A mixed-integer nonlinear programming model for minimising construction site noise levels through site layout optimisation

A.W.A. Hammad[a], D. Rey[a] and A. Akbarnezhad[a]

[a]School of Civil and Environmental Engineering, University of New South Wales, Australia
E-mail: a.hammad@unsw.edu.au, d.rey@ unsw.edu.au, a.akbarnezhad@ unsw.edu.au

Abstract –

Activities undertaken on a construction site are often accompanied with high levels of noise. Addressing the issue of noise pollution in construction is gaining significance with the growing awareness about the social and environmental components of sustainable construction and the increasing numbers of projects being undertaken in congested urban areas. The documented methods for reducing noise pollution in construction include controlling (1) the noise produced at the source; (2) noise levels reaching a receptor; (3) noise propagated along the transmission path. Methods addressing the latter points use the fact that attenuation of noise increases as the transmission path gets longer. Thus the efficiency of such methods can be improved considerably through optimising the arrangement of temporary facilities on construction sites, with respect to a receptor, making use of noise attenuation due to distancing noisy facilities away from noise-sensitive receivers. The building under construction can also be used as a barrier to the noise transmission path, where obstruction of particular facilities from a given receiver can help in producing lower levels of sound as measured at the receptor. The available literature on site layout planning is extensive but limited to only achieving traditional construction project objectives (travel and material handling cost, safety, etc.). This paper presents a mixed integer non-linear programming (MINLP) model that optimises the location of temporary facilities on site in order to minimise the sound levels measured at a pre-defined receptor. The present model is expressed in three stages: (1) defining the noise objective function; (2) implementing model constraints; and (3) application of COUENNE to solve the MINLP for a case study.

Keywords – construction site layout; mixed integer nonlinear programming; MINLP; optimisation; construction noise estimation; sustainability

1 Introduction and Literature review

Minimising the pollution caused by construction activities, in all its categories, is an important aspect of sustainable construction. Pollution on a construction site occurs when contamination or harm at any level is caused to the surrounding communities [1]. In particular, construction activities are renowned for the high levels of noise that they produce. Hence, the reduction of sound produced on a construction site happens to be an important objective in sustainable construction.

Construction noise will most often cause a nuisance to the residents surrounding the construction site. The response of a human to a particular sound depends on how the ear perceives that sound, since the frequency response of the ear varies with sound intensity. At low intensities the ear's response to a change in frequency of the sound is more varied compared to the almost flat response made for high intensity sounds. To take into account this variation in the reaction of the ear, the A-weighted frequency response curve is adopted, where sound level measurements are quoted in dB (A) (A-weighted decibels). The A-weighted frequency response curve ensures that sound measurements are made with one frequency response that reacts well to sound at any frequency or intensity [2].

The impacts arising from noise pollution can be categorised into two main streams, namely occupational, which is concerned with the health hazards faced by on-site workers, and environmental, where the people and wildlife neighbouring the noise source are targeted [2]. Thus, noise, propagated from a construction site surrounding different communities, may lead to a disturbance in several ways. For example, manufacturing industries relying on precise measuring equipment could potentially be disrupted when exposed to high levels of sound [3]. Productivity of employees in buildings adjacent to noisy highways has been reported to be adversely affected [4]. Belojević et al. [5] conducted a study to determine the impacts noise levels had on the cognitive functioning of 45 subjects. Results indicated that subjects exposed to high sound levels had their mental capabilities lowered. A number of studies have reported findings on disruptions to both patients and health care workers caused by high sound levels initiated within a hospital. High levels of noise around hospitals, where quiet operation theatres and accurate medical equipment are vital, may have a detrimental impact on the health of hospital administered patients [6]. Morrison et al. [7] reported in their study that data analysed statistically indicated a high correlation between above-average noise levels within a hospital setting and an increase in the level of stress experienced by nurses. The authors concluded that this could lead to the possibility of medical errors being committed by healthcare workers.

Though the regulatory authorities in most developed countries have set out criteria to control the levels of noise produced by construction activities, the laws and regulations yet remain vague when addressing the issue [8]. In Australia the rules set out are usually controlled by the relevant councils within which the construction work is being undertaken. The main focus of the regulations set out by the councils is on 1) restricting working hours of machinery on construction sites between a specified time frame; and 2) setting out criteria that noise levels not exceed background levels by 5 dB(A) and 10dB(A), during the first working hour and during other working hours, respectively [9], [10]. Standards aimed at addressing noise level reduction and measurements primarily deal with the effect noise has on workers and machine operators on site [11], [12]. Nevertheless these standards can be adopted to address noise pollution subjected at the environment surrounding the construction site.

Several studies in the literature have investigated the methods applicable for controlling sound levels produced by construction equipment. Suter [13] presented a number of techniques aimed at attenuating sound levels affecting the on-site workers. The author discussed the use of electronic ear muffs that adjust noise levels across a given frequency range. The author also discoursed that a cheap and conventional way of attaining noise reductions for construction equipment was through proper maintenance of the equipment. Schneider et al. [14] included in their study the application of retrofits in construction equipment as a procedure for direct noise level reductions at the noise source**.** Schneider et al. [15] also advocated the use of retrofits on heavy equipment for achieving substantial noise level reductions. Along with the methods presented above, Standards Australia [11] details the use of barriers on construction sites to control noise levels. Attenuation is achieved either through the use of acoustic screens layered with noise absorbent materials, such as chipboard or compressed straw, which enclose the machinery under use, or through creating physical barriers, by piling up construction materials available throughout the different construction phases, to obscure a particular receiving point from the emitting noise source.

However, while considerable literature exists on estimating construction sound levels, reducing noise levels of equipment and identifying the health hazards caused by construction noise pollution, little effort has been made to investigate how construction planning affects noise pollution. An important factor affecting sound levels on a construction site is the adopted layout of the site. The level of noise experienced by a receiver located within a construction site or on the outskirts of the site will vary depending on the noise control mechanism executed on site. As discussed above, these mechanisms can be applied at the noise source, between the noise source and the receiver or at the receiving point itself.

The available literature on site layout focus mainly on optimising the locations of temporary facilities through addressing objectives such as travel cost, material handling cost, safety breaches and wildlife preservation [16]–[21]. Literature addressing noise levels on construction sites mostly emphasise the quantification of the sound levels produced. Gannoruwa and Ruwanpura [22] used simulation and a stochastic model to predict noise levels at receivers, subject to the construction stage specified by the user. Their work focussed on altering noise levels along the transmission paths by optimising sizes of barriers to be placed in obstruction to the noise path. Li [23] presented a computer system capable of calculating noise levels produced by different categories of construction equipment, with a strong emphasis on taking into account attenuation due to weather and ground conditions of the construction site. These two factors were argued to cause disturbance to the accuracy of noise levels predicted at the receiver whenever the distance of the source from the receiver exceeded 100 m. Zaiton Haron and Khairulzan Yahya [24] used Monte Carlo methods in order to predict the noise levels from equipment on a construction site. Simulation was run to collect data and the probability density functions (PDF) and cumulative distribution functions (CDF) of noise levels based on the samples obtained were plotted. The overall mean of noise levels was acquired by combining the PDFs from the multiple noise sources. The results were compared to those derived using the methodology outlined in BS 5228 [12]. Gilchrist et al. [3] implemented Monte Carlo simulation to predict noise mitigation in urban environments. Their method relied on specifying a value to represent the probability of each operating state of the equipment in use (i.e. Idle, working, and not operating). Maximum noise levels, produced by their deterministic model, were obtained from the statistical data of the simulation run. The results were validated against on –site measurements taken around a hospital surrounding the construction site.

A diverse range of equipment, including heavy equipment such as pile drivers and excavators, as well as the smaller and more frequently used equipment like saw chains, hammers, electric drills, concrete mixers and vibrators and steel benders and cutters, is employed on construction sites, each with a different size, different operating durations and different levels of generated sound. The latter group of equipment are usually stationed in temporary facilities such as steel bending yards, formwork assembly yards and concrete batching areas. These facilities can be positioned on site in a certain way as to reduce the overall noise levels reaching low-tolerance limit receivers. This is especially important if the construction site happens to be in the vicinity of noise-sensitive receptors such as hospitals, schools, etc. To the best of our knowledge, there has been no effort on optimising the construction site layout to minimise noise pollution caused by construction activities.

This paper presents a novel mathematical optimisation model for site layout planning, where the objective function is minimised to reduce noise levels on construction sites. The proposed optimisation model will be applied to and solved for an illustrative case project. The problem is formulated as a mixed integer nonlinear programme (MINLP) on General Algebraic Modelling System (GAMS) and will be solved using COUENNE, a solver originally developed at Carnegie Mellon University and IBM Research [25] .While this paper's main focus is on applying the proposed optimisation model to construction site layout planning, the model can be extended to areas such as industrial and urban planning, where sound level reduction is critical. To achieve a more realistic optimisation model, the noise objective function should also be considered along with a cost objective function, rendering the problem a multi-objective one. The latter is currently the subject of future study by the authors.

2 Construction site layout model

BS 5228 and AS 2643 present a method for estimating noise levels produced on site [11], [12]. The general format of the objective function that will be used in this section has been obtained from these standards; nevertheless some modifications were made in order to reflect the changes that happen over time during construction projects.

2.1 Notation

This section lists the index notations, scalars, parameters and variables defined in the model.

2.1.1 Sets and indices

F : set of facilities to be located, indexed by f and j .

L : set of predetermined locations on the construction site, indexed by l .

ns : Noise source within a temporary facility on construction site

b : Insulation material type

$e = (ns, f)$: Tuple to map each noise source, ns , to a facility f

s : Slab on grade (SOG) (includes ground preparation and excavation stages)

c : 1st floor columns

completion : Project completion

2.1.2 Scalars

W : Width of construction site in x- direction.

B : Length of construction site in y-direction.

Refl : Reflection effect, on noise levels measured at the receiver, due to buildings surrounding the receiving point, equal to 3 dB (A).

RLX: X-coordinate of receiver point, located around construction site.

RLY: Y-coordinate of receiver point, located around construction site.

ε : Very small positive value, equal to 5e-5.

M^A : Maximum attenuation due to barrier effect, equal to 10 dB (A), as specified in BS 5228.

T : Noise Assessment period, measured as working hours on construction site per day.

TPD: Total project duration, in months.

2.1.3 Parameters

$LAeq_{ns}$: Continuous equivalent sound pressure level, measured at 10 m from the source, obtained from BS 5228.

t_e : Time duration, over assessment period T , where noise source ns , defined over tuple e , is on.

γ^c : X-coordinate of border of building under construction, closest to receiver point.

γ^d : X-coordinate of border of building under construction, furthest away from receiver point.

CLX_l: X-coordinate of centroid of each location l on site.

CLY_l: Y-coordinate of centroid of each location l on site.

Wf_f: Width of facility f in x-direction.

Lf_f : Length of facility f in y-direction.

WL_l: Width of location l in x-direction.

LL_l: Length of location l in y-direction.

vb_f: Binary parameter set by user to equal one if noise reduction method type b is implemented at facility f, and zero otherwise.

θ_b : Value of noise reduction, measured in dB (A) obtained due to noise reduction method type b .

p_u : Point of time in the construction schedule, in months, at which milestone u is achieved.

2.1.4 Continuous and discrete Variables

cx_f: X-coordinate of centroid of facility f .

cy_f: Y-coordinate of centroid of facility f .

R_f: Euclidean distance between facility f and receiver point.

Kh_f: Distance adjustment factor for each noise source assumed to be located at the centroid of facility f .

$Attsc_f$: Average attenuation, as measured over the whole duration of the project, due to screening effect of building under construction. This variable can take on one of three values, depending on the projected construction stage and on the location of the facility from which noise is emitted.

L_e : equivalent continuous sound pressure level over tuple $e = (ns, f)$, measured in dB (A).

$DBCSLX_{f,j}$: The absolute value of the distance between centroids of facilities f and j in the x-direction.

$DBCSLY_{f,j}$: The absolute value of the distance between centroids of facilities f and j in the y-direction.

2.1.5 Binary Variables

$z_{f,l}$: Equals one if facility f is located at location l .

$\mu x_{f,j}$: Equals one if facilities f and j do not overlap in the x-direction.

$\mu y_{f,j}$: Equals one if facilities f and j do not overlap in the y-direction.

$\delta\gamma_f^c$: Equals one if cx_f is located at a coordinate greater than γ^c in the x-direction, and zero otherwise.

$\delta\gamma_f^d$: Equals one if cx_f is located at a coordinate less than γ^d in the x-direction, and zero otherwise.

$\varphi_{n,f}$: Equals one if attenuation $Attsc_f$ over construction stage n for facility f applies, and zero otherwise.

2.2 Noise objective function formulation and constraints

2.2.1 Objective function

$$\textit{Minimise} \quad 10\log_{10}\left(\frac{1}{T}\sum_e t_e 10^{\frac{L_e}{10}}\right) \tag{1}$$

Where,

$$e = (ns, f) \tag{2}$$

$$L_e = LAeq_{ns} - Kh_f + Refl - \sum_n \varphi_{n,f} Attsc_f - \sum_f \sum_b vb_f \theta_b \tag{3}$$

$$Kh_f = 20\log_{10}(\mathrm{R}_f) - 8 \tag{4}$$

$$R_f = \sqrt{(RLX - cx_f)^2 + (RLY - cy_f)^2} \tag{5}$$

Objective function (1) is the noise level equation for various activities taking place within each of the temporary facilities during the assessment period *T,* and it incorporates equations (3), (4) and (5). It gives the combined equivalent A-weighted sound pressure level for all noise sources included in the summation operator. The summation operator functions over the tuple described by equation (2), as this maps each given noise source to a particular temporary facility. Equations (3) calculate the individual continuous A-weighted sound pressure for each noise source and associated facility in tuple *e,* taking into account all factors and attenuations altering the sound levels. Equations (4) calculate the distance allowance factors for each facility, assuming the noise sources at a particular facility are located at the centroid of that facility. Equations (5) calculate the Euclidean distance between the receiver point and the centroids of the temporary facilities.

2.2.2 Facility-Location Constraints

$$\sum_{l} z_{f,l} = 1 \qquad \forall f = 1, \ldots F \tag{6}$$

$$\sum_{f} z_{f,l} \geq 1 \qquad \forall l = 1, \ldots L \tag{7}$$

$$z_{f,l} = 0 \qquad for\ l = P \tag{8}$$

Where P represents the location of the permanent building under construction

Constraints (6) ensure that one location is assigned to each facility. Constraints (7) ensure that each pre-defined location contains at least one facility. This is to try to spread out the allocation of facilities within the pre-defined locations, hence making use of all the available locations. Constraint (8) is for excluding the building construction area from being used for temporary facility assignments.

2.2.3 Facility non-overlap constraints

$$DBCSLX_{f,j} = |cx_f - cx_j| \quad \forall f = 1, \ldots F \quad \forall j = 1, \ldots F \quad f \neq j \tag{9}$$

$$DBCSLY_{f,j} = |cy_f - cy_j| \quad \forall f = 1, \ldots F \quad \forall j = 1, \ldots F \quad f \neq j \tag{10}$$

$$DBCSLX_{f,j} \geq 0.5(WF_f + WF_j)(\mu x_{f,j}), \ \forall f = 1, \ldots F \ \forall j = 1, \ldots F \ f \neq j \tag{11}$$

$$DBCSLY_{f,j} \geq 0.5(LF_f + LF_j)(\mu y_{f,j}), \ \forall f = 1, \ldots F \ \forall j = 1, \ldots F \ f \neq j \tag{12}$$

$$(1 - z_{f,l}) + (1 - z_{j,l}) + \mu x_{f,j} + \mu y_{f,j} \geq 1 \ \forall l = 1, .. L \ \forall f = 1, .. F \ \forall j = 1, .. F \ f \neq j \tag{13}$$

$$\mu x_{f,j} + \mu y_{f,j} \geq 1, \quad \forall f = 1, \ldots F - 1 \quad \forall j = 1, \ldots F \quad f \neq j \tag{14}$$

Constraints (9)-(14) ensure that two facilities located at the same location do not overlap. In particular, constraints (9) and (10) are to prevent negative distances in the x and y directions, respectively. Constraints (11), (12), (13) and (14) prevent the facilities from overlapping in the x- direction and y-direction at the same time.

2.2.4 Location boundary constraints

$$cx_f + (0.5Wf_f) \leq \left(CLX_l + (0.5WL_l)\right) z_{f,l} + \mathrm{W}(1 - z_{f,l}) \ \forall f = 1, .., F \ \forall l = 1, \ldots L \tag{15}$$

$$cx_f - (0.5Wf_f) \geq \left(CLX_l - (0.5WL_l)\right) z_{f,l} \quad \forall f = 1, \ldots, F \quad \forall l = 1, \ldots L \tag{16}$$

$$cy_f + (0.5Lf_f) \leq \left(CLY_l + (0.5LL_l)\right) z_{f,l} + \mathrm{B}(1 - z_{f,l}) \quad \forall f = 1, \ldots, F \quad \forall l = 1, \ldots L \tag{17}$$

$$cy_f - (0.5Lf_f) \geq \left(CLY_l - (0.5LL_l)\right) z_{f,l} \quad \forall f = 1, \ldots, F \quad \forall l = 1, \ldots L \tag{18}$$

Constraints (15), (16), (17) and (18) ensure that the facilities are located within the boundaries of the locations to which they have been assigned, as determined by the binary variable $z_{f,l}$.

2.2.5 Constraints for defining $Attsc_f$

$$\delta\gamma_f^c + \varphi_{1,f} \geq 1 \quad \forall f = 1, \ldots F \tag{19}$$

$$Attsc_f \geq 0 \quad \forall f = 1, \ldots F \tag{20}$$

$$Attsc_f \leq M^A (1 - \varphi_{1,f}) \quad \forall f = 1, \ldots F \tag{21}$$

$$cx_f \geq (\gamma^c + \varepsilon)(1 - \delta\gamma_f^c) \quad \forall f = 1, \ldots F \tag{22}$$

$$\delta\gamma_f^d + \varphi_{2,f} + (1 - \delta\gamma_f^c) \geq 1 \quad \forall f = 1, \ldots F \tag{23}$$

$$Attsc_f \geq \left(5\left(\sum_{s+1}^{completion} \frac{p_n}{TPD}\right)\right)\varphi_{2,f} \quad \forall f = 1, \ldots F \tag{24}$$

$$Attsc_f \leq \left(5\left(\sum_{s+1}^{completion} \frac{p_n}{TPD}\right)\right)\varphi_{2,f} + M^A (1 - \varphi_{2,f}) \quad \forall f = 1, \ldots F \tag{25}$$

$$cx_f \geq (\gamma^d + \varepsilon)(1 - \delta\gamma_f^d) \quad \forall f = 1, \ldots F \tag{26}$$

$$cx_f \leq (\gamma^c)(\delta\gamma_f^c) + \mathrm{W}(1 - \delta\gamma_f^c) \quad \forall f = 1, \ldots F \tag{27}$$

$$\delta\gamma_f^d \leq \varphi_{3,f} \quad \forall f = 1, \ldots F \tag{28}$$

$$Attsc_f \geq \left(5\left(\sum_{s+1}^{c} \frac{p_u}{TPD}\right) + 10\left(\sum_{c+1}^{completion} \frac{p_u}{TPD}\right)\right)\varphi_{3,f} \quad \forall f = 1, \ldots F \tag{29}$$

$$Attsc_f \leq \left(5\left(\sum_{s+1}^{c} \frac{p_u}{TPD}\right) + 10\left(\sum_{c+1}^{completion} \frac{p_u}{TPD}\right)\right)\varphi_{3,f} + M^A (1 - \varphi_{3,f}) \quad \forall f = 1, \ldots F \tag{30}$$

$$cx_f \leq (\gamma^d)(\delta\gamma_f^d) + \mathrm{W}(1 - \delta\gamma_f^d) \quad \forall f = 1, \ldots F \tag{31}$$

$$\varphi_{1,f} + \varphi_{2,f} + \varphi_{3,f} = 1 \quad \forall f = 1, \ldots F \tag{32}$$

Constraints (19), (20), (21) and (22), are to ensure that if the distance between the receiver and cx_f is less than the distance between the receiver and γ^c then $Attsc_f$ will equal zero. Facilities positioned at such locations are close to the receiver point, and so no attenuation of noise due to the building under construction occurs.

Constraints (23), (24), (25), (26) and (27) are to ensure that if $cx_f \le \gamma^c$ and $cx_f > \gamma^d$, then the overall $Attsc_f$ will equal $5\left(\sum_{s+1}^{completion}\frac{p_n}{TPD}\right)$, broken down as follows: 1) zero for the stages in construction preceding the casting of the SOG; and 2). $5\left[\frac{p_{s+1}+\ldots+p_{completion}}{TPD}\right]$, after the casting of the SOG occurs, until the completion point of the project. Facilities located within the aforementioned boundaries tend not to be fully obscured by the building. Hence, the 5 in the latter equation represents the value of partial blockage of noise from a given source, as noted in BS 5228 [12].

Constraints (28), (29), (30) and (31) ensure that for facilities where the distance between the receiver and γ^d is less than the distance between the receiver and cx_f, then their corresponding $Attsc_f$ will equal $5\left(\sum_{s+1}^{c}\frac{p_u}{TPD}\right)+10\left(\sum_{c+1}^{completion}\frac{p_u}{TPD}\right)$, broken down as follows: 1) zero for the period up until the SOG is casted; 2). $5\left[\frac{p_{s+1}+\ldots+p_c}{TPD}\right]$ after the casting of the SOG occurs and up until the first floor columns are casted; 3). $10\left[\frac{p_{c+1}+\ldots+p_{completion}}{TPD}\right]$ after the first floor columns are casted up until completion of the building. In such case partial blockage of noise due to the building under construction happens only the in the stages preceding the casting of the first floor columns. Once the first floor columns are casted, full blockage is assumed; hence the value of 10 is used for the later stages in the project. Facilities governed by constraints (28), (29), (30) and (31) are the ones located furthest apart from the receiver point.

It is assumed in this model that $Attsc_f$ takes on one of three values. Therefore constraints (32) ensure that $Attsc_f$ is equal to a single value for each facility f.

3 Application and numerical results

The model developed in this study was tested using a case project. The case study is a hypothetical project involving the construction of a multi-storey building. Values for the L_{Aeq} sound levels, measured in dB(A) at 10 m from the source, obtained from BS 5228 and AS 2436, for different construction equipment, is shown in table 1. It should be noted that these figures are used as indicative values only since the actual level of sound generated may vary depending on a number of different equipment-related factors such as the manufacturer, model, age, condition of equipment, and the way the equipment is being used [2].

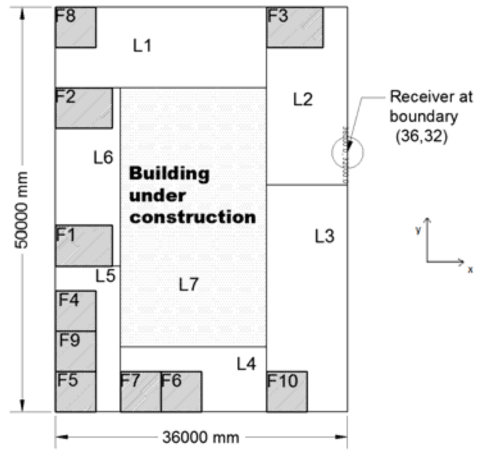

Figure 1. Optimal layout of temporary facilities

Table 2 shows the x and y coordinates of the centroids of the facilities, along with the noise sources at each of the given facilities. As shown in table 3, ten facilities were considered in the case study, with three being rectangles and the rest squares. A mixture of squares and rectangles is used to showcase the capability of the model in handling various dimensions of common facility shapes. Facilities considered include a site office, concrete batch plant, false-work yard, formwork assembly yard, steel welding and cutting yards, toilets, labour residence and a material warehouse. Table 4 presents the dimensions of the predefined locations on the construction site. Table 5 shows in which facilities acoustic screens are applied as a noise reduction measure.

Figure 1 presents the optimal layout of temporary facilities on site. Noise levels are measured at the receiver, assumed to be a hospital, located on the outskirts of the building at coordinates (36, 32). It is apparent from this figure that facilities are placed as far away from the receiver point as permitted by the boundaries of each of the predefined locations. The nosiest facilities are located at the opposite end of the site away from the receiver.

The model was executed on GAMS and solved using COUENNE. An overall optimal noise level of 75.9481 dB (A) was obtained from the solver. Computations were performed 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 model took 923 seconds for it to be solved to optimality, which is reflected in the fact that the objective function is non-convex, hence requiring multiple branching.

Table 1. Noise sources and their levels

Noise source LAeq @ 10 m (BS 5228)		
Noise source symbol	Noise source	LAeq @ 10m dB (A)
S1	Club Hammer	79
S2	Hand held electric saw	81
S3	Concrete mixer	76
S4	Welder	73
S5	Generator	73
S6	Hand grinder	110
S7	Gas cutter	89
S8	Concrete Vibrator	78
S9	Drill	87
S10	Nail gun	73
S11	Angle grinder	80
S12	Toilet	75
S13	Air-con	50
S14	Normal Conversation	60
S15	Printer	80
S16	Quiet room	40
S17	Material Hoist	68

Table 2. Noise sources and centroids of facilities

Noise source at each facility along with the optimised locations of temporary facilities				
Noise source at each facility	Facility symbol	Location	x-centroid coordinate (m)	y-centroid coordinate(m)
S1, S9	F1	L6	3.5000	20.5000
S1, S2	F2	L6	3.5000	37.5000
S3, S8	F3	L3	29.5000	47.5000
S4, S5	F4	L2	2.5000	12.5000
S6, S7	F5	L5	2.5000	2.5000
S10, S11	F6	L1	15.5000	2.5000
S12	F7	L4	10.5000	2.5000
S13	F8	L1	2.5000	47.5000
S14, S15	F9	L5	2.5000	7.5000
S16, S17	F10	L6	28.5000	2.5000

Table 3. Dimensions of facilities

Pre-defined dimensions of temporary facilities			
Facility	Facility Name	Width of facility in x-direction in m (*Wf*)	Length of facility in y-direction in m (*Lf*)
F1	Falsework	7	5
F2	Formwork assembly	7	5
F3	Concrete Batch Plant	7	5
F4	Steel welding yard	5	5
F5	Steel cutting yard	5	5
F6	Formwork assembly	5	5
F7	Toilets	5	5
F8	Labour residence	5	5
F9	Offices	5	5
F10	Warehouse	5	5

Table 4. Dimensions of predefined locations

Dimensions of pre-defined locations		
Location	Width of location in m (*WL*)	Length of location in m (*LL*)
L1	26	10
L2	10	22
L3	10	28
L4	18	8
L5	8	18
L6	8	22

Table 5. Application of acoustic screens

Facilities where acoustic screens are in place		
Acoustic Screen	Noise reduction achieved (AS 2436)	Facilities
Compressed Straw	28	F2, F6
Plywood	16	F1
Chipboard	26	F3

4 Conclusion

In this study a mixed integer nonlinear mathematical optimisation model was presented, which is aimed at minimising noise levels measured at a specified receiver by optimising the layout of temporary facilities on a construction site. The model was tested out on a case study, where it was solved to optimality. Future work will involve improving the computational efficiency of the model, considering multiple receivers with different noise-sensitivity thresholds around the site, upgrading the model to incorporate more noise reduction mechanisms as decision variables and the inclusion of a cost minimisation objective to establish a multi-objective optimisation construction site layout problem.

5 References

[1] P. M. Chapman, "Determining when contamination is pollution — Weight of evidence determinations for sediments and effluents," *Environment International*, vol. 33, no. 4, pp. 492–501, May 2007.

[2] F. Fricke, "Construction Site Noise," *Architectural Science Review*, vol. 28, no. 1, pp. 12–22, 1985.

[3] A. Gilchrist, E. N. Allouche, and D. Cowan, "Prediction and mitigation of construction noise in an urban environment," *Canadian Journal of Civil Engineering*, vol. 30, no. 4, pp. 659–672, Aug. 2003.

[4] S. Abo-Qudais and H. Abu-Qdais, "Perceptions and attitudes of individuals exposed to traffic noise in working places," *Building and Environment*, vol. 40, no. 6, pp. 778–787, Jun. 2005.

[5] G. Belojević, E. Öhrström, and R. Rylander, "Effects of noise on mental performance with regard to subjective noise sensitivity," *Int. Arch Occup Environ Heath*, vol. 64, no. 4, pp. 293–301, Nov. 1992.

[6] D. J. MacKenzie and L. Galbrun, "Noise levels and noise sources in acute care hospital wards," *BUILDING SERV ENG RES TECHNOL*, vol. 28, no. 2, pp. 117–131, May 2007.

[7] W. E. Morrison, E. C. Haas, D. H. Shaffner, E. S. Garrett, and J. C. Fackler, "Noise, stress, and annoyance in a pediatric intensive care unit," *Critical Care Medicine January 2003*, vol. 31, no. 1, pp. 113–119, 2003.

[8] M. J. Ballesteros, M. D. Fernández, S. Quintana, J. A. Ballesteros, and I. González, "Noise emission evolution on construction sites. Measurement for controlling and assessing its impact on the people and on the environment," *Building and Environment*, vol. 45, no. 3, pp. 711–717, Mar. 2010.

[9] City of Sydney, "Regulation of construction noise." 2014.

[10] E. P. A. V. State Government of Victoria, "Prohibited times for residential noise | Environment Protection Authority | EPA Victoria," 2014. [Online]. Available: http://www.epa.vic.gov.au/your-environment/noise/residential-noise/prohibited-times-for-residential-noise. [Accessed: 01-Mar-2014].

[11] Standards Australia, "Standards Australia 2010, Guide to noise and vibration control on construction, demolition and maintenance sites, AS2436," 2010.

[12] BSI British Standards, "British Standards: Code of Practice for Noise and Vibration Control on Construction and Open Sites - Part 1: Noise, BS 5228," British Standards Institution., 2009.

[13] A. H. Suter, "Construction Noise: Exposure, Effects, and the Potential for Remediation; A Review and Analysis," *AIHA Journal*, vol. 63, no. 6, pp. 768–789, 2002.

[14] S. Schneider, E. Johanning, J. L. Bélard, and G. Engholm, "Noise, vibration, and heat and cold," *Occup Med*, vol. 10, no. 2, pp. 363–383, Jun. 1995.

[15] W. W. Aljoe and Bureau of Mines, *The Bureau of Mines noise-control research program : a 10-year review*. [Avondale, Md.] : U.S. Dept. of the Interior, Bureau of Mines, 1985.

[16] S. Easa and K. Hossain, "New Mathematical Optimization Model for Construction Site Layout," *Journal of Construction Engineering and Management*, vol. 134, no. 8, pp. 653–662, 2008.

[17] A. Khalafallah and K. El-Rayes, "Automated multi-objective optimization system for airport site layouts," *Automation in Construction*, vol. 20, no. 4, pp. 313–320, Jul. 2011.

[18] H. Li and P. Love, "Site-Level Facilities Layout Using Genetic Algorithms," *Journal of Computing in Civil Engineering*, vol. 12, no. 4, pp. 227–231, 1998.

[19] X. Ning and K. C. Lam, "Cost–safety trade-off in unequal-area construction site layout planning," *Automation in Construction*, vol. 32, pp. 96–103, Jul. 2013.

[20] H. Sanad, M. Ammar, and M. Ibrahim, "Optimal Construction Site Layout Considering Safety and Environmental Aspects," *Journal of Construction Engineering and Management*, vol. 134, no. 7, pp. 536–544, 2008.

[21] P. Zouein, H. Harmanani, and A. Hajar, "Genetic Algorithm for Solving Site Layout Problem with Unequal-Size and Constrained Facilities," *Journal of Computing in Civil Engineering*, vol. 16, no. 2, pp. 143–151, 2002.

[22] A. Gannoruwa and J. Y. Ruwanpura, "Construction noise prediction and barrier optimization using special purpose simulation," in *Simulation Conference, 2007 Winter*, 2007, pp. 2073–2081.

[23] H. Li, "A computer system for predicting noise levels from construction equipment," *Building Research & Information*, vol. 23, no. 4, pp. 205–210, 1995.

[24] Zaiton Haron and Khairulzan Yahya, "Monte Carlo Analysis for Prediction of Noise from a Construction Site," *Journal of Construction in Developing Countries*, vol. 14, no. 1, pp. 1–14, 2009.

[25] P. Belotti, "Couenne: a user's manual," *Technical Report*, 2009.