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Optimisation of construction site layout using a hybrid simulation-based system

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ABSTRACT

The layout of temporary facilities for a construction project greatly impacts project performance as demonstrated in many prior studies. This paper demonstrates how the site layout process can be automated for specific types of construction. Utility tunnel construction was selected as the specialty area, for which a partially automated site layout application was built. This approach integrates general purpose simulation for modelling space, logistics and resource dynamics with genetic algorithms for optimizing the layout based on various constraints and rules. We achieve this by implementing a site layout optimisation system within a simulation environment which already models tunnel construction processes. The new modelling strategy provides a medium for seamless integration between the resulting site layout and the discrete event production simulation models. The paper describes the approach taken and the system developed, presenting a practical case study from a tunnelling project in Edmonton, Canada to illustrate the system's performance and its validation.

1. Introduction and background

Construction site layout is a planning task, which follows the substantial completion of design drawings for a project but prior to construction. Site layout planning generally involves identifying the type and number of temporary facilities, sizing the facilities, and locating them. Planners must comply with many considerations, such as increasing construction productivity, decreasing site congestion and providing a safe work environment during the process of laying out a site [26].

Efficiently using site space to accommodate resources throughout a construction project is fundamental to the success of any project undertaking; simulation models offer a powerful tool for visualising and manipulating the space and activities that occur on construction sites. An effective plan for optimising site layout can directly improve the allocation and use of project resources, leading to more efficient processes and better schedule and profit outcomes. As such, the issue has attracted the attention of many researchers, and various site layout models have been developed.

More studies based on artificial intelligence (AI) were conducted to assign a set of predefined facilities to any available space onsite; these continue to be of high interest today. Models were developed by applying a knowledge-based system (CONSITE [10]; SightPlan [26]; MovePlan by [27]; MoveSchedule [28]), geographic information system (GIS) based systems (ArcSite [4]), Computer-Aided Design (CAD)-based systems [18,22,21,20,17], and fuzzy decision support system [25]. Efforts have also been given to applying genetic algorithms (GA) to developing models solving site layout problems [8,19,16,24,5]. In particular, Osman et al. [21] introduced the approach of utilizing genetic algorithms (GA) within the CAD environment to optimise the location of temporary facilities on site. The system utilises CAD as input/output media and employs GA to

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perform the optimisation process with the objective function of minimising total transportation costs between site facilities, a target echoed by many other researchers.

Most of this previous research in construction site layout tends to simplify site layout representation in order to achieve practical systems. Many existing models also take the sole objective of minimising travel cost, whereas the proposed simulation model takes a comprehensive view of site layout and usage. The test models were implemented with a fixed number of temporary and permanent facilities, as well as limited site shapes and orientations.

This paper presents a successfully developed site layout simulation template integrated with genetic algorithm (GA) as an optimisation tool for automating site layout problems and seeking a near-optimum construction site layout for utility tunnel construction. Together with the existing tunnelling model developed by the University of Alberta, this introduced template steps up to the generation of a comprehensive modelling system for tunnel construction projects; the simulation tool inherits some of the existing template's features with respect to consistency, but it is enhanced with more flexibility and better extendibility.

The template presented in this paper was created in *Simphony*, a simulation engine for building general and special purpose simulation models developed under the Natural Science and Engineering Research Council (NSERC) Industrial Research Chair Program in Construction Engineering and Management at the University of Alberta. It provides a standard, consistent, and intelligent environment for the development and utilisation of special purpose simulation tools in construction. The engine supports graphical, hierarchical, modular, and integrated modelling with great ease, while users have access to a single program that allows them to build simulation models in an intuitive and user-friendly manner [1,7].

Genetic algorithms are a class of stochastic search algorithms based on the mechanics of natural evolution and biogenetics. While randomised, GA is still a structured search and parallel evaluation of nodes in the search space. Implementing GA begins with randomly initialising a group of points (chromosomes), followed by evaluating the structures and allocating reproductive opportunities in such a way that the chromosomes representing a better solution are more likely to reproduce and undergo a sequence of operations such as crossover and mutation – along the lines of "survival of the fittest" in Darwin's evolution theory. The iterative process of selecting and combining good chromosomes continues for a number of generations until a solution is found.

Unlike many other optimisation methods relying on information about the gradient of the function to guide the direction of the search, which always fail when encountering discontinuous functions, GA works from a population of well-adapted diversity instead of a single point. As a robust search method, GA is stochastic, flexible, incorporates parallel-search procedures, and requires little information. These features making it capable of tackling large complex problems, especially the search spaces with many local optima where other methods have experienced difficulties. According to Al-Tabtabai and Alex [2], the use of GA in optimisation is appropriate when the space to be searched is large, when it is known not to be perfectly smooth and unimodal, when it is not well understood, if the fitness function is noisy, or if the task does not require a global optimum to be found.

Although no studies of applying integrated GA and simulation in construction site layout (particularly in tunnel construction) have been reported, GA has been successfully applied to numerous areas in construction engineering and management search problems because it is generic in nature and little information is needed about the problem domain. These areas include resource scheduling [3,13,23], schedule and cost optimisation problems [6,15,11], and cost estimating and control [12,14].

This paper considers the analysis of a tunnel construction site layout problem, first defining the relative parameters and activities. It then evaluates hard and soft constraints in determining the geometry of site layout and applies GA to encode the space in two dimensions. Based on these suppositions, the paper describes how the tunnel model is implemented in the *Simphony* environment. Lastly, this method is applied to a case study taken from the North Edmonton Sanitary Tunnel (NEST) System project in Edmonton, Alberta, demonstrating how site planning can benefit from the integration of GA's search and optimisation abilities with the ease and adaptability of the *Simphony* modelling environment.

2. Tunnel construction site layout problem

The main activities of tunnel construction involve sinking shafts (hand or mechanical excavation), excavating undercut and/or tail tunnel, constructing tunnel, and lining the facilities wherever necessary. The essential resources required for the tasks include a tunnel boring machine (TBM), a crane or hoist, and liner materials. Table 1 lists some other equipment and materials that could be required for the process.

Although tunnel construction is unique, the site layout in tunnelling projects follows two sets of rules: those common to all construction projects and those that are specific to tunnelling. For example, common rules include ones such as "the traffic path must be wide enough for trucks to drive over", "materials must be positioned to avoid double handling and unnecessary movements", and "the administration office should be away from noise and free from disruptions". As well, legal rules and regulations must be considered for safety reasons. As such, the size of the facilities can be affected by construction type, contract type, project size, and project location [10]. These rules prescribe a general direction for arranging a site layout rather than outlining precise instructions for the site.

According to Tommelein and Zouein [27], when a construction project is of a common type that has been built repeatedly, its design concepts lend themselves to generalisation. In the case of tunnel construction projects, the shaft generally appears

Table 1
Potential resources required for tunnel construction process

Activities	Excavation of a shaft (by machine)		Excavation of undercut and tail tunnel	Construction of a tunnel
	By machine	By hand		
Appropriate resources may include	Crane Drilling rig Backhoe Loader Temporary liners Vactor	Crane Overhead protection Compressor Loader Temporary liners Vactor	Crane or Hoist Overhead protection Compressor Loader Temporary liners Tugger and muck cars Welder	Electricity Air quality monitoring Ventilation Track Communication systems Liner material Compressed air

as the only permanent facility on site; all temporary facilities are sized and positioned around the shaft based on shaft configuration and tunnel size. A permanent facility is defined as a site facility that has fixed position while maintaining a close relationship with temporary facilities [10]. In this study, the shaft is considered to be a permanent facility. Dedicated areas refer to the site places occupied by trees, existing buildings, and other areas marked unavailable or unsafe where no temporary facilities are allowed to be positioned. Temporary facilities adopted on the tunnelling site can be categorised as hoisting equipment (crane, hoist, etc.), electrical equipment (power trailer, switch gear, construction boxes, etc.), and miscellaneous equipment (crew trailer, ventilation system, area for storage of segments, etc.). An important feature of tunnel construction is the employment of moles (TBM), including both totally enclosed moles and open-face moles. The type of mole used provides a particular set of rules to estimate the needs for temporary facilities; as such, project size plays a key role in the selection of facilities. The type of hoisting equipment utilised must be taken into account as well.

3. Logical and geometrical constraints

Hamiani [9] stated that the constraints for site layout can be established through the desired qualities of the layout shaped by relationships between facilities and the work area or by relationships among the facilities themselves. Prior to the operation of placing facilities, all potential constraints have to be identified, and the locations of all facilities on site must adhere to those constraints. In this study, the objective function is essentially an equation expressing how well the constraints are fulfilled. By way of satisfying the underlying constraints, the process of seeking practical locations for temporary facilities is carried out.

3.1. Spatial representation

In general terms, our approach attempts to model a user-defined polygon site using an orthogonal two-dimensional reference system. Any space that is neither a dedicated area nor occupied by a permanent facility is detected as an available space for allocating temporary facilities. The site polygon is further composed of a set of sides (site boundaries), each of which is defined by two end points, represented by x- and y-coordinates as input parameters as demonstrated in Fig. 1. Each side can thus be identified by the corresponding equation derived from the following equation:

$$y = a_i x + b_i, \tag{1}$$

where i has a maximum value of the number of polygon edges.

The facilities are represented by similar schema as the site representation. In general terms, most temporary facilities for tunnel construction can be considered to be rectangular in shape. Hence, all temporary facilities are abstracted and represented by rectangles, which are further represented by their central points, appropriate orientations varying from 0° to 360° and user-defined dimensions (refer to Fig. 1). Dedicated areas are assigned with the same type of representation, except that all location-related information is user-defined. A circular shaft is represented by the diameter and centre point coordinates while a rectangular shaft has an identical type of representation as in the dedicated areas. The spatial relationships among facilities include overlap (including equivalence and partial equivalence), containment, parallel/perpendicular, distance, adjacency (disjoint), orientation, closeness (close to and far from), and access. These expressions have proven sufficient to describe the relationships among facilities on tunnel construction site. Euclidean distance (straight-line distance between two points) is used as the distance metric in this study.

3.2. Hard constraints

Hard constraints represent two-dimensional geometric relationships between two facilities or between a temporary facility and an obstacle that must be met. Common hard constraints for generic site layouts are non-overlapping occurring between any facilities and all temporary facilities inside site boundaries (containment).

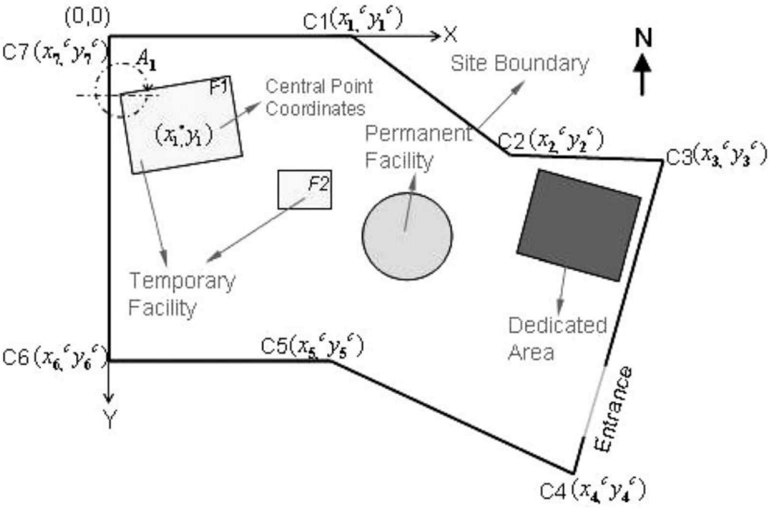

Fig. 1. Graphical representation of a tunnel construction site.

Considering the simplified site layout of Fig. 2, given the coordinates (x_1,y_1) of one of its corners, the length of the facility l (user-defined), the width of the facility w (user-defined), and the clockwise rotation angle A_g (from when the long side is parallel to the X-axis), the coordinates of the other three corners and centre point can all be calculated (omitted here).

The non-overlapping constraint requires no more than one facility set up on one specific area; exclusive conditions include aerial utilities appearing on site and specific requirements by users. For two rectangular facilities, conditions A-1 and A-2 explain the overlapping scenarios.

3.2.1. Condition A-1. Certain corners of one rectangle are inside the other rectangle

As shown in Fig. 3, one or more corners of one rectangle are interior to the other rectangle; in this case, intersections are identified by comparing half of the perimeter of facility 2 and the sum distance from each corner of facility 1 to the four sides of facility 2 and vice versa. Given the coordinates of $C_1^1(x_1^1, y_1^1)$ and the rotating angle of facility 1(A_g^1), corner $C_4^2(x_4^2, y_4^2)$ is inside facility 1. The sum distance between C_4^2 and each side of facility 1 ($d_1 + d_2 + d_3 + d_4$, calculated by Eqs. (2)–(5)) is $l_1 + w_1$, which is the sum of the length and width of facility 1. The sum distance between any point outside facility 1 and four sides of facility 1 is greater than $l_1 + w_1$

$$d_1 = x_4^2 \times \sin(A_g^1) - y_4^2 \times \cos(A_g^1) + y_1^1 \times \cos(A_g^1) - x_1^1 \times \sin(A_g^1), \tag{2}$$

$$d_2 = -x_4^2 \times \cos(A_g^1) - y_4^2 \times \sin(A_g^1) + y_1^1 \times \sin(A_g^1) + x_1^1 \times \cos(A_g^1) + l_1, \tag{3}$$

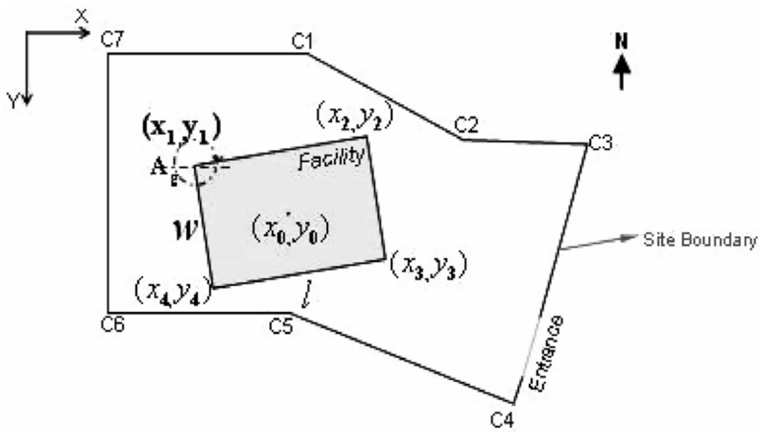

Fig. 2. Facility representation.

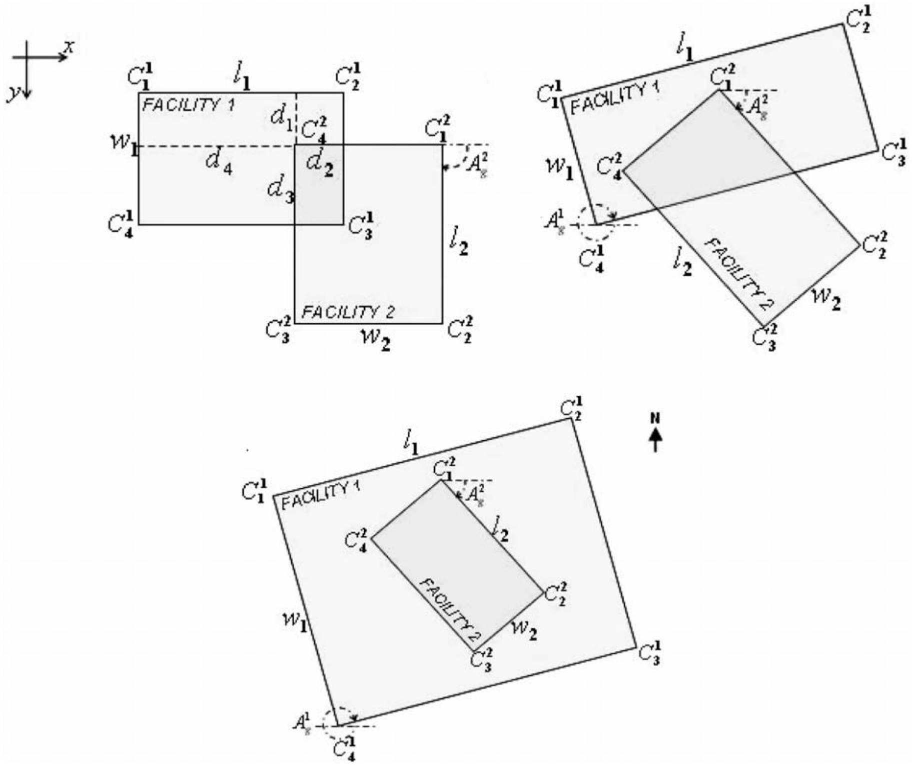

Fig. 3. Rectangular facility and rectangular facility.

$$d_3 = x_4^2 \times \sin(A_g^1) - y_4^2 \times \cos(A_g^1) + y_1^1 \times \cos(A_g^1) - x_1^1 \times \sin(A_g^1) + w_1, \tag{4}$$

$$d_4 = -x_4^2 \times \cos(A_g^1) - y_4^2 \times \sin(A_g^1) + y_1^1 \times \sin(A_g^1) + x_1^1 \times \cos(A_g^1). \tag{5}$$

3.2.2. Condition A-2. No corner of one rectangle is inside the other rectangle

Fig. 4 presents the only other colliding cases. If none of the rectangle's corners is inside the other, then one of the two diagonals of one rectangle must be intersecting interior to the rectangle with no less than one diagonal of the other rectangle once overlapping occurs.

Again, given the coordinates for Corners $C_1^1,\ C_3^1,\ C_1^2,\ C_3^2$, the respective diagonal equations connecting C_1^1 and C_3^1, C_1^2 and C_3^2 are as follows:

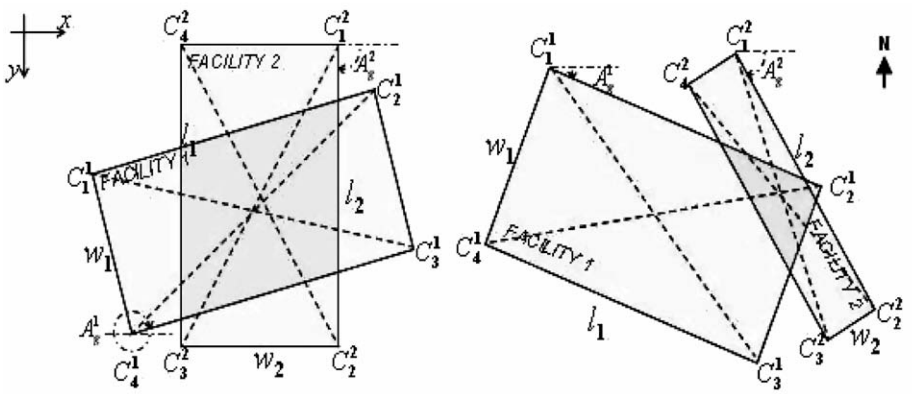

Fig. 4. Rectangular facility and rectangular facility.

$$y = \frac{y_3^1 - y_1^1}{x_3^1 - x_1^1} \times x + \frac{x_3^1 \times y_1^1 - x_1^1 \times y_3^1}{x_3^1 - x_1^1} \quad (\text{Perpendicular to } X\text{-axis case} : x = x_1^1), \tag{6}$$

$$y = \frac{y_3^2 - y_1^2}{x_3^2 - x_1^2} \times x + \frac{x_3^2 \times y_1^2 - x_1^2 \times y_3^2}{x_3^2 - x_1^2} \quad (\text{Perpendicular to } X\text{-axis case} : x = x_1^2). \tag{7}$$

Similarly, equations can be applied to the other two diagonals. At maximum, four points of intersection can be obtained. If one intersection point's coordinates are (x_k,y_k), the next step is to check whether either of them is inside both rectangles by applying the following inequalities:

$$(x_k - x_1^1) \times (x_k - x_3^1) \leqslant 0, \tag{8}$$
$$(y_k - y_1^1) \times (y_k - y_3^1) \leqslant 0, \tag{9}$$
$$(x_k - x_1^2) \times (x_k - x_3^2) \leqslant 0, \tag{10}$$
$$(y_k - y_1^2) \times (y_k - y_3^2) \leqslant 0. \tag{11}$$

Once inequalities 8–11 are all satisfied, point (x_k,y_k) can be declared as an overlapping area that exists between two facilities.

For one rectangular and one circular facility, conditions B-1 and B-2 explain the overlapping scenarios.

3.2.3. Condition B-1. Centre of circle is interior to rectangle

Suppose the circle has a diameter d and is centred at $C_0(x_0,y_0)$; the distance between C_0 and each edge of facility 1 is d_1, d_2, d_3 and d_4 (calculated), respectively (refer to Fig. 5). A similar method to A-1 can be applied to check if C_0 is inside of facility 1.

3.2.4. Condition B-2. Centre of circle is outside rectangle

Fig. 6 explains another overlapping scenario. If the minimum value among d_1, d_2, d_3 and d_4 is $d_{\min}$, and the corresponding side is E_j, then if

$$d_{\min} < \frac{d}{2}, \tag{12}$$

is satisfied, we proceed to test the following conditions.

If the two adjacent sides of side E_j for the rectangle are E_{j+1} and E_{j-1}, and assuming that the sum distance between C_0 and E_j, and C_0 and E_{j+1} amount to the length of E_j, then the circle and the rectangle intersect.

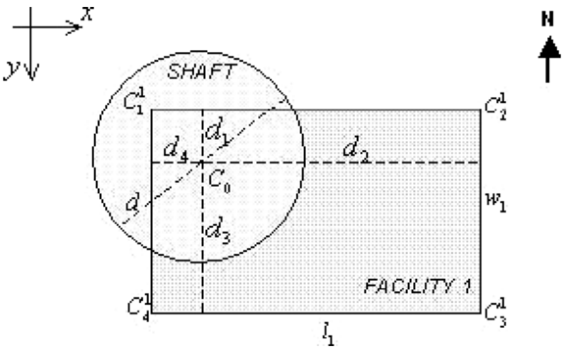

Fig. 5. Rectangular facility and circular shaft (1).

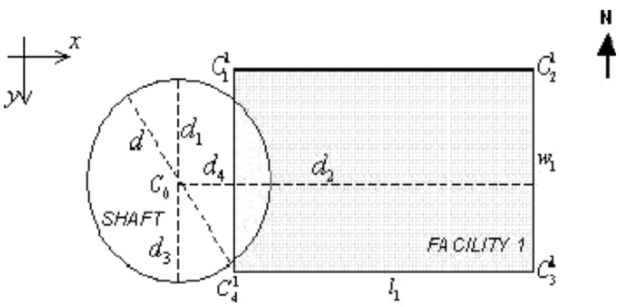

Fig. 6. Rectangular facility and circular shaft (2).

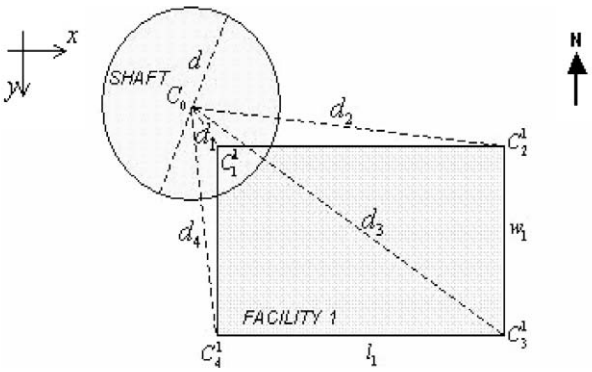

Fig. 7. Rectangular facility and circular shaft (3).

The only other overlapping scenario is shown in Fig. 7. If Inequality 13 is satisfied, then the circle and the rectangle are overlapping with each other

$$\min(d_1, d_2, d_3, d_4) \leqslant \frac{d}{2}. \tag{13}$$

Other hard constraints incorporated in the developed template are:

- Inside site boundaries constraint: all temporary facilities should lie inside site boundaries.
- Orientation constraint: spoil muck bin and draw works should be located on different sides of the shaft.
- Access constraint: traffic routes are required to have a width of 4 m between every pair of specific facilities.

3.3. Soft constraints

If we assess the satisfaction scheme of the constraints with functions, then hard constraints would be represented by some discrete function, such as binary functions, taking a value of 0 or 1 using a threshold value; conversely, a suitable continuous function would be utilised to represent soft constraints. Soft constraints express less strict preferences in terms of the conditions' proximity weights. The function value rises or falls in a continuous manner according to the nature of the specific soft constraint it represents. The corresponding function of each soft constraint might reflect two facilities' orientation desirability, equipment accessibility, closeness desirability, and so on.

A commonly used soft constraint on tunnel construction sites is the parallel/perpendicular constraint (example: power trailer runs parallel to tunnel centre line). It limits the orientation of one facility to be either parallel or perpendicular to another. Subsets of this constraint are the largest edges of the interacting facilities parallel to each other (condition (a)), and any edge of one facility is parallel (or perpendicular) to the other one (condition (b)). Once the facilities are parallel or perpendicular, as required, a full satisfaction score is obtained; otherwise, descending scores of different conditions can be calculated accordingly. Two equations expressing the mentioned conditions were inferred and shown below, used for assessing conditions (a) and (b), respectively

$$FitS = Wt \times \frac{(90 + 180 \times \mathrm{int}(|A_g^1 - A_g^2|/180) - |A_g^1 - A_g^2|)^2}{90^2}, \tag{14}$$

$$FitS = Wt \times \frac{(|45 + 90 \times \mathrm{int}(|A_g^1 - A_g^2|/90) - |A_g^1 - A_g^2||\mathrm{mod}45)^2}{45^2}, \tag{15}$$

where *FitS* represents the satisfaction score; *Wt* denotes the weight of the specified condition among all other conditions; A_g^1 and A_g^2 are clockwise rotating angles of the two interacting facilities.

If facilities 1 and 2 in Fig. 8 are supposed to satisfy the parallel constraint in any manner, then evidently location 2 for facility 2 would have a higher satisfaction score. Similarly, if facility 1 represents the power trailer, since the slope of its short edge equals that of the tunnel centre line in Fig. 8, then this layout has a full satisfaction score in satisfying this sample constraint.

The other soft constraints incorporated in this study include:

- Distance constraint: the distance between the centre points of the spoil muck bin and hoist is preferred to be 6 m.
- Adjacency constraint: two tool cribs should be placed next to each other.
- Closeness constraint: electrical facilities should be close to each other.

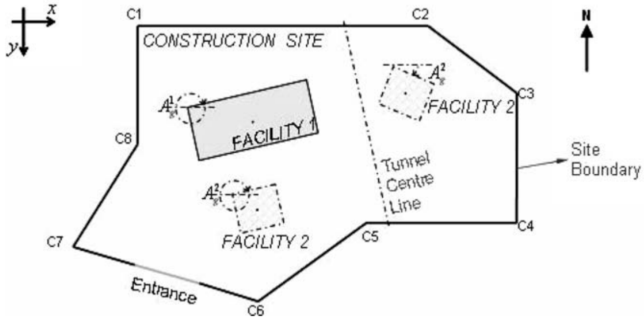

Fig. 8. Representation of parallel/perpendicular constraint.

4. Genetic algorithms

4.1. Genetic algorithm solution encoding

As illustrated in Fig. 9, real-valued encoding is applied to assign n temporary facilities. Each gene has two attributes: its ID (sequence number) and the facility rotating angle or either of the coordinates, depending on its sequence in the chromosome. To help map attributes of temporary facilities to gene positions, all temporary facilities are ranked backstage based on their ID once they are created in *Simphony*. Therefore, the objective of solving the site layout problem is transformed into a matter of finding the optimum set of values for the genes in the chromosome matrix (from *X1* to *An* in Fig. 9).

4.2. Genetic operators

Selection and elitism operator: This is the first operator applied to a population with the goal of enabling chromosomes with good fitness to have a higher probability of contributing offspring in the next generation. A variation of rank selection with elitism is used as a selection scheme. Each chromosome is associated with a selection probability (P_i). By generating random numbers and comparing the numbers with each P_i repeatedly, $(N_{\mathrm{ch}} - N_{\mathrm{el}})/2$ pairs of parents are selected for performing the next operation. Fig. 10 graphically illustrates this operator.

Crossover operator: The selected pairs of chromosomes from the anterior operator partially exchange information with each other. Two-point crossover technique is adopted in this research so as to get rid of endpoint effect and reduce positional bias. To perform the operation, two random numbers R_{C1} and R_{C2} are generated according to Eqs. (16)–(18), and the pair of chromosomes undergo crossover at the cut-off points R_{C1} and R_{C2}, as shown in Fig. 11. By employing Eqs. 17 and 18, every group of genes together representing a temporary facility is protected from being destroyed.

$$R_C = Rnd \times (3 \times NF), \qquad (16)$$

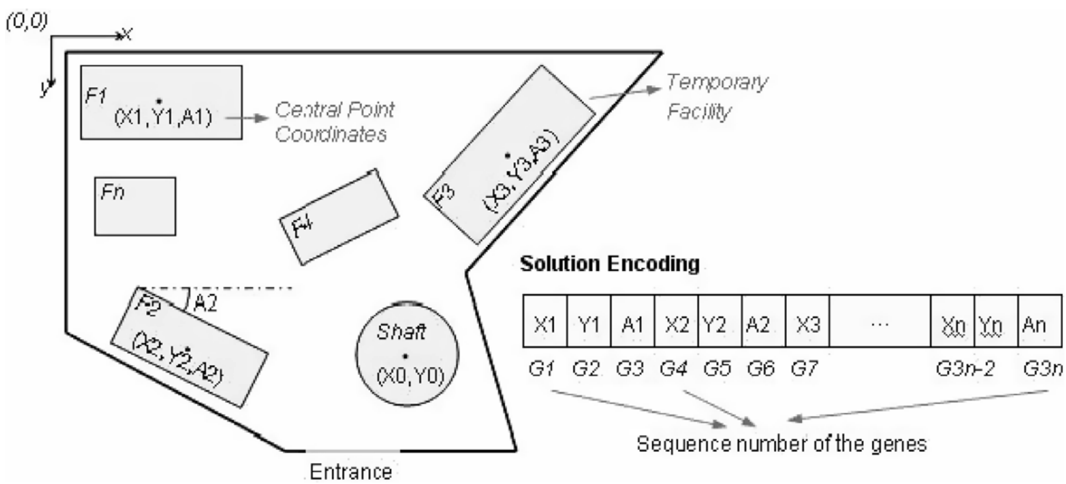

Fig. 9. GA encoding of two-dimensional space.

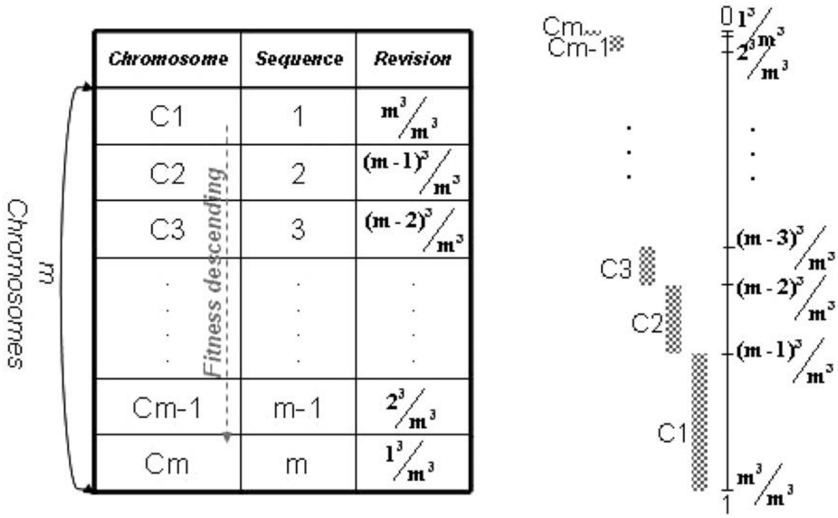

Fig. 10. GA selection operator.

$$\text{If int } (R_C \bmod 3) = 2, \quad \text{then } R_C = R_C + 1, \tag{17}$$

$$\text{If int } (R_C \bmod |3) = 1, \quad \text{then } R_C = R_C + 2, \tag{18}$$

where R_C is the value required for seeking the cut-off point, *NF* represents number of temporary facilities appearing on the tunnel site; *RND* is a random number in the range of 0–1 inclusively generated by *Simphony*.

Mutation operator: This operator is mainly used to interrupt current stagnation in improvement by introducing new genetic information into the population in a random manner. A modified random offset mutation operator is developed in this study to attain the required function. Fig. 12 is an illustration of the mutation operator used in this study. A probability of mutation (P_M) is selected; chromosomes (elite members are excluded) will be implemented by selection and crossover operators that will be partially mutated. To carry out mutation operations, each gene in the selected chromosome is visited and replaced by a new randomly generated value at certain probabilities, termed mutation rate (R_M). To guarantee that valid positions of the facilities are generated or assigned, random values given to the genes mutated are limited within ranges, shown in Fig. 12. The operator repeatedly operates on all selected chromosomes, and once it is done, the current population is entirely replaced by the newly generated one.

4.3. Fitness function

The fitness function provides a measure for evaluating how far each incorrectly placed number is from its correct place. The fitness or objective function in the present study can be expressed as Eq. (19), in which *T.F.* represents the total fitness

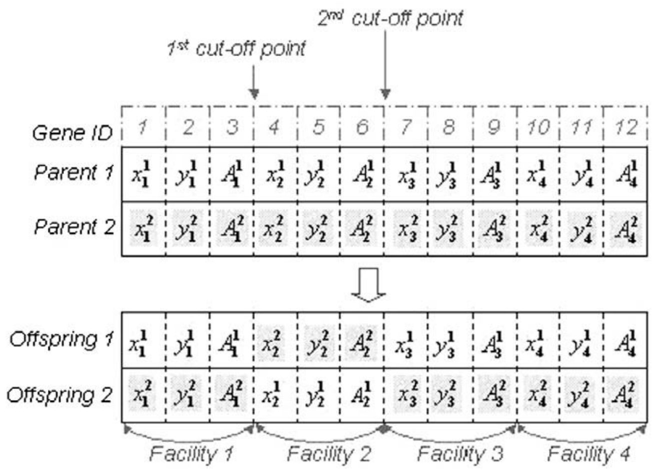

Fig. 11. Two-point crossover operation.

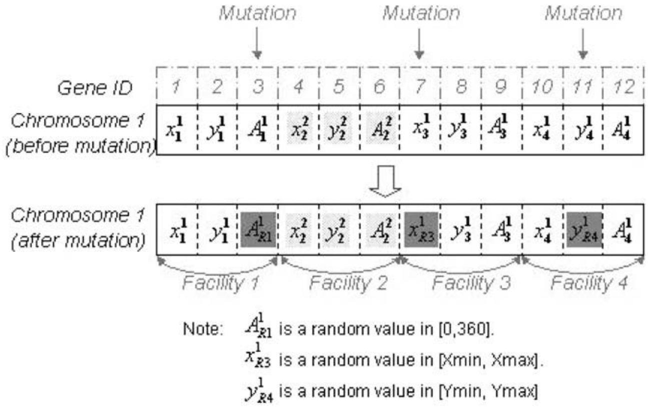

Fig. 12. Mutation operation.

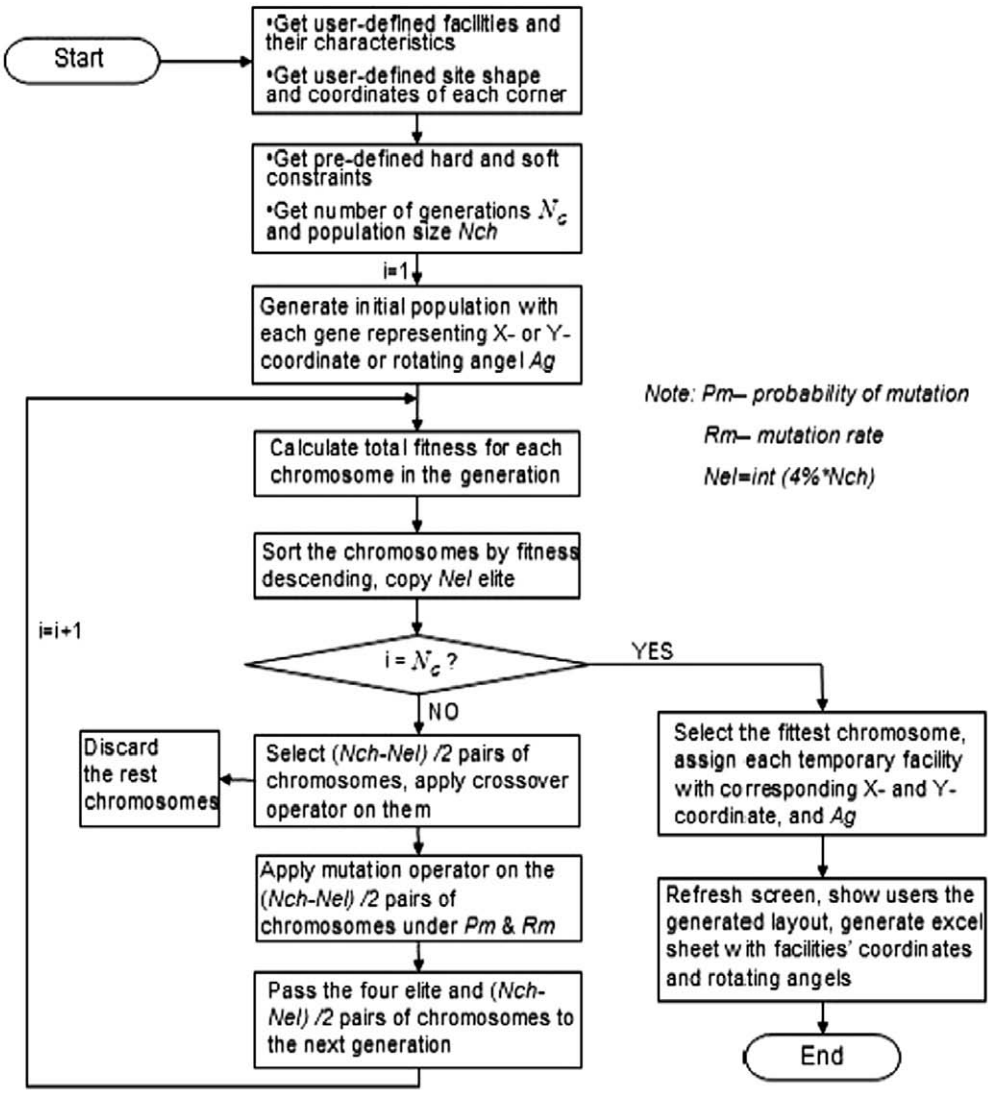

Fig. 13. Generic algorithm flowchart.

value and *FitS* indicates the proximity weight assigned to each aforementioned constraint. Using the proposed fitness function has the advantage of being comprehensive, as multiple objectives can be translated into certain categories of the constraints. The system is thus able to avoid solely minimizing travel distance or travel cost.

$$T.F. = \sum FitS. \tag{19}$$

"Desired relationship between facilities" was scaled into "must", "absolutely necessary," "important", etc., with "proximity weight" assigned to each scale of constraints. For the hard constraints, *T.F.* stays constant once all of them are satisfied; conversely, a value equal to the corresponding weight would be deducted from *T.F.* For soft constraints, a relatively high weight value is assigned to a group of facilities with a specified constraint if the relationship is desirable; a zero value will be taken

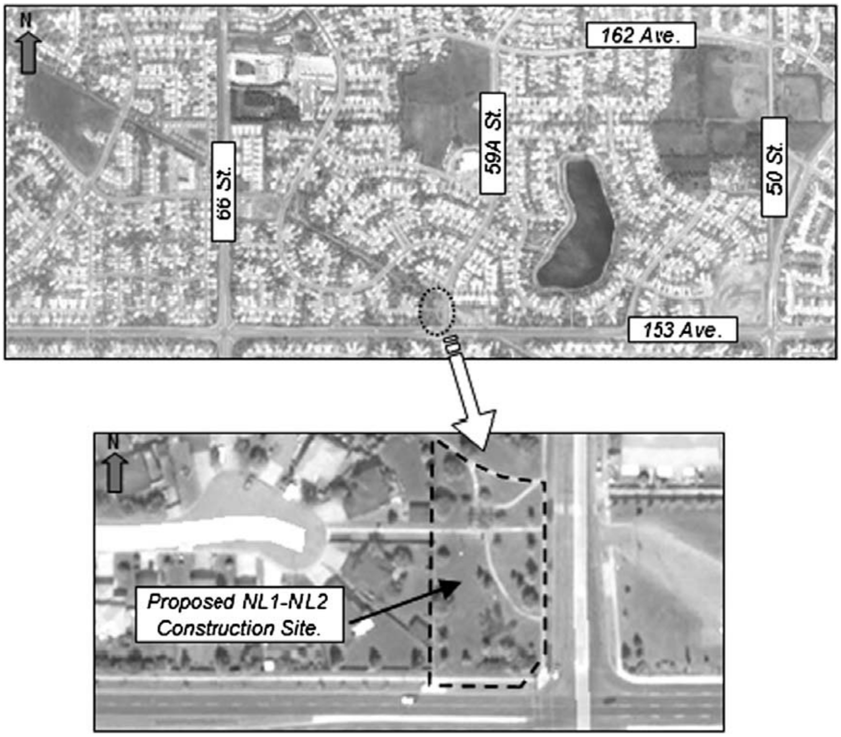

Fig. 14. NL1–NL2 tunnel construction site overview.

Table 2
Temporary facilities and dimensions adopted for NEST NL1–NL2 project

Temporary facility		Number of facilities	Dimensions	
Category	Name		Length (m)	Width (m)
Misc.	Field office	1	16	3
	Site parking (9 stalls)	1	27	6
	Portable Privy	1	1.5	1
	Ventilation system	1	4.3	1.2
	Tool crib	2	3	2
	Propane tank	1	2	1
	Area for miscellaneous supplies	1	8	4
	Area for storage & Heating of concrete segments	2	12	3
Hoisting	Crane	1	11.5	6
	Spoil pile	1	7	7
Electrical	Mole cable lay down platform	2	12	4.5
	Electric compressor building	1	5.5	2.5
	Switch gear	2	3	1.5

when the constraint is not met. Accordingly, to achieve a high fitness value, relationships with high proximity weights are always satisfied first.

For instance, given the desired relationship of one facility "inside site boundaries" is "must," then its proximity weight is assigned to be 0/−200 (Y/N); if the desired relationship of power trailer running parallel/perpendicular to tunnel centre line (if existing) is "important," then its proximity weight is assigned to be 10/0 (Y/N). If the power trailer is inside the site boundaries and runs parallel to the tunnel centre line, then the total fitness value is

$$T.F. = FitS\ (\text{inside boundaries}) + FitS\ (\text{parallel/perpendicular}) = 0 + 10 = 10.$$

5. Optimisation procedure

The developed system has been implemented via *Simphony*. The *Simphony* interface enhances users' comprehension and improves technical communication. It is also highly extendible in adding new hard or soft constraints related to productivity and safety.

Fig. 13 shows the optimisation procedure flowchart. In the initialisation phase, the system generates a set of random yet confined coordinates and rotating angles for the user-defined temporary facilities as genes in each chromosome. The generated *x*- or *y*-coordinates are limited in a detected range $(x_{\min}, x_{\max})$ or $(y_{\min}, y_{\max})$ (within site boundaries) while the range for the rotating angle is $(0^\circ, 360^\circ)$ so as to avoid the infeasible positions and narrow down the search space. Each chromosome is a layout solution that can be evaluated according to the total fitness calculated. The evolutionary phase repeats the Selection–Crossover–Mutation–Fitness Calculation–Chromosomes Arrangement procedure, with the termination criterion being the maximum number of generations N_G.

Once the optimum layout solution is found in the last generation, the coordinates and rotating angles represented by the genes in the chromosome are automatically assigned to the corresponding temporary facility, and each facility abstracted on the screen in the *Simphony* environment then adjusts its own position and angle, thus producing the graphical output. A summary for the output is created simultaneously through Microsoft Excel.

6. Case study

6.1. Problem statement

The development of the integrated systems leads to improvement in many areas, such as modelling any hypothetical construction alternative for evaluating various site layouts. This section presents the performance evaluation of the developed modelling system through an actual project, analysing the input information provided and giving a summary of how the modelling result is generated.

The selected project is part of the NEST (North Edmonton Sanitary Tunnelling) system undertaken by the City of Edmonton, named NEST NL1–NL2. The tunnelling site is located at 59A Street, with a near-polygon shape and an approximate area of 2500 m^2 (see aerial map in Fig. 14). The site was required to accommodate 17 temporary facilities, listed in Table 2. Permanent facilities and dedicated areas are shown in Fig. 14, with site corners and entrances indicated.

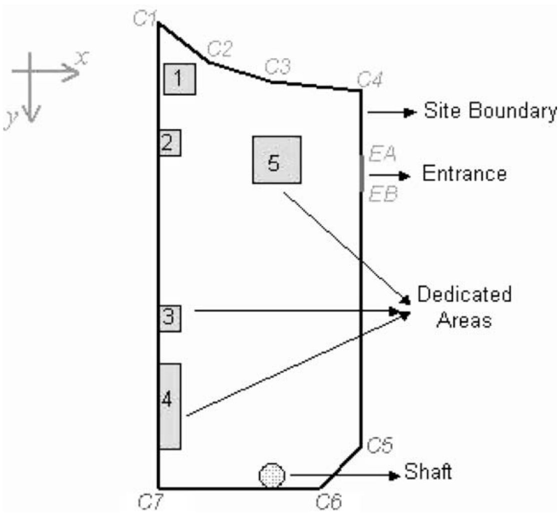

Fig. 15. Simplified layout of permanent facility and dedicated areas.

6.2. Simulation model

In mapping the NEST NL1–NL2 Project construction site onto the *Simphony* interface, the modelling system starts with generating the tunnelling site and objects. Site boundaries and site entrance are created first, once the coordinates of the seven site corners identified are finished being input. These appear simultaneously with the shaft and test hole, which are automatically generated with default positions. Once the orthogonal two-dimensional reference system shown in Fig. 15 is defined, the coordinates and dimensions of the dedicated areas and the shaft, as well as coordinates of the seven site corners and site entrances are identified and input to the system. Site facility elements representing dedicated areas are then created based on the site geometry according to the specified coordinates and dimensions. Next, the 17 temporary facilities are generated as well, with the specified dimensions located anywhere within the *Simphony* interface.

At the commencement of laying out the site in the system, the permanent facility, i.e., the shaft, and dedicated areas are relocated based on the positions assigned to the corresponding representing elements or to the parent element. In succession, the tunnel centre line is generated accordingly. In this case, the tunnel's orientation is simply east–west.

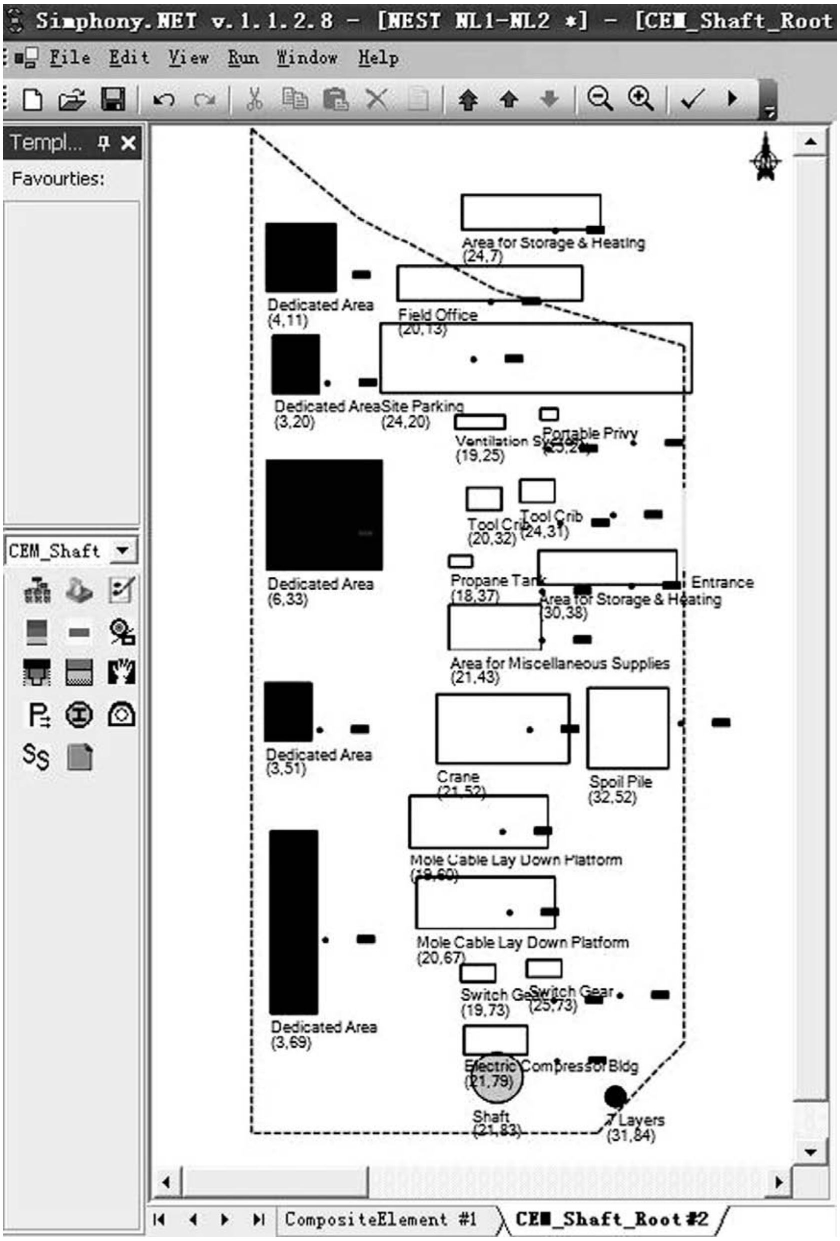

Fig. 16. Initial generated layout.

GA optimisation of the temporary facilities' locations is activated subsequently. Note that in the proposed model, the probability of mutation P_M is set to be 0.2 and the mutation rate R_M is assigned to be 0.3 to achieve the highest fitness values resulting from many trials. "Number of Generations" and "Number of Chromosomes" are set to be 1000 and 100 individually for the project studied.

The initial generated layout (before the model is triggered) from the modelling system is shown in Fig. 16; a comparison of the generated layout from the optimisation system associated with the layout from project engineers is shown in Fig. 17.

The generated layout shown in Fig. 17A received a total fitness value of 220, compared to the value of 108 received by the project engineers' layout (Fig. 17B), which was produced using the same evaluating constraints. In general, the developed system was able to generate a site layout close to the actual tunnelling site arrangement, with some differences that were in favour of the constraints assigned for this study.

The generated site is not guaranteed to be an ideal construction site for the interacting facilities of this project, but it is a near-optimum one based on the constraints adopted since it satisfies all constraints well. The site planner considered the modelling result to be satisfactory and found the developed system a useful site layout tool; the planner commented that the modelling system had great potential for being adopted in construction practice.

Upon the completion of the near-optimum site layout seeking process at the parent model level, the system automatically calculates the distance between the spoil pile and dirt dumping location, as well as the distance of the shaft and the spoil pile. The crane loading and unloading time is therefore calculated backstage based on its average speed and the distances, and applied as input to the "crane loading/unloading element" for the purpose of tunnelling model, as graphically illustrated in Fig. 18. The "earth moving" component, on the other hand, is triggered whenever the volume of "soil pile" reaches a certain pre-set level, and generates total travel time for delivering the dirt. This integrated model is run for 100 m of tunnelling, and outputs are partially given in Table 3.

Note that the outputs generated from the integrated model at this stage are only for illustrative purposes; further work will be performed to maximise the benefits of integration. The results produced by the integrated model facilitate

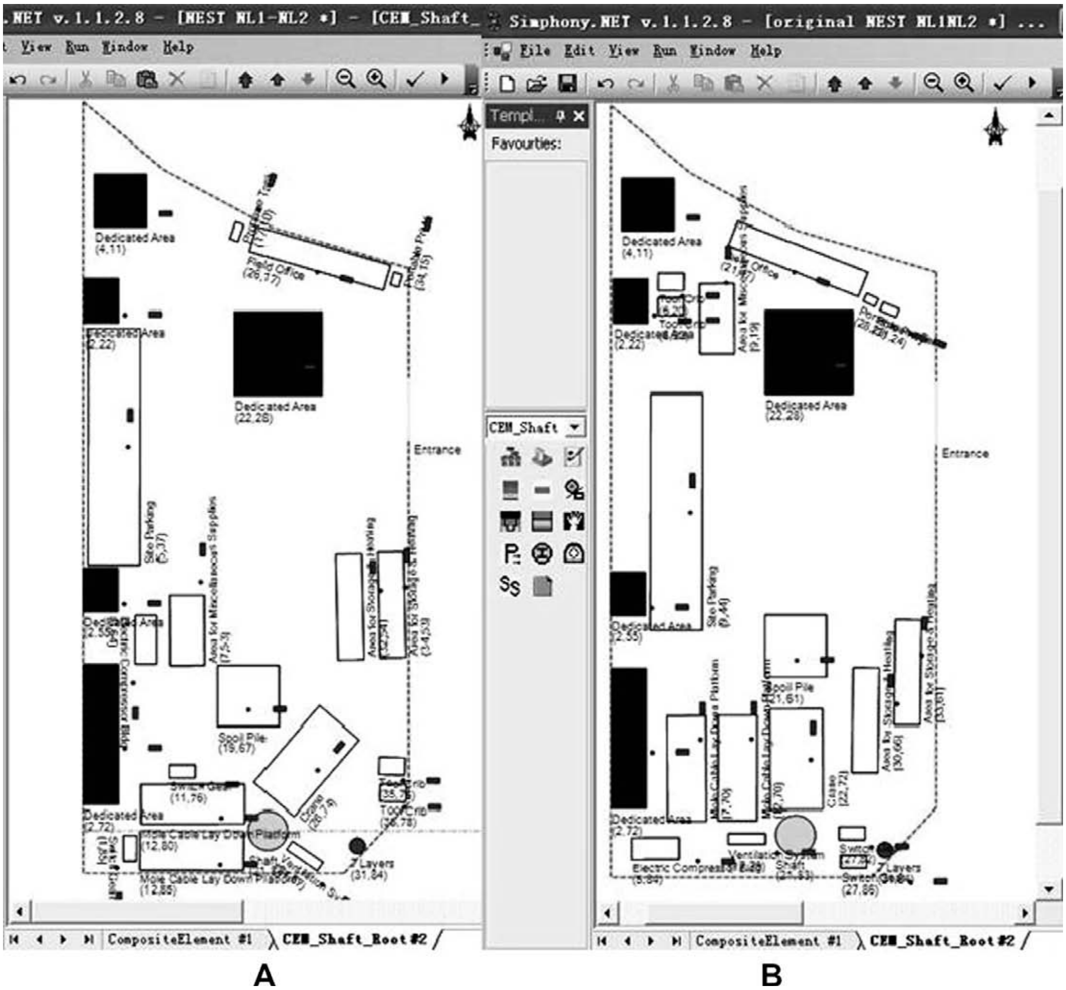

Fig. 17. Comparison of automated system assignment of temporary facilities (A) and the proposed site layout by project engineers (B).

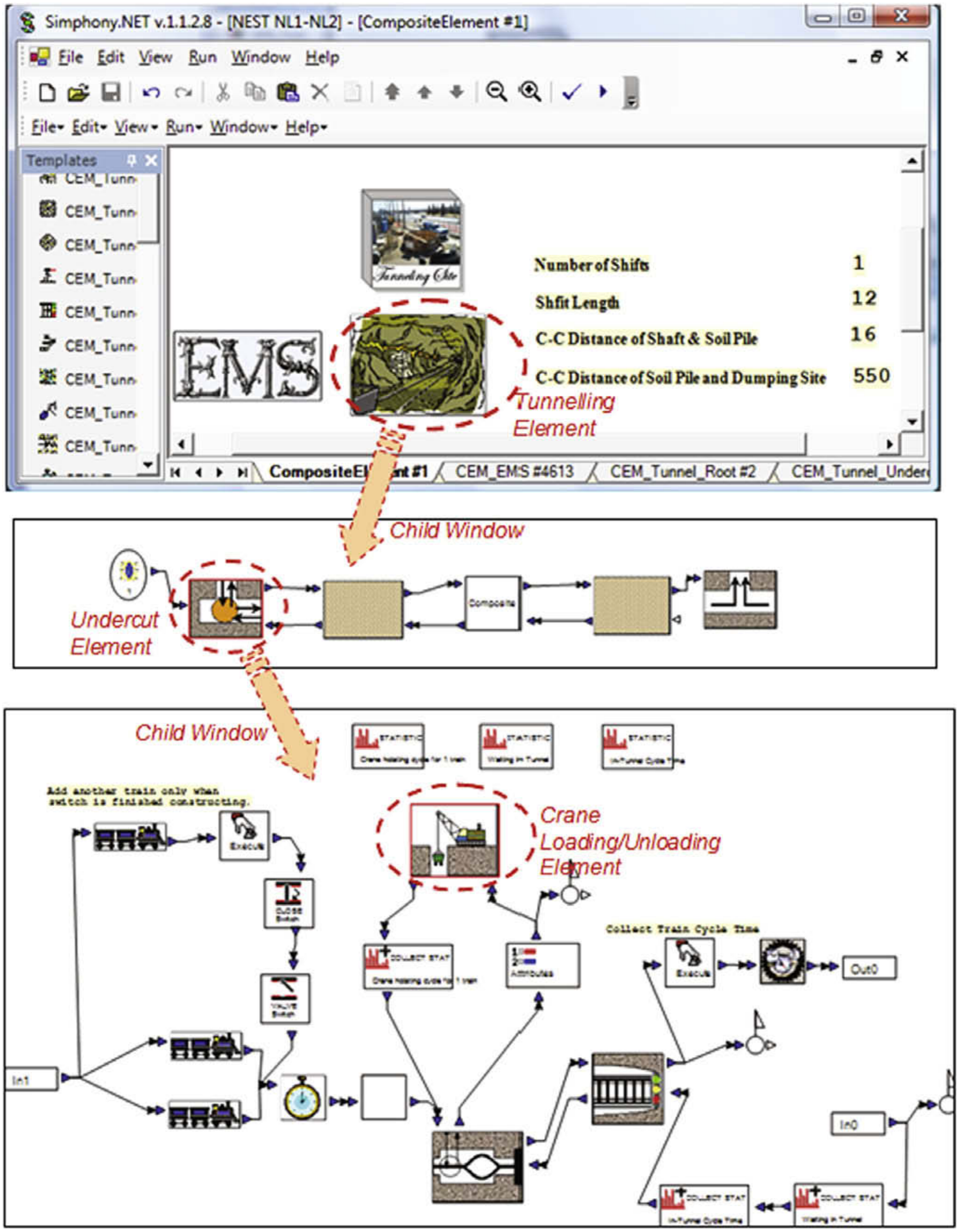

Fig. 18. Illustration of the templates' integration.

Table 3
Outputs (partially) from the integrated simulation model

Output	Value
Crane loading/unloading time (min)	4.8
Crane total loading duration (min)	6198.8
Truck total travel duration (min)	708
TBM idle duration (min)	487
Tunnelling productivity (m per day)	4.25

decision-making, and interactions such as spoil pile relocation could be further arranged accordingly. Integration of these three templates will be presented in detail in future papers.

7. Conclusions

This paper presents an integrated simulation system developed to incorporate the intricate search and optimisation abilities of GA and the *Simphony* platform, which provides a fast, easily manipulated, and risk-free environment in which to experiment with different planning alternatives. Some distinguishing features of the developed system are summarised below.

Any construction site can be accurately abstracted and represented as a polygon in the developed system with user-defined dimensions. Temporary facilities are represented by rectangles with system-generated rotating angles to the site borders.

Eight categories of hard and soft constraints among site facilities were formulated, and dozens of breakdown constraints specific to the tunnelling site were identified, covering issues related to access, material storage and handling, and safety. Hence, the decision of locating facilities is made not only on a distance basis, but also based on several other important factors. The current domain-specific constraints may not be comprehensive enough to cover all of the aspects in construction projects; however, the developed system is fairly flexible in further updating or adding any hard or soft constraints as well as their proximity weights.

The proposed simulation system can be easily extended to accommodate more disciplines and strategies and to produce more advanced outputs as users require. As such, it is quite compatible with other *Simphony* templates, which will facilitate the future work of this study. The developed modelling system enables users who are knowledgeable in tunnelling to create a model and experiment with different scenarios without the developer's instruction.

As the limitations of the developed system are improved, more soft constraints could be explored to make the template more comprehensive, and actual paths could be considered for connecting facilities instead of rectilinear distance. Furthermore, future work on the system could augment the handling of dynamic layout problems, better equipping the system to deal with site layout problems common to most construction projects.

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