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A multi-objective mixed integer nonlinear programming model for construction site layout planning to minimise noise pollution and transport costs

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ABSTRACT

The achievement of a sustainable industry in the construction sector requires the consideration of environmental and social impacts of the operations involved, along with the traditionally imperative economic factors affecting the construction project. An implicit social and environmental factor commonly linked with construction is the noise pollution resulting from activities taking placing during the various construction stages. The levels of sound recorded at receivers positioned in the vicinity of the construction site may be considerably affected by the site layout adopted. Site layout planning with the objective of minimising the construction noise levels has not been investigated in the available literature. To ensure a balance between economic, social and environmental impacts, the planning of the site should also account for the economic factors associated with the monetary costs of material transportation between facilities, rendering the problem a multi-objective one. This paper presents a novel multi-objective mixed integer nonlinear programming model that minimises noise levels at multiple receivers surrounding the construction site, as well as on-land material transportation costs, through site layout optimisation. An improved transportation cost model accounting for several transportation modes is presented. A Pareto front, listing nondominated global optimum solutions, is obtained for a case study tested using the ε-constraint method.

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1. Introduction

Enhancing sustainability in the construction industry requires the achievement of a balance between economic, social and environmental impacts of construction activities. Noise pollution, resulting from the operation of construction equipment, is one of the leading social and environmental impacts attributed to the construction sector [1]. The disturbances caused by noise pollution are grouped generally into two main categories; occupational disturbances, which encompass the impacts of noise on on-site workers, and environmental disturbances, where effects are directed at the environment surrounding the construction site [2].

The abundant literature on clarifying the risks and hazards associated with being subjected to noise is a clear indication of the extent to which this matter is significant. Many studies have covered various aspects of health disorders that are a direct result of exposure to noise. Some of these adverse health impacts include: an increase in the risk of ischemic strokes; hypertension; increase in the risk of cardiovascular disease; associated risks that lead to myocardial infraction; noise induced hearing loss; physiological, emotional and psychological impacts; and pregnancy complications in females [3–12]. Not only does noise cause health ailments, but its impact can disrupt a wide range of industry sectors. Gilchrist et al. [13] argued that in manufacturing industries, where the reliance on precise measuring equipment is a vital part of the production system, vibrations due to loud noise can interfere with the performance of such equipment. Economic drop backs, in terms of loss in productivity, were also reported due to workers being exposed to high noise levels [14,15]. On a wider scale, in areas where revenue is generated from tourism, high levels of noise will often dispel tourists and will also lead to a decrease in the wildlife population surrounding the area exposed to noise [16].

Methods for managing sound levels on construction sites are wide and varied. One facet which plays a central role in limiting the total noise disturbance experienced by the neighbourhood surrounding construction sites is the layout of the different facilities supplementing the work activities on-site [17]. A major controlling factor, when it comes to layout planning, in regulating sound levels reaching a particular receiver point in the vicinity of the construction site, is the distance separating the noise emitting source and the receiver, together with any barriers that may disrupt the sound propagation path [18]. Hence, the arrangement of facilities on a construction site is an important aspect, not only in determining the transportation cost resulting from the movement between facilities but also in influencing the sound levels

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dispersed to the surrounding residents. Those on-site facilities involved in the construction process are identified based on two categories, namely, permanent and temporary [19,20]. Permanent facilities have a pre-assigned configuration on the construction site. These include access points to the building undergoing construction, for the passage of materials into and out of the building construction area, the buildings under construction, other pre-existing facilities required to be of use during the construction process [20], and permanent natural obstacles. On the other hand, temporary facilities do not have predetermined positions outlined by design guidelines or imposed by natural site conditions and the surrounding environment. In other words, the task of positioning these temporary facilities is often left to the project managers/site engineers.

The above-mentioned process of allocating different facilities to the available locations on a construction site to find an optimum layout configuration is referred to in the literature as the Site Layout Planning (SLP) problem [21]. SLP has been extensively researched, with primary focus on solving the problem based on the economic component of sustainability, i.e., costs of material handling and onsite transportation. The inclusion of environmental and social sustainability objectives in SLP is limited. Sustainability objectives addressed in previous studies on SLP include minimising safety hazards [17,19,22,23], minimising wildlife interference during airport construction projects (preservation of wildlife around airports) [24], minimising environmental hazards by delineating locations on construction sites deemed to be too close to susceptible sources (e.g., Schools) and preventing facilities from being located in these prohibited areas [25]. To the best of our knowledge, objectives such as minimising construction pollution in all its categories (noise, air, etc.) have not been investigated.

From a computational point of view, construction SLP is considered a challenging problem known to be NP-complete [26]. Applying an exact algorithm that yields the global optimum solution is thus challenging for such a class of problems, especially given the tendency of NP-hard problems to increase exponentially in complexity with increasing problem size [27]. Past attempts in the literature have focused very closely on the use of meta-heuristic optimisation techniques such as (1) genetic algorithms (GA) [26,28–33], (2) ant colony optimisation (ACO) [27,34–36], (3) simulated annealing [37], (4) particle swarm optimisation (PSO) [38–40], and (5) harmony search (HS) [41]. Recent studies have focussed on applying new meta-heuristic algorithms to address the problem, and on identifying different interpretations of the SLP, based on whether or not a timing schedule is incorporated to track the construction activities and tasks taking place [42,43].

However, a drawback of meta-heuristic optimisation techniques is their tendency to produce results that are near optimal rather than optimum. This is mainly due to the underlying mechanisms that meta-heuristics are founded on; being reliant on random search, with less emphasis on mathematical relations between the variables involved [44]. When an optimal solution is sought, an algorithm implementing exact solving methods should be utilised. A number of attempts to obtain optimum solutions to the SLP problem using linear programming (LP), mixed integer programming (MIP) and mixed integer nonlinear programming (MINLP) have been reported in the literature [20,45,46]. These studies are mostly limited to minimising the transportation costs between facilities. Furthermore, to reduce the complexity of the overall model, studies have mainly relied on a simple representation of path delineation whereby a direct measure adopting the Euclidean or the Manhattan approach was used to determine the travel distance. This however may not represent the actual onsite transportation requirements, especially when obstacles and forbidden areas, such as facilities and construction areas, prevent direct travel.

This paper presents a novel mathematical model for the multi-objective optimisation of the construction site layout, where emphasis is placed on sustainable SLP, with two objective functions being examined: (1) minimising the total on-land transportation costs associated with material handling between the different allocated facilities and (2) minimising the construction noise pollution realised at receiver points located within close proximity to the construction site. The first objective function incorporates a newly developed method that tries to outline reasonable movement approximations within the construction site, while the second objective function has been developed to take on a number of noise attenuation factors at multiple receiver points. The way in which the model has been formulated allows a global optimum solution to be reported, if present.

The proposed optimisation model is applied to and solved for an illustrative case project. The problem is formulated as a MINLP model and solved using SCIP, a constraint integer programming optimisation engine [47,48]. The MINLP is NP-hard since it is a generalisation of mixed integer programming (MIP), which is already NP-hard. The solver used to obtain solutions to the SLP problem in this paper successively divides the problem into smaller sub-problems, through a branching process, such that the MINLP problem is solved to global optimality. All our tests were conducted without any limit imposed on the computing time; therefore the solutions provided in our manuscript for the construction site layout problem are optimal.

While the main focus of this paper is on the application of the proposed optimisation model to construction SLP, the model can be extended to other fields such as industrial and urban planning, where sound level reduction is a crucial issue to tackle.

2. Modelling the construction site layout problem

2.1. Model development

Fig. 1 presents an overview of the model development stage. The process starts by converting the transportation cost function and noise level function into a single format, where constraints for the two objectives are combined. Once the collective constraints and objective functions are obtained, the parameters of the problem are estimated in order to provide suitable data for the optimisation process to be carried out. The individual objective functions together with their constraints are explained in the following sections.

2.2. Notations

A description of the notation of different sets, parameters and variables used in this paper is presented in Tables 1–3.

2.3. Model formulation

2.3.1. Objective functions

In this paper, two objective functions are formulated. The first objective function (Eq. (1)) defines the on-land transportation costs associated with the movement between the different facilities on a construction site. To enable the convening of the variations in noise levels recorded due to the configuration of facilities adopted on site, it is important to quantify the noise permeating from within the facilities. The second objective function (Eq. (2)), is a representation of the logarithmic nonlinear summation of sound levels produced by more than one noise source linked to an operating facility; this allows for the computation of the total resultant sound levels emitted from dispersed source points. The mathematical representation of the aforementioned objective functions is presented below:

$$\text{Minimise} \sum_i \sum_j \sum_t C_t F_{ijt} d_{ij} \tag{1}$$

$$\text{Minimise} \quad \max_{r \in R} \left\{ 10 \log_{10} \left(\frac{1}{10} \sum_s \sum_i t_s 10^{\frac{L_{\mathrm{sir}}}{10}} \right) \right\} \tag{2}$$

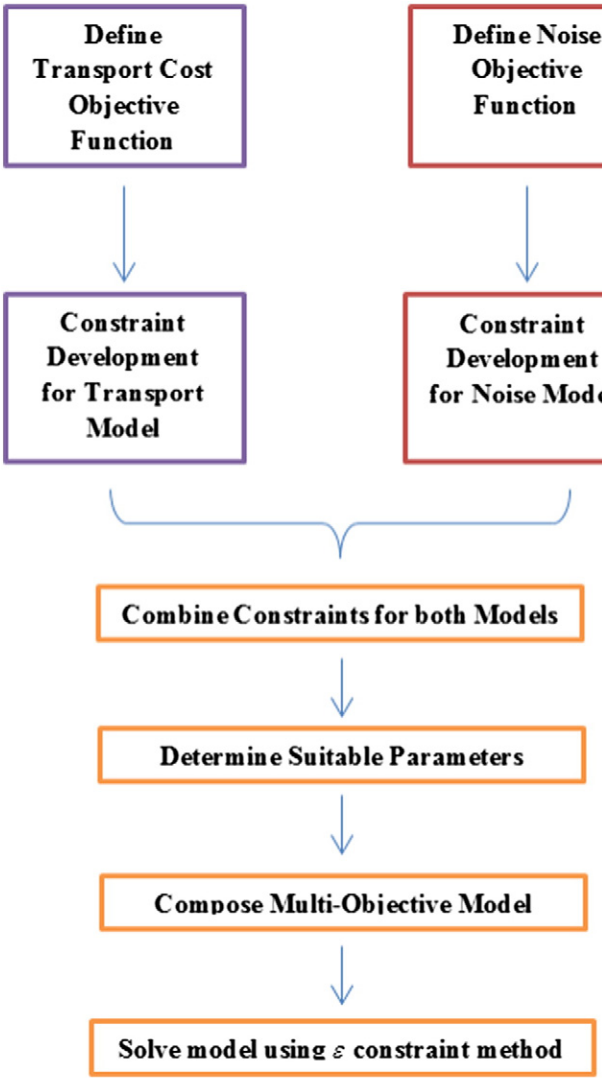


Fig. 1. Overview flowchart depicting model development stages.

A single variable, d_{ij}, is included in Eq. (1), which represents a specified Manhattan distance metric between two facilities, i and j. Only the on-land transportation costs are included in this study. The on-land distance is multiplied by the frequency of travel parameter, F_{ijt}, defined over several on-land transportation modes t, such as mixer trucks and forklifts, used to transport material between the facilities. Frequency parameters for different transport modes are merged together. This merge of travel frequencies is made possible since the formulation of Eq. (1) is summed over three indices, namely facilities i and j, and transport mode t. The summation over transport modes ensures that the individual matrices corresponding to each of the transport modes are combined into a global frequency matrix. The cost, C_t, of operating each of these transport

Table 1
Notation of Sets employed in this study.

Notation	Description
F_T	Set of all temporary facilities to be allocated a position on-site
F_P	Set of all permanent facilities with predefined positions on-site
$F: F_T \cup F_P$	Set of all facilities on site
L	Set of all available locations within which temporary facilities will be allocated
M	Set of all nonavailable locations, within which permanent facilities are allocated
$V = \{(i,m): \forall\ i \in F_P\ \exists!\ m \in M: \lambda_{im} = 1\}$	Mapping each permanent facility to its predefined location
C_m	Set of corners assigned to each location $m \in L \cup M$
R	Set of receivers located around construction site. These represent buildings surrounding the construction site at which noise levels are quantified.
N	Set of noise sources

Table 2
Notation of defined parameters.

Notation	Description
$LAeq_s$	Continuous equivalent sound pressure level, measured at 10 m from the source s
F_{ijt}	Frequency of travel by transportation mode t, from facility i to facility j
C_t	Cost of operating transportation equipment t
δ_{mn}	Binary parameter which equals one if two locations m and n are deemed to be far from one another, and zero otherwise.
λ_{im}	Binary parameter which equals one if facility i has a predefined location m assigned to it, and zero otherwise.
W	Width of construction site, in the horizontal x direction
B	Length of construction site, in the vertical y direction
Wf_i	Width of facility i in the x direction
Lf_i	Length of facility i in the y direction
$BCX^m{}_p$	x-coordinate of corner p at location m
$BCY^m{}_p$	y-coordinate of corner p at location m
$D^{mn}{}_{pq}$	Distance between corners p and q located at locations m and n respectively
CLX_m	x-coordinate of centroid of location m
CLY_m	y-coordinate of centroid of location m
WL_m	Width of location m in the horizontal x direction
LL_m	Length of location m in the vertical y direction
RLX_r	x-coordinate of receiver r
RLY_r	y-coordinate of receiver r
$f^x{}_r$	x-coordinate of furthest point on construction site measured with respect to receiver r
$f^y{}_r$	y-coordinate of furthest point on construction site measured with respect to receiver r
G	Sound reflection factor due to buildings surrounding construction site.

Table 3
Notation of continuous and binary variables.

Variable type	Notation	Description
Continuous	$d_{ij} \geq 0$	Distance between facility i and j, such that $i \neq j$.
	$d_{ij}^s \geq 0$	Distance between facilities i and j positioned at locations deemed close to one another, such that $i \neq j$.
	$d_{ij}^{mn} \geq 0$	Distance between facilities i and j positioned at locations deemed far from one another, such that $i \neq j$.
	$c_i^x \geq 0$	x-coordinate of centroid of facility i.
	$c_i^y \geq 0$	y-coordinate of centroid of facility i.
	L_{sir}	Equivalent continuous sound pressure level measured at receiver r, due to noise source s emitted from facility i.
	α_{ir}	Sound attenuation due to barrier effect for each facility i located away from receiver r.
	K_{ir}	Distance attenuation factor for each facility i located away from receiver r.
Binary	$\tau^{x1}{}_{ij} \in \{0, 1\}$	Equals one if $c^x{}_i$ is less than the left border of facility j, so that facilities at the same location do not impede vertical movements within that location (see Fig. 2a).
	$\tau^{x2}{}_{ij} \in \{0, 1\}$	Equals one if $c^x{}_i$ is greater than the right border of facility j, so that facilities at the same location do not impede vertical movements within that location (see Fig. 2b).
	$\tau^{y1}{}_{ij} \in \{0, 1\}$	Equals one if $c^y{}_i$ is less than the bottom border of facility j, so that facilities at the same location do not impede horizontal movements within that location (see Fig. 2c).
	$\tau^{y2}{}_{ij} \in \{0, 1\}$	Equals one if $c^y{}_i$ is greater than the top border of facility j, so that facilities at the same location do not impede horizontal movements within that location (see Fig. 2d).
	$\mu^x{}_{ij}$	Equals one if facility i and j do not overlap in the horizontal x direction.
	$\mu^y{}_{ij}$	Equals one if facility i and j do not overlap in the vertical y direction.

modes is applied to the objective function to produce a weighted frequency distance dollar measure of movements between facilities.

The available literature on the quantification of noise in construction sites focuses primarily on developing deterministic models to predict sound levels produced by the construction equipment, with some studies offering slight insight into the optimisation of sound attenuation barriers [13,49–52]. The general format of the noise level equation employed in this study (Eq. (2)) has been adopted from the Australian and British codes for noise control on construction and open sites [18,53], although some adjustments were made to the sound function (1) to include attenuations due to the barrier effect of the building activities/ facilities on site and (2) to allow the function to compute the noise levels at more than one receiver surrounding the construction site.

In the noise standards referred to in this article, the sound levels of equipment active during construction activities are measured in energy equivalent sound levels, L_{Aeq}, where the frequency response change due to noise intensity is taken into account [18,53]. To allow for the nonlinear frequency response of the ear to noise at different intensities, all values of sound levels are measured in A-weighted decibels [2].

The format of the noise objective function (Eq. (2)) is of the minimax form; this allows the model to optimise the locations of the facilities in order to minimise the maximum noise level measured at the multiple receivers positioned around the construction site. The receivers are taken to represent noise-sensitive buildings surrounding the site, such as hospitals, schools, libraries or even residence dwellings.

2.3.2. Model constraints

2.3.2.1. Distance constraints. The process of calculating the travel distances between facilities on a construction site was devised after extensive review of the available site layout literature and its exemplification of on-land movements. A major setback identified in previous studies is the overly simplified Euclidean or Manhattan distance metric used to estimate the length of travel routes. Specifically, obstacles and travel barriers are commonly ignored and thus the travel distances are not appropriately estimated [20,23,26,29,31,32,34,39,40,45,46,54–59]. To improve the travel distance estimation, Sanad et al. [25] assumed a single predetermined route on the construction site along which the Manhattan distance is used for measuring movement. In their approach, however, the Euclidean distance is adopted to get to the route between the individual facilities, which may again lead to inaccuracies in distance estimations if obstacles are present between facilities and the main predetermined route. The use of least cost path algorithms such as the A* algorithm and Dijkstra's algorithm to demarcate a collision-free path between two points on a construction site has also been applied, although application is usually limited to small scale cases, with the requirement of depicting the problem using graph theory [60,61].

To model a more realistic movement scenario, a proposal is made such that two separate measures are adopted that depend on the location of facilities with respect to each other. The transportation distance between the facilities is represented by the summation of the short Manhattan distances, d^s_{ij}, between facilities located at locations considered to be close to one another (i.e., adjacent), as deemed by the predefined binary parameter, δ_{mn}, and the long Manhattan distances, d^{mn}_{ij}, for facilities located in areas attributed to be far from one another [62]. These distances are translated through Eqs. (3)–(6) as follows:

$$d_{ij} = \sum_{m\in L}\sum_{n\in L} z_{im}\cdot z_{jn}\cdot d^s_{ij} \quad \forall i,j\in F: i\neq j,\ \delta_{mn}=0 \tag{3}$$

$$d_{ij} = \sum_{m\in L}\sum_{n\in L} z_{i,m}\cdot z_{j,n}\cdot d^{mn}_{ij} \quad \forall i,j\in F: i\neq j,\ \delta_{mn}=1 \tag{4}$$

$$d^s_{ij} = \left|c^x_i - c^x_j\right| + \left|c^y_i - c^y_j\right| \quad \forall i,j\in F: i\neq j \tag{5}$$

$$d^{mn}_{ij} = \min_{\substack{p\in C_m\\ q\in C_n}} \left\{\left|c^x_i - BCX^m_p\right| + \left|c^y_i - BCY^m_p\right| + \left|c^x_j - BCX^n_q\right| + \left|c^y_j - BCY^n_q\right| + D^{m,n}_{p,q}\right\} \quad \forall i,j\in F: i\neq j \ \ \forall m,n\in L: \delta_{mn}=1 \tag{6}$$

In particular, the long distance, defined by Eq. (6), is computed as the minimum over all available corner points, *p* and *q*, associated with each location, *m* and *n*, at which the facility is positioned. Each location is assumed to be linked to some specified corner points, where each of these points directs the flow of travel vertically up or down and/or horizontally right or left. Fig. 2 illustrates the mechanism behind splitting up the distances into d^s_{ij} and d^{mn}_{ij}. This mapping of facilities to corner points ensures that travel occurs along the edges of obstacles and not through the forbidden region in the middle. For the purpose of easing the process of solving the model, the distance constraints are linearised using common mathematical programming approaches [63].

2.3.2.2. Noise constraints. In order to compute effectively the noise levels produced by the facilities on the construction site, three noise constraints are implemented, which are all embedded in the noise objective function (Eq. (2)), and are presented as follows:

$$L_{sir} = LAeq_s - K_{ir} + G - \alpha_{ir} \quad \forall s\in N \ \ \forall i\in F \ \ \forall r\in R \tag{7}$$

$$\alpha_{ir} = 10\frac{\sqrt{\left(c^x_i - RLX_r\right)^2 + \left(c^y_i - RLY_r\right)^2}}{\sqrt{\left(f^x_r - RLX_r\right)^2 + \left(f^y_r - RLY_r\right)^2}} \quad \forall i\in F\ \forall r\in R \tag{8}$$

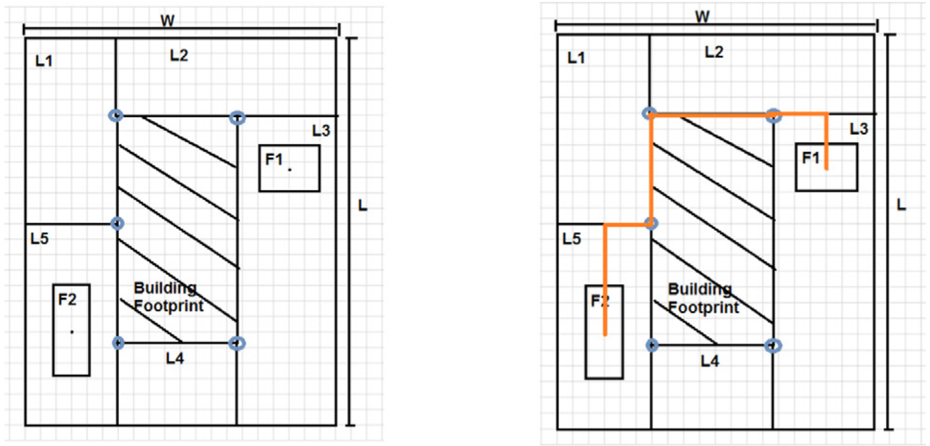
$$K_{ir} = 20\log_{10}\sqrt{\left(RLX_r - c^x_i\right)^2 + \left(RLY_r - c^y_i\right)^2} - 8 \quad \forall i\in F \ \ \forall r\in R \tag{9}$$

Eq. (7) computes the equivalent continuous sound pressure level of different noise sources, *s*, at different facilities, *i*, and with respect to different receivers, *r*. All sound attenuation factors, such as ground and barrier effects, and intensifications, mainly due to sound reflections from buildings adjacent to receivers, are incorporated in Eq. (7). The average sound attenuation factor due to the barrier effect of different facilities and other obstructions blocking the noise protruding from facility *i* and as is measured at receiver *r* is represented by α_{ir} in Eq. (8). This factor is computed as a fraction of the maximum barrier effect achievable, which is specified as 10 dB(A) in AS2436 and BS5228 [18,53]. Given that the SLP problem in this paper is modelled as a static one, as has been assumed in a number of studies in the literature, including Wong et al., Li and Love and Hammad et al. [46,58,64], an average attenuation value is computed to account for the overall duration of the project. Eq. (8) therefore ensures that the barrier effect of noise is highest when the facility is located furthest from the receiver. Eq. (9) represents the distance adjustment factor between the noise source, at facility *i*, and receiver *r*. The procedure followed to obtain noise estimates in the aforementioned standards is in line with findings presented in the report conducted by the Construction Industry Research and Information Association (CIRIA) [65]. Scientific quantifications behind many of the equations used for noise prediction and estimation are explained in further detail in [66].

2.3.2.3. Facility assignment constraints. To ensure that facilities are assigned to the available locations given, the following conditions, concerning the binary variable z_{im}, are set:

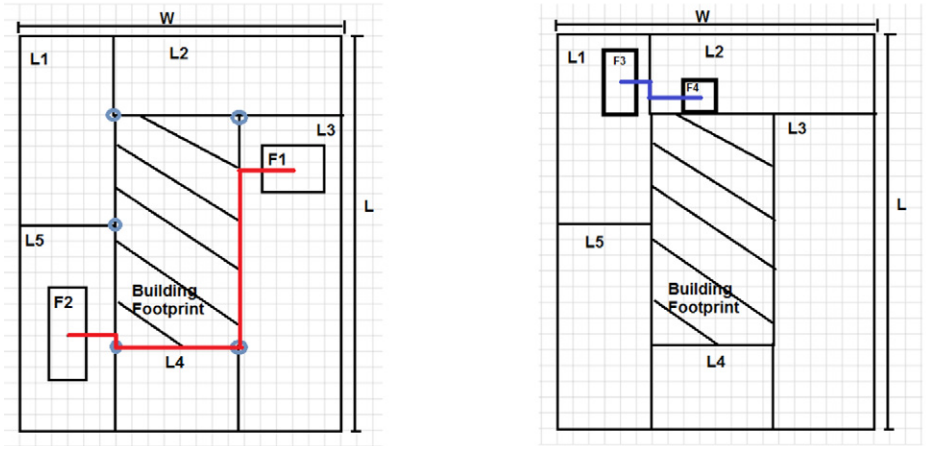
$$\sum_{m\in L} z_{im} = 1 \quad \forall i\in F_T \subseteq F \tag{10}$$

$$\sum_{i\in F_T} z_{im} \geq 1 \quad \forall m\in L \tag{11}$$



(a) Two corners associated with each location, highlighted by the blue circles

(b) A single scenario depicting d_{ij}^{mn}



(c) Another plausible scenario depicting d_{ij}^{mn}

(d) Route followed when d_{ij}^{s} is calculated

Fig. 2. Routes followed by d_{ij}^{s} and d_{ij}^{mn}.

$$z_{im} = 1 \quad \forall (i,m)\in V \qquad (12)$$

Eq. (10) ensures that each of the temporary facilities gets mapped onto a single available location. Eq. (11) defines the allocations within each location, where all available locations are required to accommodate more than one temporary facility. This warrants that the site does not become over-compacted, with the temporary facilities being required to be spread out amongst all the available locations, and not just confined to a particular area. Eq. (12) predefines the space occupied by the permanent facilities with which other facilities will be interacting.

2.3.2.4. Nonoverlap constraints. When two or more facilities are allocated to the same location, they have to be placed in such a manner so as to prevent overlaps. This constraint is applied using Eqs. (13)-(15):

$$\left|c_i^x - c_j^x\right| \geq 0.5\left(Wf_i + Wf_j\right)\cdot \mu_{ij}^x \quad \forall i,j\in F_T : i\neq j \qquad (13)$$

$$\left|c_i^y - c_j^y\right| \geq 0.5\left(Lf_i + Lf_j\right)\cdot \mu_{ij}^y \quad \forall i,j\in F_T : i\neq j \qquad (14)$$

$$1 + \mu_{ij}^x + \mu_{ij}^y \geq z_{jn} + z_{im} \quad \forall i,j\in F_T : i\neq j \forall m,n\in L : m = n \qquad (15)$$

When the binary variable, μ_{ij}^x, equals one, no overlap takes place between the facilities within the same location m in the horizontal x direction specified (Eq. (13)). The same is true for the case when μ_{ij}^y equals one, although this time no overlap occurs in the vertical y direction (Eq. (14)). At least one of these cases must hold for a feasible facility configuration to be obtained at any one location, as is given by Eq. (15). Cases addressed by these former equations are illustrated in Fig. 3.

2.3.2.5. Location boundary constraints. To prevent facilities from being positioned outside the specified borders of the available locations, Eqs. (16)–(19) are formulated:

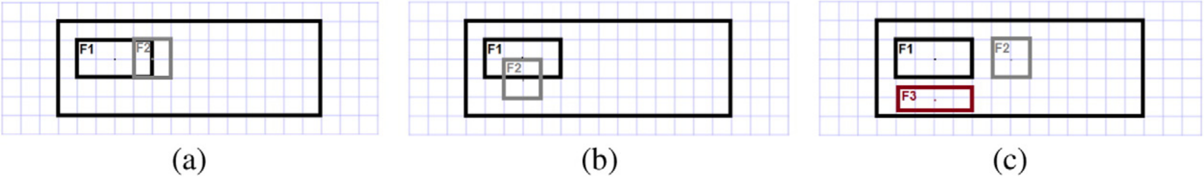
$$cx_i + (0.5Wf_i) \leq (CLX_m + 0.5WL_m)z_{im} + W(1 - z_{im}) \quad \forall i\in F \ \forall m\in L \qquad (16)$$

$$cx_i - (0.5Wf_i) \geq (CLX_m - 0.5WL_m)z_{im} \quad \forall i\in F \ \forall m\in L \qquad (17)$$

$$cy_i + (0.5Lf_i) \leq (CLY_m + 0.5LL_m)z_{im} + B(1 - z_{im}) \quad \forall i\in F \ \forall m\in L \qquad (18)$$

$$cy_i - (0.5Lf_i) \geq (CLY_m - 0.5LL_m)z_{im} \quad \forall i\in F \ \forall m\in L \qquad (19)$$

Eqs. (16) and (17) require that the width of the facility, Wf_i, does not exceed the width of the locations, WL_m, in the horizontal x direction. On



(a) (b) (c)

Fig. 3. Illustration of overlaps between temporary facilities positioned at the same location; (a) unpermitted horizontal overlap, (b) unpermitted vertical overlap, and (c) permitted configuration.

the other hand, Eqs. (18) and (19) ensure that the vertical length of the facility, Lf_i, is kept within the vertical boundaries of the assigned location. All the preceding constraints must hold for a feasible facility layout.

2.3.2.6. Travel interference constraints. To avoid travel interference, between facilities within a particular location, Eqs. (20)–(25) are implemented:

$$c_i^x \le c_j^x - 0.5Wf_j + W\left(1-\tau_{ij}^{x1}\right) \quad \forall i,j \in F_T : i \ne j \tag{20}$$

$$c_i^x \ge c_j^x + 0.5Wf_j - W\left(1-\tau_{ij}^{x2}\right) \quad \forall i,j \in F_T : i \ne j \tag{21}$$

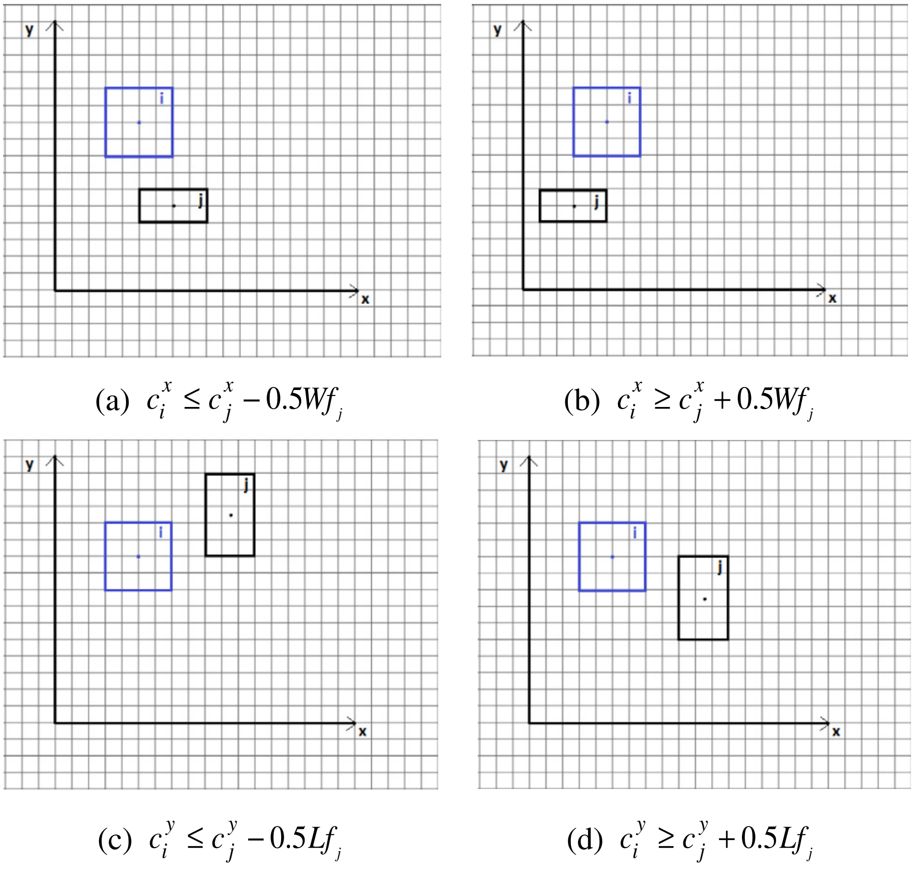
$$c_i^y \le c_j^y - 0.5Lf_j + B\left(1-\tau_{ij}^{y1}\right) \quad \forall i,j \in F_T : i \ne j \tag{22}$$

$$c_i^y \ge c_j^y + 0.5Lf_j - B\left(1-\tau_{ij}^{y2}\right) \quad \forall i,j \in F_T : i \ne j \tag{23}$$

$$1 + \tau_{ij}^{x1} + \tau_{ij}^{x2} \ge z_{im} + z_{jn} \quad \forall i,j \in F_T : i \ne j \quad \forall m,n \in L : m = n \tag{24}$$

$$1 + \tau_{ij}^{y1} + \tau_{ij}^{y2} \ge z_{im} + z_{jn} \quad \forall i,j \in F_T : i \ne j \quad \forall m,n \in L : m = n \tag{25}$$

When τ_{ij}^{x1} or τ_{ij}^{x2} equals one, Eq. (20) or Eq. (21) holds, respectively, and vertical travel between facilities is not impeded (Fig. 4a and b). When two facilities are located in the same location, at least one of these conditions must be met to ensure that materials can pass freely between facilities, and this is achieved through Eq. (24). Eqs. (22) and (23) are similar to Eqs. (20) and (21) but deal with movements in the horizontal direction (Fig. 4c and d). Eq. (25) effectuates one of Eqs. (22) or (23), whenever z_{im} and z_{jm} both equal one. In essence, the incorporation of the travel interference constraints ensures that facilities are not aligned in a crowded manner. A separation distance can also be implemented within Eqs. (20)–(23) such that a minimum value is specified for the distance separating two facilities.



(a) $c_i^x \le c_j^x - 0.5Wf_j$ (b) $c_i^x \ge c_j^x + 0.5Wf_j$

(c) $c_i^y \le c_j^y - 0.5Lf_j$ (d) $c_i^y \ge c_j^y + 0.5Lf_j$

Fig. 4. Travel noninterference constraints.

2.3.2.7. Domains of continuous variables. A definition of the domains of the continuous variables employed in the multi-objective model is presented through Eqs. (26)–(33):

$$0\le c_i^x\le W\ \ \forall i\in F \tag{26}$$

$$0\le c_i^y\le B\ \ \forall i\in F \tag{27}$$

$$d_{ij}\ge 0\ \ \forall i,j\in F: i\ne j \tag{28}$$

$$0\le d_{ij}^s\le W+B\ \ \forall i,j\in F: i\ne j \tag{29}$$

$$0\le d_{ij}^{mn}\le 3(W+B)\ \ \forall i,j\in F: i\ne j\ \ \forall m,n\in L:\delta_{mn}=1 \tag{30}$$

$$L_{\text{sir}}\ge 0\ \ \forall s\in N\ \ \forall i\in F\ \ \forall r\in R \tag{31}$$

$$0\le \alpha_{ir}\le 10\ \ \forall i\in F\ \ \forall r\in R \tag{32}$$

$$K_{ir}\ge 0\ \ \forall i\in F\ \ \forall r\in R \tag{33}$$

The centroids of the facilities in the *x* and *y* directions, cx_i and cy_i, are bounded by the width and length of the construction site, respectively. All distances and noise measures have to be greater than or equal to zero, as negative numbers are illogical.

2.3.3. ε-constraint method

To illustrate the effectiveness of the model proposed in this paper, a multi-objective analysis is carried out, whereby the two models are combined together. As discussed earlier, and portrayed in Fig. 1, the combination of the two models is done through the adaptation of the ε-constraint method. In its simplest form, this method reformulates the set of objective functions given so that one is optimised whilst the rest are executed as constraints [67]. Since in this paper only two objective functions are considered, the transformation of the multi-objective objective model into a single objective problem is as shown below:

$$\begin{array}{l}\min\left(f_1(\mathbf{x}),f_2(\mathbf{x})\right)\\ st\\ g_u(\mathbf{x})\le 0\quad \forall u=1\ldots k\\ \mathbf{x}\in X\end{array}\quad (34)\quad \xrightarrow{\qquad\qquad}\quad \begin{array}{l}\min f_1(\mathbf{x})\\ st\\ g_u(\mathbf{x})\le 0\quad \forall u=1\ldots k\\ f_2(\mathbf{x})\le z_2^*(1+\varepsilon)\ \ \forall\varepsilon=0\ldots\infty\\ \mathbf{x}\in X\end{array}\quad (35)$$

In Eqs. (34) and (35), $\mathbf{x}$ is a vector of decision variables belonging to the set of feasible solutions *X*, and z_2^* is the optimum solution of the objective function, $f_2(\mathbf{x})$, transformed into a constraint, satisfying all *k* other constraints, $g_u(\mathbf{x})$, specified for the two models. A stated range, within which nondominated solutions on the Pareto front are located, is initially obtained by solving each objective function separately. After obtaining the extreme points for each respective objective function on the Pareto frontier, the imposed restriction on $f_2(\mathbf{x})$ in Eq. (35) is relaxed gradually. This iterative procedure is continued up until the point of infinity is reached for the parameter ε, that is, when increasing ε results in the optimum solution z_1^*. This is similar to having a nonrestricted function as the constraint, where one of the objective functions is disregarded and the problem is solved through solely minimising the alternative function, $f_1(\mathbf{x})$. Overall, this method allows for other points on the Pareto front of efficient solutions to be found, aiding in the decision making process of the user.

3. Numerical application and results

The proposed model is verified on a hypothetical case study. The case study represents a shopping centre project, where the dimensions of the overall site are depicted in Fig. 5. The project is assumed to be carried out over a 3-year period. Seven temporary facilities (F1–F7) are to be allocated amongst all the available locations, and four permanent facilities (F8–F11), which act as entryways to the building under construction, are assumed to have a priori positions. The footprint of the building under construction is also considered to have a position determined a priori. The data for the parameters associated with the model are presented in Tables 4 to 11. Table 4 lists the dimensions of each temporary facility to be allocated on the construction site. Dimensions of each of the locations within the construction site are shown in Table 5, and a matrix of the binary parameter used to refer to the adjacency of each of the predetermined locations is tabulated in Table 6. Table 7 is a matrix of the predetermined access ways (permanent facilities) and their assigned locations. Table 8 represents the sound sources studied along with the facilities from which they are emanating. Three receivers (R1, R2 and R3) are assumed to be located in the vicinity of the construction site, as is annotated on Fig. 5. These receivers characterise noise-sensitive buildings. The aim is to reduce the maximum of sound levels perceived at any of these three points. Receiver R1 borders

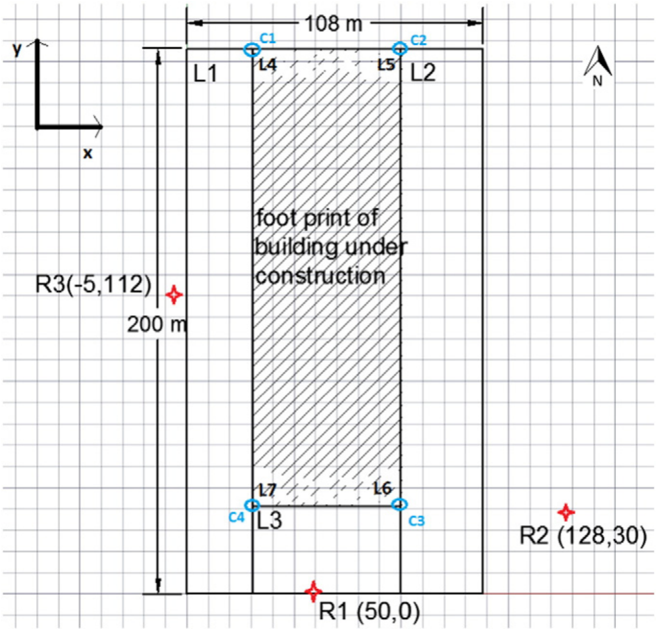


Fig. 5. Construction site of case study, representing a shopping centre.

Table 4
Temporary facilities and associated dimensions.

Facility	Symbol	Width in *x* direction (m)	Length in *y* direction (m)
Steel yard	F1	11	9
Formwork assembly	F2	11	9
Concrete batch plant	F3	11	9
False work	F4	11	9
Offices	F5	11	9
Warehouse/storage yard	F6	11	9
Generator room	F7	11	9

Table 5
Predefined locations and their corresponding dimensions.

Location	Width in *x* direction (m)	Length in *y* direction (m)
L1	24	200
L2	30	200
L3	54	32
L4	27	2
L5	27	2
L6	27	2
L7	27	2

Table 6
Matrix defining adjacency of locations on site.

Location *m*	Location *n*						
	L1	L2	L3	L4	L5	L6	L7
L1	0	1	0	0	1	1	0
L2	1	0	0	1	0	0	1
L3	0	0	0	1	1	0	0
L4	0	1	1	0	0	1	1
L5	1	0	1	0	0	1	1
L6	1	0	0	1	1	0	0
L7	0	1	0	1	1	0	0

Table 7
Matrix outlining the locations of permanent facilities.

Facility *i*	Location *m*			
	L4	L5	L6	L7
F8	1	0	0	0
F9	0	1	0	0
F10	0	0	1	0
F11	0	0	0	1

Table 8
Sound sources and corresponding facilities.

Sound source	Symbol	LA_{eq} @ 10 m (dB(A))	Associated facility
Gas cutter	S1	89	F1
Disc cutter	S2	84	F1
Club hammer	S3	79	F2, F4
Electric saw	S4	81	F2
Batching plant	S5	80	F3
Loading/unloading of scaffold poles	S6	72	F4
Air conditioner	S7	50	F5
Material hoist	S8	68	F6
Generator	S9	80	F7

the constructions site from the southern end, while the distances between receivers R2 and R3, and the nearest hoarding around the construction site are 28 m and 5 m, respectively.

Three on-land transportation modes (Tables 9–11) between the facilities are considered, namely, a CANTER 7C18 Dropside truck, with an operating cost of $27/km, a forklift truck, having an operating cost of $19/km and a cement mixer, operating at $35/km (all costs are in Australian Dollars) [68]. The transportation frequency matrices are considered to be symmetrical, so that traffic between *i* and *j* is the same as that between *j* and *i*.

The model represented by Eqs. (1)–(33) and Eq. (35) is solved using the SCIP solver. The nonconvex characteristics of our model are incorporated by the solver through linear relaxations, thus relying on tight bounds on the variables considered [48], and this is already reflected in the SLP problem where the locations are bounded by the boundaries of the construction site. Computations were implemented on a desktop computer running on Microsoft Windows 7 operating system, with Intel core i7 processor at 3.4 GHz and 16 GB of RAM. The case study presented in the paper considers two scenarios: (1) transport cost minimisation subject to noise propagation constraints and (2) noise minimisation subject to a transportation cost constraint. The time taken to reach to a solution point on the Pareto curve, where the noise objective function was integrated as a constraint in one instance, Fig. 6, and transport cost was used as a constraint in another instance, Fig. 7, ranged between 156 s and 4365 s.

Based on information inferred from the solver, the applied model has in total 63,631 variables, of which 17,691 are binary integer and 45,940 are continuous, with 81,535 individual constraints. The Pareto fronts of the multi-objective analysis carried out are shown in Figs. 6 and 7, where a line is fitted through the nondominated solutions to allow for interpolations. Two Pareto curves are plotted to illustrate the two scenarios considered. Fig. 6 depicts the outcome of the first scenario in which more influence is placed on optimising the transport cost (Eq. (1)) subject to constraints imposed on the noise function. Fig. 7 depicts the outcome of the second scenario in which a constraint is imposed on the transportation cost and the objective function optimised is the noise function (Eq. (2)). Scenario 1 could be a representative case where the main focus of the optimisation is on producing a least cost site layout configuration such that the noise limits are respected. If the greatest emphasis is on minimising noise pollution to improve social and environmental sustainability, then Pareto curve of Scenario 2, Fig. 7, can be utilised for the decision making process.

Diagrams depicting the front's two extreme point site configurations are also displayed in both aforementioned figures. For producing the layouts, a separating zone consisting of a square was used to prevent facilities from being cramped. This condition is specified such that the separating distance between two facility centroids is at least 1 m. The value was adopted for illustration purposes and other separation values can be assigned depending on how close the decision maker requires the facilities to be [33]. The constant was incorporated in Eqs. (20)–(23), as previously mentioned in the paper. All solutions

Table 9
Frequency of travel of forklift truck between facilities.

Facility *i*	Facility *j*										
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
F1	0	7000	200	4500	20	13,000	10	24,000	24,000	24,000	24,000
F2	7000	0	1000	2000	20	8900	10	14,000	14,000	14,000	14,000
F3	200	1000	0	30	20	10,000	10	50	50	50	50
F4	4500	2000	30	0	20	7500	10	11,000	11,000	11,000	11,000
F5	20	20	20	20	0	10	10	10	10	10	10
F6	13,000	8900	10,000	7500	10	0	10	9000	9000	9000	9000
F7	10	10	10	10	10	10	0	10	10	10	10
F8	24,000	14,000	50	11,000	10	9000	10	0	4000	4000	4000
F9	24,000	14,000	50	11,000	10	9000	10	4000	0	4000	4000
F10	24,000	14,000	50	11,000	10	9000	10	4000	4000	0	4000
F11	24,000	14,000	50	11,000	10	9000	10	4000	4000	4000	0

Table 10
Frequency of travel of Dropside truck between facilities.

Facility *i*	Facility *j*										
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
F1	0	40,200	300	20,000	10	33,000	10	6000	6000	6000	6000
F2	40,200	0	370	23,000	10	26,700	10	4700	4700	4700	4700
F3	300	370	0	50	10	30,000	10	75	75	75	75
F4	20,000	23,000	50	0	10	18,000	10	3500	3500	3500	3500
F5	10	10	10	10	0	10	10	10	10	10	10
F6	33,000	26,700	30,000	18,000	10	0	10	900	900	900	900
F7	10	10	10	10	10	10	0	10	10	10	10
F8	6000	4700	75	3500	10	900	10	0	250	250	250
F9	6000	4700	75	3500	10	900	10	250	0	250	250
F10	6000	4700	75	3500	10	900	10	250	250	0	250
F11	6000	4700	75	3500	10	900	10	250	250	250	0

Table 11
Frequency of travel of cement mixer truck between facilities.

Facility *i*	Facility *j*										
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
F1	0	10	10	10	10	10	10	10	10	10	10
F2	10	0	10	10	10	10	10	10	10	10	10
F3	10	10	0	0	10	10	0	3800	3800	3800	3800
F4	10	10	0	0	10	10	10	10	10	10	10
F5	10	10	10	10	0	10	10	10	10	10	10
F6	10	10	10	10	10	0	10	10	10	10	10
F7	10	10	0	10	10	10	0	10	10	10	10
F8	10	10	3800	10	10	10	10	0	10	10	10
F9	10	10	3800	10	10	10	10	10	0	10	10
F10	10	10	3800	10	10	10	10	10	10	0	10
F11	10	10	3800	10	10	10	10	10	10	10	0

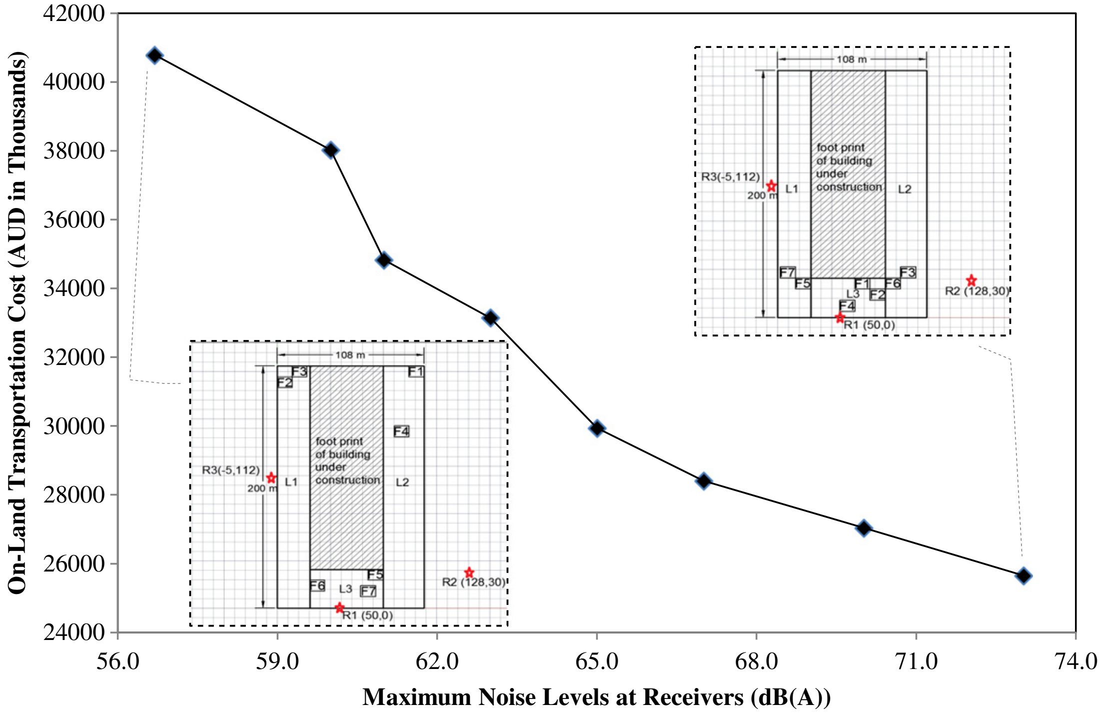


Fig. 6. Pareto front with cuts generated using noise as a constraint, Scenario 1.

acquired from SCIP, and plotted to form the efficient frontier, are the global optimum ones, as declared by the terminating status of the solver.

In the right insert of Fig. 6 is the resulting site layout for the minimal on-land transportation cost; at this particular point, prominence is placed on producing the lowest transportation cost possible; hence, facilities are placed as close to one another, and to the corresponding corners associated with each location, as is permitted by the model constraints. Fig. 6, left insert, shows the optimal configuration of the facilities solved for the noise objective function by itself. The facilities are located in such a manner as to reduce the maximum noise disturbance measured at all receivers, and so ensuring that minimal noise levels are quantified at the worst-affected noise-sensitive thresholds. Both inserts are also depicted in Fig. 7, although their positions are now reversed; the minimum site layout configuration is on the left side whilst the minimum noise configuration is now on the right.

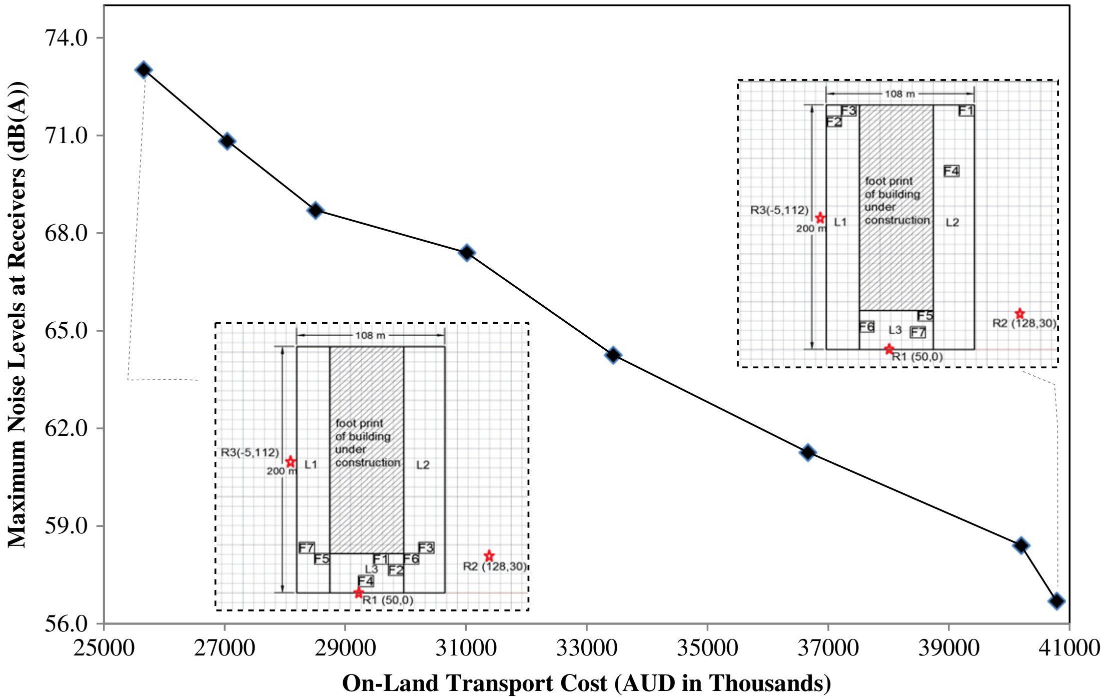


Fig. 7. Pareto front with cuts generated using transport cost as a constraint, Scenario 2.

Other points on the efficient frontier are then acquired using Eq. (35). In total, 8 points are plotted, and all of these form a curve with an incremental declining negative slope. None of the points on the front dominate one another, in the sense that there is never a solution on the efficient frontier that improves one of the objective functions without adversely affecting the other. As is displayed in Figs. 6 and 7, for the case project considered, the difference between the maximum and minimum transportation costs plotted on the Pareto curves is measured to be at around 37%. Looking at the frontier of Scenario 1, the greatest increase in cost takes place between 65 and 63 dB(A), which is measured to be around 10.7%, rendering such a shift the costliest noise reduction produced between any two sound level ranges outlined on the graph. For a hospital, where the maximum allowable sound level permitted is established at 70 dB(A) [69], a drop in the sound level from 73.1 dB(A) (extreme noise level obtained for case study) to the former set limit can be achieved for an increase in transportation cost of 5.4%, as derived from Figs. 6 and 7. In order to get a configuration with the minimal on-land transport cost, measured at a value of $25,659, it is necessary to accept a site layout generating the maximum amount of sound (73.1 dB(A)), hence forgoing a 29% improvement rate in noise levels, when compared to the site layout producing the least noise, measured at 56.7 dB(A). It is important to note that both Pareto curves of Figs. 6 and 7 have the same extreme points and hence the previous analysis applies to both Figures. For this case study, a site layout with the minimum noise level results in the maximum transportation cost, and vice versa. This result will vary depending on the locations of receivers. The major finding that the results underline however is the ample series of noise reduction levels that can be achieved through merely altering the layout of temporary facilities on the construction site.

A major reason for the inverse relationship between noise and transport cost, observed in the above illustrative case, could be related to the overall available solutions that the solver is permitted to choose from. Whenever the noise level or transportation cost is constrained, through limiting the maximum combined sound level measured at any of the receivers or through setting a certain maximum budget for producing the site layout, respectively, it may be difficult to achieve a feasible solution, thus resulting in a low chance of obtaining a site layout having the minimum on-land transportation cost or minimum noise levels, respectively. As the sound level requirement or the monetary budget is slowly relaxed, more feasible solutions appear, and therefore the chance of having one of these feasible solutions coinciding with lower on-site transportation costs or lower noise levels respectively, increases. When the noise objective function or the transport cost function is ignored, the solver has one primary aim, which is to produce a configuration that corresponds to the minimum transport cost or minimum noise level, respectively. Hence, at this stage, the solution that will be derived is the one that results in the highest sound level or largest site layout cost, respectively.

The results presented in this study clearly highlight the significance of considering a multi-objective approach when it comes to planning the layout of the construction site, as consideration of one objective function without the other may have a reverse effect on the neglected objective function. The Pareto curves of Figs. 6 and 7 also draw attention to the fact that optimising the site for minimum transportation cost may not lead to the best layout, when considering other sustainability indicators such as pollution. In such situations, a balanced approach should be taken by the decision maker when deciding on an optimal layout configuration for conflicting objective functions. The Pareto front can serve as valuable input to the decision making process for site planning.

It is important to point out that, in the above-mentioned case study, the total noise level measured at the receivers was evaluated by examining sound emitted from within the facilities only. Other sound producing equipment, such as bulldozers, tractors, etc., which may be operating outside a demarcated zone, have not been accounted for in our model. This is due to the fact that it is difficult to pinpoint the exact locations of mobile machinery at a given point in time. Such noise levels may be significant and an average value could be devised for incorporation in the site layout planning process. Additionally, for a more realistic scenario, the model presented in this study should integrate a work schedule, to accommodate the dynamic nature of the construction process. The model could also be extended for use in other layout planning problems, where minimising noise may be deemed as an essential requirement. This may include areas such as designing the layout of industrial manufacturing facilities and warehouses in highly populated zones and within close proximity to noise-sensitive receivers, along with other larger scale urban design problems. Applications to such larger cases may however require the use of meta-heuristic approaches.

4. Conclusion

A multi-objective MINLP site layout model, aimed at minimising both construction noises, at multiple receivers in the vicinity of the construction site, and on-land transportation costs was presented. A novel noise objective function and an improved transportation objective function were optimised. The transportation cost objective function takes into account travel impedance due to route blockage caused by other allocated facilities/obstacles. This is expected to result in a more realistic modelling of on-land movements between facilities, compared to previously proposed models that rely mainly on simplified Euclidean or Manhattan distances. The overall model presented was reformulated and linearised to ease the process of obtaining a global optimal solution. This is particularly crucial, given the nonconvex nature of the model due to the presence of integer variables.

The ε-constraint method was applied to group together the two sustainability objective functions established, with cuts performed on the noise objective function in one instance, and on the transport cost objective function in another instance, when solving for the Pareto front. The suggested multi-objective model relies on the definition of several decision variables including the centroids of facilities to be allocated and the noise attenuation value to be assigned to each facility, based on the relative positions of these facilities with respect to the receivers. To overcome the nonoptimality of solutions gleaned from meta-heuristics reliance was placed on using exact methods to solve the model. The model was tested on a case study to accentuate the effectiveness of the proposed objective functions and constraints and to cast their strengths, in terms of finding appropriate site layout configurations that satisfy all constraints. The work presented in this paper can be further improved by considering the dynamic nature of the construction process. Applications can also be extended to encompass areas such as industrial and urban planning, by developing heuristic algorithms to solve the proposed model.

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