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Facility planning and schedule design in the pandemic: eliminating contacts at construction workplace

Abstract

The construction industry has been severely affected by the COVID-19 pandemic and the associated restrictions on person-to-person contacts issued by the government. A construction site usually has a high number of workers working at the same time; therefore, the question of how to ensure their safety during the pandemic—that is, how to protect them from getting infected—has become an urgent problem. In this study, we propose a bi-objective integer programming model to establish the optimal schedule plan under COVID-19 regulations. We develop a solution method and conduct numerical experiments to solve and validate our model. The optimal schedule plan can avoid contacts between workers of different groups while minimizing the total costs of complying with government policy. Our proposed model can be applied in practice to help project managers establish a reasonable and cost-effective schedule plan. This study contributes to reducing the operating costs of contractors and protecting the health of construction workers.

Keywords: facility plan; schedule design; COVID-19; construction management; cleaner production

1 Introduction

As of June 2022, more than 500 million people worldwide have been infected by the novel coronavirus disease (COVID-19) (World Health Organization, 2022) and the pandemic becomes one of the greatest health crises of the 21st century to date (Van Bavel et al., 2022). Both economic and social activities have suffered (Severo et al., 2021; Zahraee et al., 2022; Sonar et al., 2022). Some economics related studies suggest that the COVID-19 has caused economic disruptions (Feng et al., 2022; Viscusi, 2020; Liu et al., 2022). The construction industry plays an important role in the national economy in terms of the number of employees (Yu et al., 2022; Benachio et al., 2020; Yi et al., 2021), but it has been hit hard by the pandemic (Aslan and Türkakın, 2022; Simpeh and Amoah, 2021). Policymakers have taken various measures, including nonpharmaceutical (e.g., mask-wearing and school closure) and pharmaceutical (e.g., vaccines and treatments) measures, to prevent the spread of the virus (Geng et al., 2021). One of its main modes of transmission is through close contacts between people; therefore, reducing person-to-person contacts is an important nonpharmaceutical way to control the spread of COVID-19 (Gabler et al., 2022). For example, British Standards Institution (2020) has issued guidelines on working safety during the pandemic and regulates that organizations should minimize physical interaction between workers to reduce the risk of infection. To this end, authorities have set new criteria in the construction industry to reduce the risk of infection among construction workers at construction sites during the pandemic. For example, Building and Construction Authority of Singapore (2022) rules that "segregated teams shall not be using same facilities at the same time".

In response to the COVID-19 pandemic, most activities have moved online. However, it is impossible to perform construction activities online. In practice, during a working day, construction workers usually have lunch and take breaks at the construction site. In view of COVID-19 regulations, construction sites should plan the number of rest areas and eating areas to be built to avoid contacts between construction workers of different groups. For example, the project manager should establish a schedule plan that avoids contacts between rebar crew workers and concrete crew workers during rest and lunch breaks. Obviously, constructing separate rest areas and eating areas is costly, and construction sites are hoping to build these facilities at minimal cost while complying with COVID-19 regulations. Therefore, it is important for contractors and project managers to establish reasonable schedule plans to achieve a trade-off between COVID-19 regulations and costs. In this study, we develop a bi-objective integer programming model to help contractors and project managers make scheduling plans that minimize the total costs of building rest and eating areas while meeting the COVID-19 regulations.

1.1 Literature review

The COVID-19 pandemic has become a global issue, leading scholars to address related topics. In this section, we mainly review two literature streams: research on solving the COVID-19 pandemic related problems with optimization methods and research on the COVID-19 pandemic in the construction industry.

Gupta et al. (2022) conduct a detailed review of operations studies related to pandemics/epidemics. They point out that the COVID-19 pandemic differs from other pandemics and encourage researchers to apply operations research methods to manage it. Tang et al. (2022) develop a mixed-integer linear program to optimize the operation cost of vaccination recipients and the travel distance between residents and vaccination recipients. Li et al. (2021a) explore the vaccination stations' location problem and considers many factors, such as travel distance and work schedule. They use a multi-objective mixed-integer nonlinear programming model to solve the problem. Li et al. (2021b) propose a bi-objective mixed-integer linear program, which aims to optimize the order assignment and scheduling of personal protective equipment during the COVID-19 pandemic. And they further develop solution methods based on Benders decomposition to give high-quality solutions. Enayati and Özaltın (2020) put forward a global optimization algorithm to make vaccine distribution decisions considering equity constraint. Through the mentioned literature, we can see that, first, operations research methods are suitable to solve many problems related to the COVID-19 pandemic, and second, the optimization problem for the COVID-19 pandemic is complex and there are usually two or more optimization objectives.

In the field of construction management, studies related to COVID-19 mainly focus on the impact of the pandemic. An investigation of the effects of COVID-19 on the construction industry by Gamil and Alhagar (2020) finds that the pandemic has led to project suspensions, job losses, time overruns, cost overruns, and financial implications. Our paper addresses a problem related to these negative outcomes. Drawing on the perspectives of the different stakeholders in construction projects, the study by Araya and Sierra (2021) using semi-structured interviews to explore the impact of COVID-19 is helpful for strategy design in the construction industry during the pandemic. An examination of the construction industry by Alsharef et al. (2021) via telephone interviews with people in the U.S. construction industry provides many management insights into the early impacts of COVID-19. Love et al. (2021) argue that COVID-19 has posed challenges to construction projects, and develop a framework for procurement during the pandemic. Araya (2021a) uses agent-based techniques to study the impact of COVID-19 on construction workers, and finds that the spread of the virus can greatly reduce the workforce available for a construction project. Our paper develops models related to the health of construction workers. Araya (2021b) applies agent-based techniques and proposes that multiple work shifts can reduce the spread of COVID-19 among construction workers. Our paper considers the work–rest–lunch schedules of workers rather than multiple work shifts. The stochastic agent-based model developed by Seresht (2022) examines the effectiveness at the micro level of wearing masks during construction projects. Nový and Nováková (2022) suggest that COVID-19 has had a positive effect on construction companies from the perspective of management experience in crisis situations. Hansen (2020) examines the effect of COVID-19 on construction contracts. Briggs et al. (2022) study the safety policies and practices implemented during the COVID-19 pandemic on industrial construction sites. Assaad and El-adaway (2021) contribute to the establishment of construction industry guidelines under COVID-19. These studies generally approach the various construction management problems caused by the COVID-19 pandemic using mainly qualitative techniques, with only a few using quantitative models.

Optimization research plays an important role in construction management (Love et al., 2014; Signor et al., 2021), and scholars should pay attention to optimization problems in construction management during the COVID-19 pandemic. To the best of our knowledge, the study by Aslan and Türkakın (2022) is the only work to date to use optimization techniques to explore COVID-19-related problems in the field of construction management. They develop a multi-objective model to determine the optimal number of workers and construction delays considering the impact of COVID-19. However, they do not pay attention to the number of facilities (e.g., eating and rest areas) to avoid an increase in infection rates. Making an appropriate plan, especially where there is a trade-off between costs and resources, is a significant problem (Kamyabniya et al., 2019; Xiao et al., 2020). Therefore, in this study, we adopt optimization techniques to help contractors and project managers make an optimal plan that can both meet the COVID-19 pandemic regulations and achieve cost-minimized resource allocation.

1.2 Objectives and contributions

The above literature review indicates that little research is focused on optimization models to study the problems occurring in construction management during the COVID-19 pandemic. Few studies explore the problem of scheduling in response to the COVID-19 pandemic, which is definitely an optimization problem. Therefore, our research has three objectives. First, we build a bi-objective optimization model to help contractors and project managers minimize the number of rest and eating areas to be built by establishing a reasonable schedule for the use of these areas. Our model reduces the costs involved while avoiding contacts between different construction groups. Second, we develop a solution method by linearizing our proposed model using Pareto theory and assign eating and rest areas to different groups of workers. Third, we conduct numerical experiments and sensitivity analysis to test the effectiveness and efficiency of the proposed model and analyze the impact of parameter changes. The theoretical and practical contributions of our study are summarized below.

1) Theoretical contributions. To date, no study has used models and algorithms to establish a reasonable schedule for the use of lunch and rest areas while minimizing the number of lunch and rest areas to be provided during the COVID-19 pandemic. Our bi-objective integer programming model minimizes the total costs of building separate lunch and rest areas, taking into account both the COVID-19 regulations in place and many practical restrictions of construction sites, such as working hours and requirements for rest and lunch breaks. We further develop a solution method to solve our proposed model using state-of-the-art solvers. By conducting numerical experiments, we demonstrate that our model and solution method are both effective and efficient in establishing a reasonable schedule for the use of lunch and rest areas while minimizing the number of these areas.

2) Practical contributions. As mentioned, contractors and project managers should follow COVID-19 regulations and try to minimize physical interactions between construction workers of different groups. Our study not only helps them follow government policy but also aims to minimize the total costs. As construction sites are places at high risk of virus transmission, our research contributes to the control of the COVID-19 pandemic while meeting the practical needs of construction sites.

The remainder of this paper is organized as follows. Section 2 presents a detailed description for our problem. Section 3 proposes models and solution methods to solve the problem. Section 4 conducts numerical experiments that show the effectiveness and applicability of the proposed methods. Conclusions are drawn in Section 5.

2 Problem description

In a construction project, construction workers are usually divided into different groups to perform different tasks. During each working day, construction workers work the same number of hours, and their lunch breaks are also fixed. In other words, the start and end times of work and lunch are regulated. For example, if work starts at 8:00 and lasts 9 hours, with a 1-hour lunch break set between 11:00 and 14:00, a construction group can start work at 8:00, spend 1 hour for lunch between 11:00 and 14:00, and finish work at 17:00. The government usually sets regulations in terms of minimum rest periods in the morning, afternoon, and whole day (Yi and Wang, 2017). For example, Hong Kong stipulates that construction workers during the afternoon work session must have 45 minutes rest in the summer months (May to September) and 30 minutes rest in other months (Construction Industry Council of Hong Kong, 2013). The Ministry of Manpower of Singapore (2019) stipulates that workers may not work more than 6 hours without a rest. New legislation in the United States requires construction workers to have a 15-minute break after working 4 hours (Construction Injury Prevention Act, 2022). The Working Time Regulation (Health and Safety Executive, 1998) of the European Union specifies that "a worker is entitled to an uninterrupted break of 20 minutes when daily working time is more than six hours. It should be a break in working time and should not be taken either at the start, or at the end, of a working day." In a work scenario, the time before 12:00 is considered morning (Yi and Chan, 2013). For example, the government may require construction workers to take at least 10 minutes of rest in the morning, 20 minutes in the afternoon, and 45 minutes in total for the whole day. Similarly, the team leader can stipulate the minimum working hours before a break, including rest, lunch, and leaving work.

To simplify notations, we divide the number of hours between the earliest start time and the latest end time of work into time units of 15 minutes. Using the example above, we illustrate the relationship between time periods and time units in Fig. 1. From 8:00 to 17:00, the number of working hours can be divided into 36 time units. We assume that the start times for work, lunch, and rest start at the beginning of a time unit.

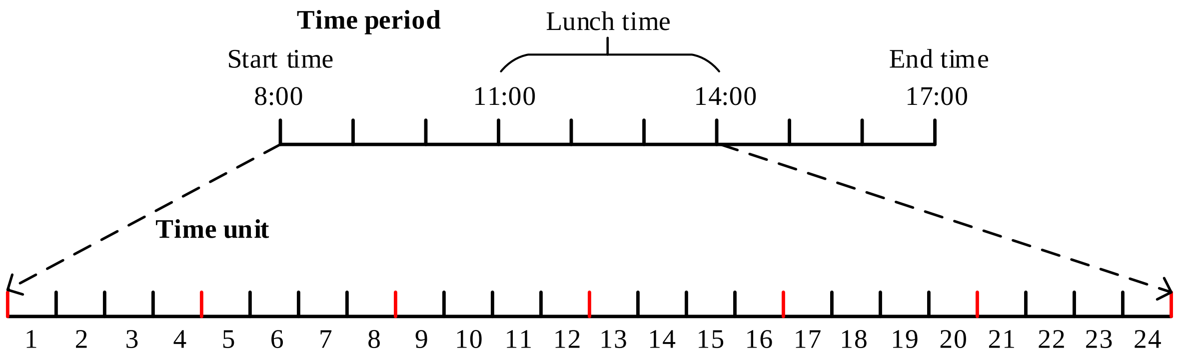

Fig. 1. An example of the relationship between time periods and time units

Different groups of construction workers usually take a break or have lunch together. However, during the COVID-19 pandemic, construction workers of different groups should avoid contacts to reduce the risk of infection—i.e., they cannot use a rest area or eating area at the same time. Therefore, project managers must establish a reasonable work–rest–lunch (WRL) schedule to minimize the number of rest and eating areas to be built while avoiding contacts between different groups. In this study, we develop models to help project managers solve the no-contact WRL (N-WRL) scheduling problem. Because of the negative effects of COVID-19 on the human body and the high risk of social transmission once workers are infected, our research is important to protect the health of construction workers, reduce the spread of the virus, and alleviate pressure on medical resources.

3 Model

3.1 Symbols and parameters

We consider a construction site that has a set of $I = \{1, \dots, |I|\}$ construction groups. Each $i \in I$ represents one group. The working hours for a working day and the work start time are denoted by W and W_s, respectively. We use parameter Q to represent the minimum duration of working, i.e., construction workers can have a rest after working at least Q minutes. The lunch duration, the earliest lunch start time, and the latest lunch end time for a working day are denoted by L, L_s, and L_e respectively. We assume that there is a minimum rest duration in the morning, in the afternoon and in a working day, denoted by RD_{am}, RD_{pm}, and RD_{day}

respectively. If there are no shortest rest duration rules, of course, the three parameters can be set to 0. Based on time interval ω, we can re-express time as the form of time units. The set of time units $T = \{1, \dots, |T|\}$ for a working day can be calculated by Formula (1). A working day starts at time unit 1 and ends after time unit $|T|$. Lunch time is between $[TU_{L_s} + 1, TU_{L_e}]$, which can be calculated by Formula (2) and Formula (3). Formula (4)–(8) calculate the number of time units required for minimum duration of working, lunch, and rest. Symbols used in our study are listed in Table 1.

$$|T| = \frac{W \times 60}{\omega} \tag{1}$$

$$TU_{L_s} = \frac{(L_s - W_s) \times 60}{\omega} \tag{2}$$

$$TU_{L_e} = \frac{(L_e - W_s) \times 60}{\omega} \tag{3}$$

$$NTU_Q = \frac{Q}{\omega} \tag{4}$$

$$NTU_L = \frac{L}{\omega} \tag{5}$$

$$NTU_{RD_{am}} = \frac{RD_{am}}{\omega} \tag{6}$$

$$NTU_{RD_{pm}} = \frac{RD_{pm}}{\omega} \tag{7}$$

$$NTU_{RD_{day}} = \frac{RD_{day}}{\omega} \tag{8}$$

Table 1. Symbols

Notions in the model	
Sets	
I	Set of construction groups, $i \in I$
T	Set of time units for a working day, $T = \{1, \dots, \lvert T \rvert\}, t \in T$
Parameters	
ω	Number of minutes of a time interval; $\omega = 15$ minutes
W	Working hours for a working day, including lunch time and rest time, $W = 9$ hours
W_s	The work start time, e.g., 8:00
Q	Minimum duration of continuous working (minute)
L	Lunch duration (minute)
L_s	The earliest start time for lunch, e.g., 11:00
L_e	The latest end time for lunch, e.g., 14:00
RD_{am}	Minimum rest duration for workers in the morning (minute)
RD_{pm}	Minimum rest duration for workers in the afternoon (minute)
RD_{day}	Minimum rest duration for workers in a day (minute)
$\lvert T \rvert$	Total time units
TU_{L_s} and TU_{L_e}	The time unit to represent lunch start and lunch end, respectively
NTU_Q and NTU_L	The time unit to represent work duration and lunch duration, respectively
$NTU_{RD_{am}}$	The time unit to represent minimum rest duration in the morning
$NTU_{RD_{pm}}$	The time unit to represent minimum rest duration in the afternoon
$NTU_{RD_{day}}$	The time unit to represent minimum rest duration in a day
Decision Variables	
r_i^t	Binary decision variable that equals 1 if workers in group i take a rest in time unit t and 0 otherwise
σ_i^t	Binary decision variable that equals 1 if workers in group i start to take a rest in time unit t and 0 otherwise
l_i^t	Binary decision variable that equals 1 if workers in group i have lunch in time unit t and 0 otherwise
θ_i^t	Binary decision variable that equals 1 if workers in group i start to have lunch in time unit t and 0 otherwise
w_i^t	Binary decision variable that equals 1 if workers in group i work in time unit t and 0 otherwise
τ_i^t	Binary decision variable that equals 1 if workers in group i start to work in time unit t and 0 otherwise
x	The number of rest areas built
y	The number of lunch areas built

Notation used in the algorithm in Section 3.4	
$f_1(\vec{X})$ and $f_2(\vec{X})$	Two objective functions
f_1 and f_2	The value of two objective functions respectively
$\vec{X}$	Feasible solutions
$\mathcal{L}$	Set of solution space
Υ	Set of objective space
$\mathcal{M}$	Set of Pareto efficient solutions
$\mathcal{F}$	Set if Pareto frontier
f^I	Ideal point
f^N	Nadir point
ϵ	Parameter to control the accuracy when solving bi-objective problem
Notation used in the algorithm in Section 3.5	
y^*	The optimal value of y
l_i^{t*}	The optimal value of l_i^t
θ_i^{t*}	The optimal value of θ_i^t
K	Set of lunch areas, $k \in K$
o_k^t	Variable that equals i if area k is occupied by group i in time unit t and 0 otherwise
π_i^*	The first time unit during which team $i \in I$ has lunch
$F(i^\#)$	The rank of lunch time of group $i^\#$
x^*	The optimal value of x
r_i^{t*}	The optimal value of r_i^t
σ_i^{t*}	The optimal value of σ_i^t
J	Set of rest areas, $j \in J$
b_j^t	Variable that equals i if rest area j is used by group i in time unit t and 0 otherwise
P_i	Set of rest times for each group i, $p_i \in P_i$
μ_{i,p_i}^*	Variable to represent the rest start time for group i's p_i-th rest
Δ_{i,p_i}^*	Variable to represent the rest duration for group i's p_i-th rest
$G(h)$	$G(h)$ equals (i, p_i), which denotes the rank of rest time of groups

3.2 N-WRL schedule model

We define two decision variables x and y to represent the number of rest areas and lunch areas required. As shown in Table 1, we also define six binary decision variables to build our model. To simplify notation, we stipulate that all workers go to work at 8:00 and get off work at 17:00 and the lunch time is from 11:00 to 14:00. Thus, $|T|$ equals 36 and time units in the morning is [1,16] and in the afternoon is [17,36]. The N-WRL schedule model can be formulated as follows.

[M1]

$$\begin{cases}\min x\\ \min y\end{cases} \tag{9}$$

subject to

$$y \geq \sum_{i\in I} l_i^t, t \in \{TU_{L_s}+1, \dots, TU_{L_e}\} \tag{10}$$

$$\sum_{t=TU_{L_s}+1}^{TU_{L_e}} l_i^t = NTU_L, \forall\, i \in I \tag{11}$$

$$\sum_{t'=t}^{t+NTU_L-1} l_i^{t'} \geq NTU_L \theta_i^t, \forall\, i \in I, t \in \{TU_{L_s}+1, \dots, TU_{L_e}+1-NTU_L\} \tag{12}$$

$$\sum_{t=TU_{L_s}+1}^{TU_{L_e}+1-NTU_L} \theta_i^t = 1, \forall\, i \in I \tag{13}$$

$$l_i^t = 0, \forall\, i \in I, t \in \left\{1, \dots, TU_{L_s}\right\} \cup \left\{TU_{L_e}+1, \dots, |T|\right\} \tag{14}$$

$$\theta_i^t = 0, \forall\, i \in I, t \in \left\{1, \dots, TU_{L_s}\right\} \cup \left\{TU_{L_e}+2-NTU_L, \dots, |T|\right\} \tag{15}$$

$$x \geq \sum_{i\in I} r_i^t, t \in \{NTU_Q+1, \dots, |T|-NTU_Q\} \tag{16}$$

$$\sigma_i^t = 0, \forall\, i \in I, t \in \{1, \dots, NTU_Q, |T|+1-NTU_Q, \dots, |T|\} \tag{17}$$

$$r_i^t = 0, \forall\, i \in I, t \in \{1, \dots, NTU_Q, |T|+1-NTU_Q, \dots, |T|\} \tag{18}$$

$$\sigma_i^t \geq r_i^t - r_i^{t-1}, \forall\, i \in I, t \in \{NTU_Q+1, \dots, |T|-NTU_Q\} \tag{19}$$

$$r_i^t \geq \sigma_i^t, \forall\, i \in I, t \in \{NTU_Q+1, \dots, |T|-NTU_Q\} \tag{20}$$

$$r_i^{t-1}\sigma_i^t = 0, \forall\, i \in I, t \in \{NTU_Q+1, \dots, |T|-NTU_Q\} \tag{21}$$

$$\sum_{t=1}^{16} r_i^t \geq NTU_{RD_{am}}, \forall\, i \in I \tag{22}$$

$$\sum_{17}^{|T|} r_i^t \geq NTU_{RD_{pm}}, \forall\, i \in I \tag{23}$$

$$\sum_{t=1}^{|T|} r_i^t = NTU_{RD_{day}}, \forall\, i \in I \tag{24}$$

$$r_i^{t-1}\theta_i^t = 0, \forall\, i \in I, t \in \left\{TU_{L_s}+1, \dots, TU_{L_e}+1-NTU_L\right\} \tag{25}$$

$$l_i^t \sigma_i^{t+1} = 0, \forall\, i \in I, t \in \left\{TU_{L_s} + NTU_L, \dots, TU_{L_e}\right\} \tag{26}$$

$$\textstyle\sum_{t'=t}^{t+NTU_Q-1} w_i^{t'} \geq NTU_Q \tau_i^t, \forall\, i \in I, t \in \left\{1, \dots, |T| + 1 - NTU_Q\right\} \tag{27}$$

$$\tau_i^t \geq w_i^t - w_i^{t-1}, \forall\, i \in I, t \in \{2, \dots, |T|\} \tag{28}$$

$$w_i^{t-1} \tau_i^t = 0, \forall\, i \in I, t \in \{2, \dots, |T|\} \tag{29}$$

$$\tau_i^1 = 1, \forall\, i \in I \tag{30}$$

$$w_i^t = 1, \forall\, i \in I, t \in \{1, \dots, NTU_Q, |T| + 1 - NTU_Q, \dots, |T|\} \tag{31}$$

$$r_i^t + l_i^t + w_i^t = 1, \forall\, i \in I, t \in T \tag{32}$$

$$x \in Z_+ \tag{33}$$

$$y \in Z_+ \tag{34}$$

$$r_i^t \in \{0,1\}, \forall\, i \in I, t \in T \tag{35}$$

$$\sigma_i^t \in \{0,1\}, \forall\, i \in I, t \in T \tag{36}$$

$$l_i^t \in \{0,1\}, \forall\, i \in I, t \in T \tag{37}$$

$$\theta_i^t \in \{0,1\}, \forall\, i \in I, t \in T \tag{38}$$

$$w_i^t \in \{0,1\}, \forall\, i \in I, t \in T \tag{39}$$

$$\tau_i^t \in \{0,1\}, \forall\, i \in I, t \in T. \tag{40}$$

In the above model, Equation (9) minimize the total number of rest areas and lunch areas. Constraints (10) ensure that there are enough areas for lunch. Constraints (11)–(15) places restrictions on regulations related to lunch. In detail, (11)–(12) guarantee that each group can have a L minutes consecutive lunch time between time units $[TU_{L_s} + 1, TU_{L_e}]$. Constraints (13) mean that each worker can only have lunch once a day. Constraints (14) and Constraints (15) guarantee that lunch time should be within the specified time interval. Constraints (16) ensure that there are enough areas for rest. Constraints (17)–(24) are restriction formulas for the regulations related to rest. Specifically, Constraints (17)–(18) ensure that construction workers can only take rest or get off work after working Q minutes. Constraints (19)–(20) restrict the relationship between the starting and the state of rest. Constraints (21) guarantee that worker have to go to work after finishing a rest. Constraints (22)–(24) require that the total rest time should be up to the standards. Constraints (25)–(26) make sure that workers cannot have lunch immediately after rest and cannot rest immediately after lunch. Constraints (27)–(31) restrict the minimum working duration, the relationship between the starting and the state of work, and the work intervals. Constraints (32) state that workers can only have one state at the same time, including working, taking a rest, or having lunch. Constraints (33)–(40) give the domain of decision variables (Luo et al., 2020).

3.3 Linearization of the model

Model [M1] is difficult to solve because Constraints (21), (25), (26) and (29) have nonlinear product terms. To transform [M1] into an integer linear programming model, we linearize the four constraints as follows:

$$r_i^{t-1} + \sigma_i^t \leq 1, \forall\, i \in I, t \in \{NTU_Q + 1, \dots, |T| - NTU_Q\} \tag{41}$$

$$r_i^{t-1} + \theta_i^t \leq 1, \forall\, i \in I, \forall\, i \in I, t \in \left\{TU_{L_s} + 1, \dots, TU_{L_e} + 1 - NTU_L\right\} \tag{42}$$

$$l_i^t + \sigma_i^{t+1} \leq 1, \forall\, i \in I, t \in \left\{TU_{L_s} + NTU_L, \dots, TU_{L_e}\right\} \tag{43}$$

$$w_i^{t-1} + \tau_i^t \leq 1, \forall\, i \in I, \forall\, i \in I, t \in \{2, \dots, |T|\}. \tag{44}$$

As r_i^t and σ_i^t are binary decision variables, Constraints (21) hold in three cases: $r_i^{t-1} = \sigma_i^t = 0$; $r_i^{t-1} = 1, \sigma_i^t = 0$; and $r_i^{t-1} = 0, \sigma_i^t = 1$. Therefore, Constraints (41) are equivalent replacements of Constraints (25). Similarly, we can use Constraints (42), (43) and (44) to replace Constraints (25), (26) and (29), respectively. Now, we transform [M1] into an integer programming model:

[M2]

Objective (9)

subject to Constraints (10)–(20), (22)–(24), (27)–(28), (30)–(44).

3.4 Dealing with bi-objective

The N-WRL schedule model is a bi-objective combinatorial optimization problem. A bi-objective formulation is important because many problems involve multiple or conflicting objectives and decision makers have to make trade-offs (Qi et al., 2021). In our case, the two objectives—minimizing the number of rest areas to be built and minimizing the number of lunch areas to be built—need to be simultaneously optimized because both of them are helpful in reducing costs and ensure worker safety. Due to the complexity of the problem, which will be addressed in Section 3.6, finding an optimal solution that simultaneously optimizes both objectives is usually difficult. Among the existed studies, there are many solution methods towards bi-objective problems and we refer to Bérubé et al. (2009) to solve our N-WRL schedule model. The methodology proposed by Bérubé et al. (2009) is widely used in dealing with bi-objective problems in many areas and is proven to be useful and efficient, such as vehicle routing (Zarouk et al., 2022; Zhen et al., 2020) and scheduling (Rao et al., 2020; Zhang et al., 2022).

To simply notation, we reformulate our model into a general form:

$$\min f(\vec{X}) = \left(f_1(\vec{X}), f_2(\vec{X})\right) \ s.t.\ \vec{X} \in \mathcal{L}. \tag{45}$$

$f_1(\vec{X})$ and $f_2(\vec{X})$ are the two objectives and $\vec{X}$ represents feasible solutions. We use set $\mathcal{L}$ to denote the set of solution space and set $\Upsilon = \{f = (f_1, f_2): f_1 = f_1(\vec{X}), f_2 = f_2(\vec{X}), \forall\, \vec{X} \in \mathcal{L}\}$ to denote the set of objective space.

Definition 1: (Dominance relation). Let $f \in \Upsilon$ and $f' \in \Upsilon$. f' dominates f if and only if $f_1{}' \le f_1$ and $f_2{}' \le f_2$ where at least one inequality is strict. We say $f' \succ f$. For example, f_A dominates f_B in fig. 2.

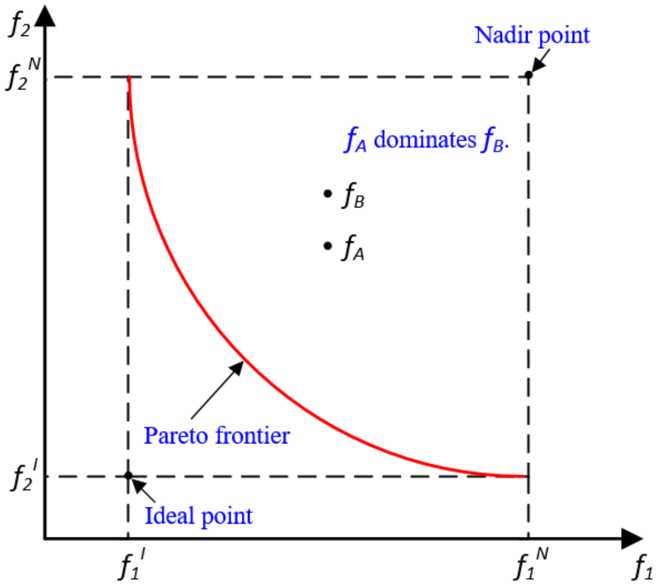

Fig. 2. Illustration of definitions

Definition 2: (Pareto efficiency). A solution $\vec{X} \in \mathcal{L}$ is Pareto efficient if and only if $\nexists\, \vec{X}' \in \mathcal{L}$ such that $f(\vec{X}') \succ f(\vec{X})$.

We use set $\mathcal{M}$ to denote the set of Pareto efficient solutions and set $\mathcal{F} = \{f = (f_1, f_2): f_1 = f_1(\vec{X}), f_2 = f_2(\vec{X}), \forall\, \vec{X} \in \mathcal{M}\}$ to denote the set of Pareto frontier (see Fig. 2). According to Bérubé et al. (2009), we can transform Formula (45) into two ϵ-constraints problems—$R_1(\epsilon_2)$ and $R_2(\epsilon_1)$:

$[R_1(\epsilon_2)]$

$$\min f_1(\vec{X}) \tag{46}$$

subject to

$$\vec{X} \in \mathcal{L} \tag{47}$$

$$f_2(\vec{X}) \leq \epsilon_2 \tag{48}$$

$[R_2(\epsilon_1)]$

$$\min f_2(\vec{X}) \tag{49}$$

subject to

$$\vec{X} \in \mathcal{L} \tag{50}$$

$$f_1(\vec{X}) \leq \epsilon_1 \tag{51}$$

Definition 3: (Ideal point). $f^I = (f_1{}^I, f_2{}^I)$ with $f_1{}^I = \min_{\vec{X}\in\mathcal{L}} f_1(\vec{X})$ and $f_2{}^I = \min_{\vec{X}\in\mathcal{L}} f_2(\vec{X})$.

Definition 4: (Nadir point). $f^N = (f_1{}^N, f_2{}^N)$ with $f_1{}^N = \min_{\vec{X}\in\mathcal{L}}\{f_1(\vec{X}): f_2(\vec{X}) = f_2{}^I(\vec{X})\}$ and $f_2{}^N = \min_{\vec{X}\in\mathcal{L}}\{f_2(\vec{X}): f_1(\vec{X}) = f_1{}^I(\vec{X})\}$.

The illustration of the Ideal point and the Nadir point is shown in Fig. 2. We can use the following algorithm to obtain exact Pareto frontier based on the reduction on ϵ_2. Algorithm 1 involves only single-objective integer program, which can be solved by CPLEX (He et al., 2022; Qu et al., 2022; Wang et al., 2022; Wu et al., 2022; Yan and Wang, 2022). For more details and the proof of Algorithm 1, please see Bérubé et al. (2009).

Algorithm 1: Pareto frontier of bi-objective problems with integer values

Step 1. Compute f^I and f^N.

Step 2. Set $\mathcal{F}' = \{(f_1{}^I, f_2{}^N)\}$ and $\epsilon_2 = f_2{}^N - \nabla$ ($\nabla = 1$).

Step 3. While $\epsilon_2 \geq f_2{}^I$:

Solve $R_1(\epsilon_2)$ and add the optimal solution value $(f_1{}^*, f_2{}^*)$ to set $\mathcal{F}$.

Set $\epsilon_2 = f_2{}^* - \nabla$.

Step 4. Remove dominated points from $\mathcal{F}'$ and we have the set of Pareto frontier $\mathcal{F}$.

Proposition 1. (Bérubé et al., 2009): All points in the set of Pareto frontier are within the rectangle formed by $(f_1{}^I, f_2{}^I)$, $(f_1{}^I, f_2{}^N)$, $(f_1{}^N, f_2{}^N)$ and $(f_1{}^N, f_2{}^I)$.

Corollary 1: If the Ideal point f^I is the same as the Nadir point f^N, then there is only one point in the set of the Pareto frontier.

Proof:

The equality of the Ideal point f^I and the Nadir point f^N implies ${f_1}^I = {f_1}^N$ and ${f_2}^I = {f_2}^N$. Thus, the coordinates of the four points of the rectangle are the same, i.e., the rectangle degenerates to a point. Therefore, there is only one point in the set of the Pareto frontier.

3.5 Assignment of lunch and rest areas

The optimal solutions of model [M2] can give the minimum number of lunch areas and rest areas built, and the lunch and rest time units for each group. However, model [M2] cannot directly tell the project manager in which area each group should have lunch and take a rest. Obviously, it is not reasonable to change places for a group during lunch period or during the same rest period. Next, we prove that given the optimal solutions of our model, there exists a shift strategy without changing lunch or rest areas.

Proposition 2. For an optimal solution to model [M2], there exists a lunch area allocation plan such that each group has lunch in only one area for NTU_L time units. That is, a group does not have to change lunch area during lunch.

Proof:

We use y^*, l_i^{t*}, and θ_i^{t*} to denote the optimal values of y, l_i^t, and θ_i^t to model [M2], respectively, $i \in I$, $t \in T$. Thus, the minimum number of lunch areas is y^* and we use set $K = \{1, \dots, y^*\}$ to denote the set of lunch areas, indexed by k. To simplify expression, we define variable o_k^t, which equals i if area k is occupied by group i in time unit t and 0 otherwise. From Constraints (12), we can know that if $\theta_i^{t*} = 1$, $l_i^{t*} + \cdots + l_i^{t+NTU_L-1,*} = NTU_L$, i.e., $l_i^{t*} = \cdots = l_i^{t+NTU_L-1,*} = 1$. Therefore, we define π_i^* as the first time unit during which team $i \in I$ has lunch, that is

$$\pi_i^* = \textstyle\sum_{t \in T} t\theta_i^{t*}, \forall\, i \in I. \quad (52)$$

We sort the groups $i \in I$ according to increasing order of π_i^*, denoted by $F(1), \dots, F(i^\#), \dots, F(|I^\#|)$, (ties can be broken arbitrarily), where $I^\# = I$ (we introduce $I^\#$

simply for clarity). That is, group $F(1)$ is the earliest one to have lunch and group $F(|I^{\#}|)$ is the last one to have lunch. Mathematically, $\pi^*_{F(i^{\#})} \le \pi^*_{F(i^{\#}+1)}$, $i^{\#} = 1, \dots, |I^{\#}| - 1$.

The assignment of work groups to lunch areas can be conducted using Algorithm 2.

Algorithm 2: An assignment algorithm for having lunch in one area

Step 1. Sort all groups $i \in I$ according to increasing order of π^*_i, and save the mappting relations between i and $i^{\#}$, denoted by $i = F(i^{\#})$ and $i^{\#} = F^{-1}(i)$, i.e., group i is the $i^{\#}$-th one to have lunch.

Step 2. For each $i^{\#} = 1, \dots, y^*$, assign group $F(i^{\#})$ to lunch area $k = i^{\#}$, and set $o^t_k = \cdots = o_k^{t+NTU_L-1} = F(i^{\#})$. // Allocate y^* lunch areas to the first y^* groups that have lunch.

Step 3. For each $i^{\#} = y^* + 1, \dots, |I^{\#}|$, set $o^t_k = \cdots = o_k^{t+NTU_L-1} = F(i^{\#})$ for an arbitrary empty area k in time unit $\pi^*_{F(i^{\#})}$, i.e., in the time unit in which group $F(i^{\#})$ starts to have lunch. // We can always find such an area because Constraints (10) imply $\sum_{F(i^{\#\prime}) \in I \setminus \{F(i^{\#})\}} l_{F(i^{\#\prime})}^{\pi^*_{F(i^{\#\prime})}*} \le y^* - l_{F(i^{\#})}^{\pi^*_{F(i^{\#})}*} = y^* - 1$ and Constraints (12) guarantee that the lunch time is consecutive NTU_L time units.

Proposition 3. For an optimal solution to model [M2], there exists a rest area allocation plan such that each time a group rests, it rests in only one area. That is, a group does not have to change rest area during a rest.

Proof:

We use x^*, r_i^{t*}, and σ_i^{t*} to denote the optimal values of x, r_i^t, and σ_i^t to model [M2], respectively, $i \in I$, $t \in T$. Thus, the minimum number of rest areas is x^* and we use set $J = \{1, \dots, x^*\}$ to denote the set of rest areas, indexed by j. We define variable b_j^t, which equals i if rest area j is used by group i in time unit t and 0 otherwise. As each group i can take more than one rest for a working day, we use set $P_i = \{1, \dots, |P_i|\}$ to denote the set of rest times for each group i, indexed by p_i. The values of $|P_i|$ can be calculated by Equation (53):

$$|P_i| = \sum_{t \in T} \sigma_i^{t*}, \forall\, i \in I. \tag{53}$$

We define variable μ_{i,p_i}^* as the rest start time for group i's p_i-th rest and variable Δ_{i,p_i}^* as the rest duration for group i's p_i-th rest:

$$\mu_{i,p_i}^* = \min\{t \big| \sigma_i^{1*} + \cdots + \sigma_i^{t*} = p_i \text{ for } p_i \in P_i, \forall\, t \in T\}, \forall\, i \in I \tag{54}$$

$$\Delta_{i,p_i}^* = \min\left\{N \big| r_i^{t*} \times r_i^{t+1*} \ldots \times r_i^{t+N*} = 0 \text{ for } t = \mu_{i,p_i}^*, t \in T\right\}, \forall\, i \in I, p_i \in P_i. \tag{55}$$

We sort the groups $i \in I$ and the rests $p_i \in P_i$ according to the increasing order of μ_{i,p_i}^*, denoted by $G(1), \ldots, G(h), \ldots, G(|H|)$ (ties can be broken arbitrarily), where $(i, p_i) = G(h)$ and $|H| = \sum_{i \in I} \sum_{t \in T} \sigma_i^{t*}$. That is, $G(1)$ is the first rest among all groups and $G(|H|)$ is the last one. Mathematically, $\mu_{G(h)}^* \leq \mu_{G(h+1)}^*$, $h = 1, \ldots, |H| - 1$.

The assignment of work groups to rest areas can be conducted using Algorithm 3.

Algorithm 3: An assignment algorithm for staying in one area during a rest

Step 1. Sort all groups $i \in I$ and the rests $p_i \in P_i$ according to increasing order of μ_{i,p_i}^*, and save the mappting relations between (i, p_i) and h, denoted by $(i, p_i) = G(h)$, i.e., group i's p_i-th rest (i, p_i) is the h-th one to start rest.

Step 2. For each $h = 1, \ldots, x^*$, assign group $G(h)$ to rest area $j = h$, and set $b_j^t = \cdots = b_j^{t+\Delta_{G(h)}^*-1} = G(h)$. // Allocate x^* rest areas to the first x^* rests among all groups.

Step 3. For each $h = x^* + 1, \ldots, |H|$, set $b_j^t = \cdots = b_j^{t+\Delta_{G(h)}^*-1} = G(h)$ for an arbitrary empty rest area j in time unit $\mu_{G(h)}^*$, i.e., in the time unit in which group $G(h)$ starts a rest. // We can always find such an area because Constraints (16) imply $\sum_{G(h') \in I \setminus \{G(h)\}} r_{G(h')}^{\mu_{G(h')}^*{}^*} \leq y^* - r_{G(h)}^{\mu_{G(h)}^*{}^*} = x^* - 1$ and Constraints (19)–(21) guarantee that the duration of a rest is consecutive.

3.6 Problem complexity

We analyze the problem complexity in this section.

Proposition 4. If RD_{am}, RD_{pm}, and RD_{day} are all zero, then the minimum number of lunch areas is $\left\lceil \frac{|I|}{\left\lfloor \frac{L_e - L_S}{L} \right\rfloor} \right\rceil$.

Proof:

If RD_{am}, RD_{pm}, and RD_{day} are all zero, then we can only consider the lunch duration requirement. We first calculate the maximum lunch times, that is $\left\lfloor \frac{L_e - L_S}{L} \right\rfloor$. For example, the earliest lunch start time is 11:00, the latest lunch end time is 14:00, and the lunch duration is 60 minutes, then the maximum lunch times within the lunch intervals will be 3, i.e., 3 groups can use the same lunch area. We round down this result because the maximum lunch time should be an integer. And we calculate the minimum number of lunch areas by $\left\lceil \frac{|I|}{\left\lfloor \frac{L_e - L_S}{L} \right\rfloor} \right\rceil$. We round up this result to avoid contacts between workers.

Proposition 5. Suppose that the lunch interval is fixed, i.e., $L_e - L_s = L$, and $RD_{day} = 0$. Then we can optimize the rest schedule in the morning and in the afternoon independently. If we only consider the schedule in the morning, the rest time must lie in $[W_s + Q, L_s - Q]$. Thus, the minimum number of rest areas in morning will lie in $[\left\lceil \frac{|I|}{\frac{L_S - Q - (W_S + Q)}{RDam}} \right\rceil, \left\lceil \frac{|I|}{\left\lfloor \frac{L_S - Q - (W_S + Q)}{RDam} \right\rfloor} \right\rceil]$.

Proof:

The time range $[W_s + Q, L_s - Q]$ is obvious because we restrict that workers can take a rest only after working Q minutes. Then the minimum rest times a group can take is $\left\lfloor \frac{L_S - Q - (W_S + Q)}{RDam} \right\rfloor$, thus the maximum number of rest areas could be $\left\lceil \frac{|I|}{\left\lfloor \frac{L_S - Q - (W_S + Q)}{RDam} \right\rfloor} \right\rceil$. Of course, if we do not round down $\frac{L_S - Q - (W_S + Q)}{RDam}$, we can have a lower bound of the number of rest areas.

From the above analysis, we can see both rest areas and lunch areas could vary based on the parameter settings. And the decision variables will increase as the number of groups increase. To be more specific, the number of decision variables is $(6 * |T| * |I| + 2)$ because we have 6 binary decision variables for each group in each time unit and have 2 decision variables that representing the number of lunch and rest areas. We believe the difficulty of solving this problem is mainly due to Q and L and the growing number of decision variables as we increase the problem size. Our numerical studies below also suggest that the problem is difficult and the CPU time increases with problem size. Considering that the scale of the problem size in the practical construction industry scenarios where our model is applied is not too large, we believe our model is sufficient for practical needs and the subsequent experiments also confirm this point.

4 Numerical experiments

In this section, we report the results of numerical experiments that are used to validate the effectiveness and efficiency of our N-WRL model. The experiments are run on a laptop computer equipped with 2.60 GHz of Intel Core i7 CPU and 16 GB of RAM, and models were solved by CPLEX Python API 20.1.0.

4.1 Basic results

We assume that a working day starts at 8:00 and finishes at 17:00, with a lunch break set between 11:00 and 14:00. Thus, $|T| = 36$, $TU_{L_s} = 12$, $TU_{L_e} = 24$. We set the minimum working time and lunch time to 60 minutes, i.e., $NTU_Q = NTU_L = 4$. Referring to Yi and Wang (2017), we set $RD_{am} = 15$ minutes and $RD_{pm} = 30$ minutes, i.e., $NTU_{RD_{am}} = 1$, $NTU_{RD_{pm}} = 2$, and $NTU_{RD_{day}} = 3$. Suppose that there are four groups of construction workers, namely the rebar team, the concrete team, the carpentry team, and the electrician team. We solve [M2] by CPLEX and there is only one Pareto optimal solution. (According to Corollary 1, when the Ideal point is the same as Nadir point, there will be only one point in the set of Pareto frontier. Moreover, the subsequent examples also have one Pareto optimal solution and hence we only report the results of one solution.) The optimal schedule plan is shown in Table 2 and we further convert time units to real time in Fig. 3. Results show that one rest area and two lunch areas need to be established.

Table 2. Optimal schedule plan in time units

	Work		Rest		Lunch
	Morning	Afternoon	Morning	Afternoon	
Group 1	[1,12] [14,16]	[17,18] [23,26] [29,36]	[13]	[27,28]	[19,22]
Group 2	[1,5] [7,16]	[21,25] [27,30] [32,36]	[6]	[26] [31]	[17,20]
Group 3	[1,4] [6,12]	[17,21] [24,36]	[5]	[22,23]	[13,16]

Group 4	[1,9] [11,16]	[17,20] [25,28] [31,36]	[10]	[29,30]	[21,24]

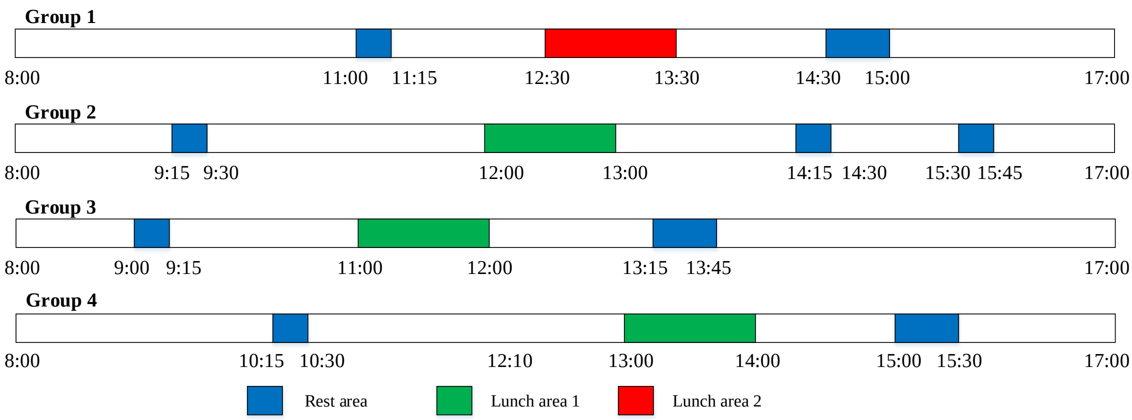

Fig. 3. Optimal schedule plan

4.2 Sensitivity analysis

Next, we conduct a sensitivity analysis to analyze the effect of parameter changes on the results of our model. First, we relax the lunch time rules. As shown in Fig. 4, we set the lunch start time earlier and postpone the end time. The results show that the construction site can provide one less lunch area when the lunch time interval is increased by 1 hour. However, increasing this interval by 30 minutes or 45 minutes has no effect. Moreover, the change in lunch time has no effect on the number of rest areas.

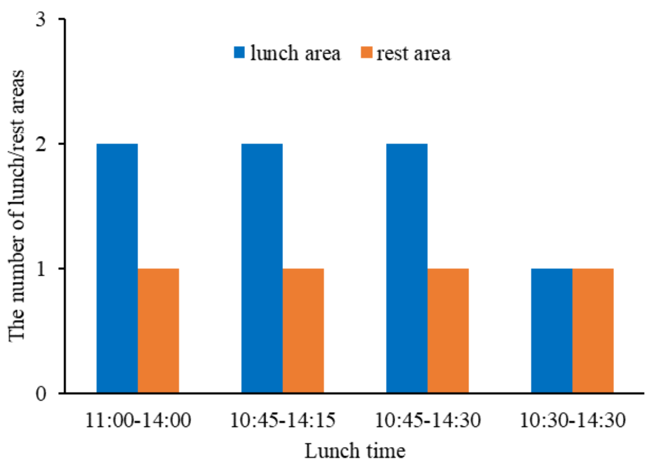

Fig. 4. Impact of lunch time

Second, we change the minimum duration of rest in the morning and afternoon and report the optimal solutions in Fig. 5. As the duration of rest increases, more rest areas need to be built to avoid contacts between different groups of construction workers. Similar to the results of our analysis above, changes in rest time do not affect the number of eating areas.

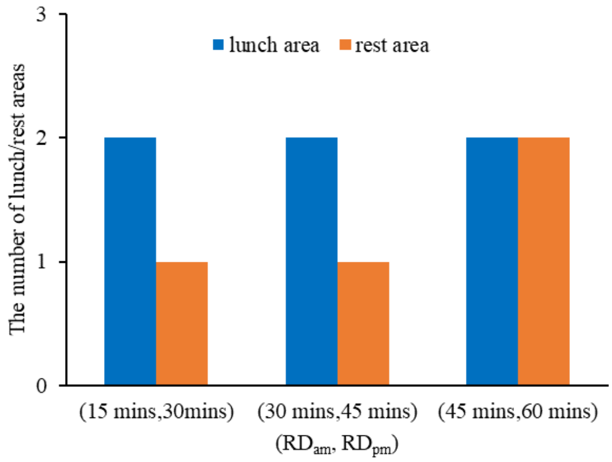

Fig. 5. Impact of rest time

Finally, we change the number of groups. The results indicate that the construction site needs more eating and rest areas as the number of groups increases (see Fig. 6). From a practical point of view, Fig. 6 provides guidelines for project managers to decide how many eating and rest areas to build according to the number of project groups. For example, if a project has eight groups of construction workers, at least three eating areas and two rest areas are needed. Moreover, Figure 6 indicates the minimum number of lunch and rest areas needed to keep construction workers safe from infection during COVID-19. The Centers for Disease Control and Prevention (CDC) in the United States defines close contact through proximity and duration of exposure as contact with infected people less than 6 feet away (CDC, 2022). Workers using the same area to eat or rest will definitely have contact with others less than 6 feet away. Supposing that a group has 15 workers, every reduction in the lunch or rest area will increase the number of people that each worker comes into close contact with. If one of the 15 contracts COVID-19, none of the close contacts will be able to continue working, jeopardizing the health of the workers and significantly affecting the progress of the construction project.

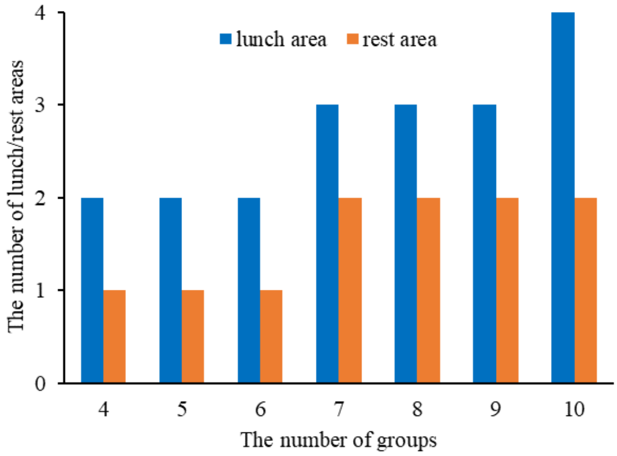

Fig. 6 Impact of the number of groups

We also report in Table 3 the CPU time required to solve our model as the number of groups increases. Moreover, we further validate the efficiency of our model using a larger number of groups: we set $|I|$ to 20, 30, 40, and 50. The largest instance can be solved within 4 minutes, which are efficient enough for practical use. Since the numbers of lunch and rest areas to build is a medium-term decision, our model is efficient enough for practical purposes.

Table 3. Computational efficiency

$\|I\|$	CPU Time (s)
4	0.81
6	8.22
8	22.05
10	23.84
20	146.06
30	117.00
40	132.00
50	227.00

5 Conclusion

From a theoretical point of view, by considering the COVID-19 regulations, we develop a bi-objective integer programming model that takes into account the reduction of physical contacts between construction workers of different groups and the practical requirements of construction sites, such as working hours and requirements for rest and lunch breaks. Our model can help contractors and project managers establish a contactless schedule plan at minimal cost. By adopting the proposed solution method, our numerical experiments show the effectiveness and efficiency of our N-WRL model. Moreover, our analysis indicates that the model is effective in reducing infection and close contact through proximity and duration of exposure.

From a practical point of view, the construction industry is highly labor-intensive, which makes it susceptible to the COVID-19 pandemic. For example, nearly 40% of construction workers in Hong Kong were infected with the COVID-19 pandemic from December 2021 to March 2022 (Sing Tao Daily, 2022). And some new regulations towards the social distancing make many workers eat their lunch along the roads outside the construction sites. Soliman et al. (2022) suggest that the most important motivational factor in construction industry during the COVID-19 is job security. Therefore, planning in advance and delineating lunch and rest areas are vital for workers' security and are also important for the operations of the whole construction industry. Moreover, because of the high number of workers on construction sites and the high risk of virus transmission, our research contributes to the control of the COVID-19 pandemic and helps contractors reduce costs.

This study is not without limitations. We assume that construction workers have a fixed start and end time of work, the same as before the COVID-19 outbreak. Therefore, in this study, we develop a schedule model using fixed work start and end parameters. However, in response to the pandemic, working hours may have become more flexible in many industries. In this case, the scheduling problem is more complicated. In future research, more flexible working hours could be considered and studies could provide a more comprehensive scheduling model. Finally, randomness in the problem should be considered in future studies by stochastic optimization models (Wang et al., 2021; Huang and Wang, 2022).

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