{tdr}, \quad (5)$$

where: *Total Utility* denotes the whole utility of the alternative for the president of the resort;  $U_{WTD}$  is the utility of walking time delay for pedestrians ( $WTD$ );  $U_{avd}$  is the utility of average delay;  $U_{tdr}$  is the utility of total duration;  $w_1$ ,  $w_2$ , and  $w_3$  are the weights of the utilities of the three attributes. *Total Utility*,  $U_{WTD}$ ,  $U_{avd}$ , and  $U_{tdr}$  all have a value between 0 and 1;  $w_1 + w_2 + w_3 = 1$ .

Table 2. Comparison of the four alternatives

Indexes of project performance	Number of assigned work crews			
	1		1	
<i>WTD</i> (man-seconds)	629831	<i>WTD</i> (man-seconds)	629831	<i>WTD</i> (man-seconds)
Average delay (seconds/man-day)	19.81	Average delay (seconds/man-day)	19.81	Average delay (seconds/man-day)
Total duration (days)	141	Total duration (days)	141	Total duration (days)

The composition of the utility function varies depending on the preference of the decision maker. Based on an interview with the president of the resort we obtained the utility curves of the three attributes. Let's take the utility curve of the average delay as an example. The utility of the minimum average delay of the four alternatives is set as 1, and the utility of the maximum average delay of the four alternatives is set as 0. We use three questions in the interview with the president to estimate the average delays that will lead to a utility value of 0.5, 0.75, and 0.25 respectively (these three average delay values are represented by  $x$ ,  $y$ , and  $z$  in the following). The first question is: "If the increase of average delay from 19.81 to  $x$  and the increase of average delay from  $x$  to 56.89 are not any different to you, what do you think is the most suitable value for  $x$ ?". The second question is "If the increase of average delay from 19.81 to  $y$  and the increase of average delay from  $y$  to  $x$  are not any different to you, what do you think is the most suitable value for  $y$ ?". The final question is: "If the increase of average delay from  $x$  to  $z$  and the increase of average delay from  $z$  to 56.89 are not different to you, what do you think is the most suitable value for  $z$ ?".

Through these three questions, we can obtain  $x$ ,  $y$ , and  $z$  as well as five average delay values that are derived from utility values 1, 0.75, 0.5, 0.25, and 0, respectively. Based on these five sets of values, we can further estimate the utility curve of the average delay and use statistical software to obtain a utility function that approximates the curve. The utility curves and functions of the other two attributes can also be obtained following the same approach. The utility curves of the three attributes are illustrated in Figures 8, 9, and 10.

With the utility curves and functions of the three attributes shown above, we can compute the utility value of each attribute in each alternative. The results are shown in Table 3. Later, we invite the president to determine the weight for each attribute in total utility. The three attributes are weighted as follows:  $w_1 = 0.35$ ,  $w_2 = 0.35$ ,  $w_3 = 0.3$ . Finally, we can obtain the total utility of each alternative via Eqn (5). As shown in the right hand column of Table 3, the maximum total utility appears when two work crews are assigned. Hence, for the president of the resort, the assignment schedule involving two work crews is the best suggested solution. Figure 11 shows the near-optimal schedule with two work crews proposed by the model. In Figure 11, the two work crews are shown in black bars and white bars.

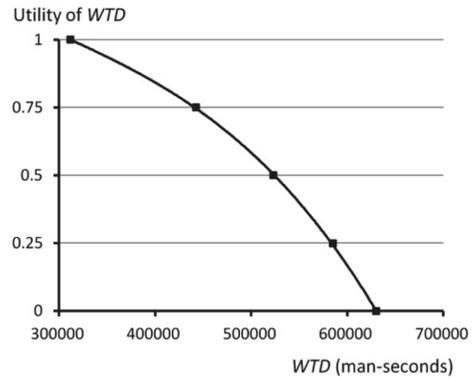


Fig. 8. Utility curve of WTD

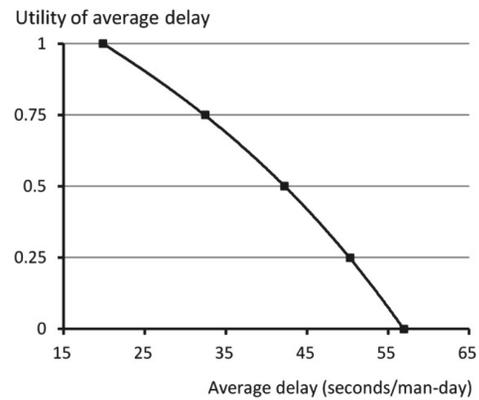


Fig. 9. Utility curve of average delay

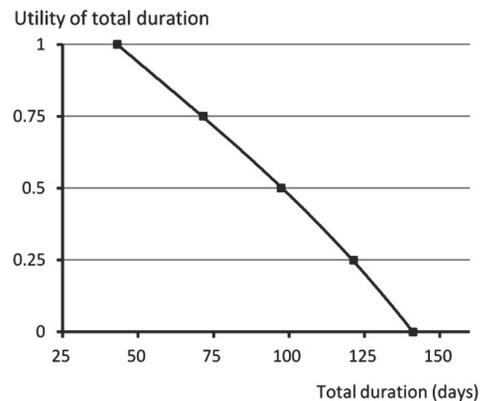


Fig. 10. Utility curve of total duration

**Conclusions**

In this paper, we analyzed the characteristics of a pedestrian area renovation project. We also compared its differences with new construction, and discussed the zoning

Table 3. Comparison of the total weighted utilities

Number of assigned work crews	Utility of WTD ( $U_{WTD}$ )	Utility of average delay ( $U_{avd}$ )	Utility of total duration ( $U_{tdr}$ )	Total weighted utility
	$w_1 = 0.35$	$w_2 = 0.35$	$w_3 = 0.3$	
1	0	1	0	0.350
2	0.879	0.956	0.738	0.864 *
3	0.896	0.744	0.922	0.851
4	1	0	1	0.650

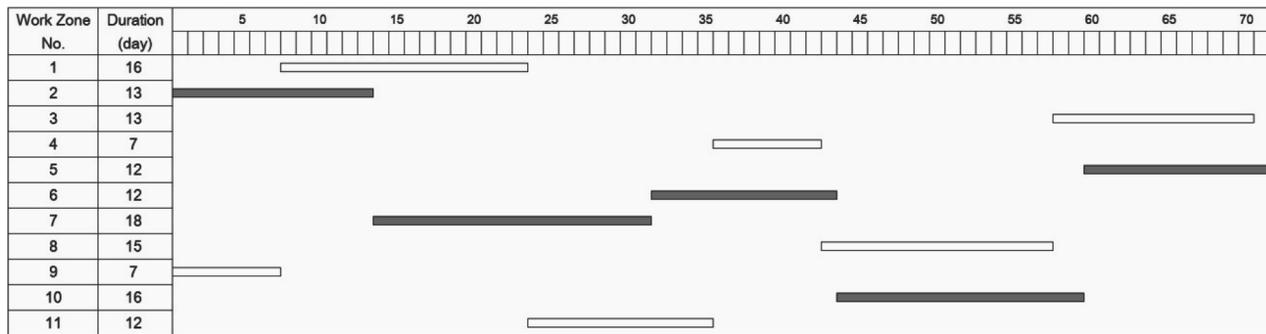


Fig. 11. Assignment schedule of two work crews

methods for maintaining the operation during the renovation project. We then proposed an integrated model to support an appropriate work schedule. The proposed model estimated the walking impact by simulation and assigned the work crews by ant colony optimization (ACO). By building a pedestrian activity network in VISSIM, a microscopic simulation engine, the model simulated and calculated the walking time delay (*WTD*) caused by the closure of a work zone. Through the pheromone updating in ACO, a near-optimal work schedule with a near-minimum *WTD* was found by iterations. Unlike other ACO applications, we grouped ants into teams to represent work crews and viewed the paths of an ant team as a solution. We also demonstrated the strength of this ant team mechanism for both problem framing and the optimization process.

In addition, a renovation project involving the public pedestrian area in a villa resort was employed to evaluate the feasibility of the proposed model. Four work crews were available to perform the renovation. The contractor applied the model to find the near-optimal assignment schedule with minimal *WTD* for different numbers of work crews. This evaluation took into account not only the *WTD* but also the average delay and the total duration of the project, in order to provide the owner and the contractor with some support in making the final decision for the work schedule.

Based on our research of optimization methods and the simulation of computing mechanisms, we proposed an integrated model to solve a practical problem. The novelty and the contributions of this paper include:

- 1) Most of the previous studies on project scheduling focused on the minimization of total duration under resource-constrained conditions without paying much attention to the inconvenience to the public as a result of the delays caused by the work-zone closures. This paper offers an in-depth discussion and analysis of the interactions between renovation work and pedestrians and shows the importance of minimizing this type of negative public impact.
- 2) Previous studies never proposed an approach to quantify the impact of a renovation on pedestrians. In this paper, we proposed three indices quantifying the impact of a renovation, including the walking time delay (*WTD* for pedestrians), the average delay, and the total duration of the project. These three indices allowed us to compare the impact caused by

different work crew assignment schedules. In addition, we integrated the three indices into a multi-attribute utility model, which provides project planners sufficient decision support to plan the assignments for the work crew.

- 3) In this paper, we applied and calibrated the simulation engine, VISSIM, to fit real-life pedestrian walking behaviours. Compared with complicated mathematical models that need much time and effort to build, our simulation applications enable project planners to easily estimate the walking time delays for pedestrians before starting a renovation project.
- 4) Ant colony optimization (ACO) is being increasingly applied in the area of civil engineering. However, most of them tend to address new construction projects. In this paper, we modified the conventional ACO algorithm into a team-based ACO algorithm and applied it to the assignment of renovation work crews, which is a matter of maintenance management of built environments. We believe our work has widened the scope of the applications of ACO in civil engineering.

Future researchers can build a multi-objective decision support model for evaluating alternative solutions using different numbers of work crews, so that the average delay and the total duration can be considered in the optimization process. In the future, the effect of zoning should be further investigated because different work-zoning solutions (such as dividing a zone into more and smaller work zones) may result in different levels of walking impact. Researchers could also use different values for the parameters in ACO,  $\rho$ ,  $\alpha$ , and  $\beta$ , to improve the performance of the ACO for this model.

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