Towards an optimal work pattern for construction workers in hot weather: a case study in Hong Kong

Wen Yi [1*], Albert P.C. Chan [2]

[1] PhD, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; E-mail address: yiwen96@163.com (corresponding author)

[2] Professor and Interim Dean, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; E-mail address: albert.chan@polyu.edu.hk

Abstract

Having established a Monte Carlo simulation-based algorithm to optimize work-rest schedule in a hot and humid environment, this paper attempts to develop the algorithm and identify an optimal work pattern which may maximize the direct-work rates and minimize the health hazard due to heat stress to the workers concerned. Traditionally, construction workers in Hong Kong start work at 8:00 am and finish work at 6:00 pm, having one hour lunch break between 12:00 pm and 1:00 pm, and an additional break of 30 min at 3:15 pm. Construction workers can beat the heat by starting earlier to avoid some extreme conditions which may occur at certain times of a day. By maintaining the current practice of 9-hour working duration for a day, twenty-one additional work patterns with different start and finish times were proposed and evaluated by the developed optimization algorithm. An optimized schedule (direct-work rate of 87.8%) of working from 7:30 am to 12:00 pm with a 20 min break at 9:40 am; having lunch break between 12:00 pm and 1:00 pm; and working from 1:00 pm to 5:30 pm with a 30 min break at 3:00 pm is proposed. The proposed work pattern not only maximizes direct-work rates but also minimizes the occurrence of heat stress on construction site. This will enable policy makers to derive solid guidelines for working in hot weather. Since the proposed work pattern is developed specifically for the construction industry, more work is needed to further investigate other industries and to other climates to provide a holistic view in future.

Keywords: Construction industry; Direct-work rates; Hot and humid climate; Monte Carlo simulation; Work patterns; Work-rest schedule;

Introduction

Since the past decade, the impact of climate change has led to an increased frequency and intensity of extreme temperatures (Luber and McGeehin 2008). Working people are particularly exposed to these heating trends in tropical and sub-tropical countries, where excessive workplace heat exposures linked to the outdoor ambient thermal environment are a traditional part of local life, but heat waves in cooler countries are also affecting workers' health and productivity (Lundgren et al. 2013). The Washington State Department of Labor and Industries (WSDLI) (2008) estimated six million workers in the United States were exposed to occupational heat stress as a potential safety and health hazard. In tropical and equatorial regions, the proportion of the worker population exposed to heat stress may even be higher. Traditionally employees engaged in the construction industry account for 6-10% of the total labor force (International Labour Organization 2013), but they have a much higher risk of work-related illnesses and accidents than workers in other branches of industry and the public sector (Choudhry and Fang 2008; Yi et al. 2012). Fall of person from height, contact with equipment, and exposures to harmful substances or environments accounted for the majority of fatalities in this industry (Bureau of Labor Statistics 2006). Health and safety of construction workers deserve greater attention from governments and the research community.

The nature of the Hong Kong construction industry is inherently complex and demanding within its meteorological and business environments (Yip and Rowlinson 2009). The environment of high temperature and humidity with low wind speed is insufferable. Heat stress, having caused preventable and lamentable deaths, is hazardous to construction workers in hot and humid summer of Hong Kong (Apply Daily 2007&2010). In a survey conducted in Hong Kong during 2011, 17 of 37 trades reported cases of heat-induced illness on construction sites (Rowlinson et al. 2013). To address the pressing need of the industry, the Hong Kong government and the industry have promulgated a series of fundamental practice notes and guidelines on working in hot weather and provided some recommendations on proper work arrangement (e.g., take regular breaks, rotate duties, reschedule works to cooler periods such as early morning) (Construction Institute Council 2008; Department of Health 2010; Labour Department 2010). Health and safety measures for construction workers, in particular those related to work arrangement, linked up to scientific and clinical parameters are urgently needed.

In addition to the above-mentioned demanding environmental conditions, the business environment of the construction industry in Hong Kong is highly competitive which puts construction workers prone to stress and burn-out at work (European Foundation for the Improvement of Living and Working Conditions 2011). Construction projects in Hong Kong are characterized as “fast track” with severe penalties for delays, leading to “unrealistically compressed delivery programs” (Tang 2001). Thus, construction workers are frequently required to work for long and irregular hours. In this case, how construction workers spend their working time is of great concern. Craft working time utilization often reflects the presence of ‘organizational imposed constraints’ that hinder the improvement of construction productivity (Maloney 1990). Traditionally, construction workers in Hong Kong start work at 8:00 am and finish work at 6:00 pm, having one hour lunch break between 12:00 pm and 1:00 pm with an additional break of 30 min at 3:15 pm. Typical working hours on a construction site in Hong Kong are 9 hours (excluding lunch break), Monday-Saturday, resulting in a 54-h work week, which is 6 hours more than the SA8000 reference standard (International Labour Organization 2007). However, working overtime beyond these periods and even on rest days is not uncommon in the local industry. Such undesirable physical working conditions have been found to be common stressors of construction workers. To protect the well-being of construction workers in hot seasons, the Hong Kong Construction Association (HKCA) has taken initiatives to pilot a different work pattern in summer of 2012 to start work at 7:45 am in the morning and finish work at 6:15 pm in the afternoon, having a 1.5 hours lunch break in between. In addition, workers are given a 15 min break in both the morning and afternoon sessions (Hong Kong Wen Wei Po 2011). This pilot scheme addresses two issues: (a) introduce additional rest time in the morning, and (b) start work earlier to beat the heat wave. Konz (1998) points out that both the amount of recovery (rest) and the distribution are important. By maintaining the current 9-hour working duration for a day, this paper attempts to evaluate the effectiveness of the pilot scheme and identify an optimal work pattern which may maximize the direct-work rates and minimize the health hazard due to heat stress to the workers concerned.

Problem Description

Earlier research work by Yi and Chan (2013a) has provided a Monte Carlo simulation (MCS)-based algorithm to simulate an optimized work rest schedule by taking workers’ health and direct-work rates into account. The optimization algorithm focused on the duration of direct-work time (DT) from the perspective of productivity improvement where little attention was paid to the strain that workers endured during working at heat exposure. Taking the estimation of workers' strain into the optimization algorithm can achieve a better balance between direct-work rates in the construction industry and workers' health and safety hazards against hot and humid climate.

Furthermore, the optimal work-rest schedule proposed in earlier study (Yi and Chan 2013a) was simulated within the constraint of a prescribed work pattern (8:00 am-12:00 pm in the morning and 1:00 pm-5:00 pm in the afternoon). However, further enhancement may be achieved by thinking outside the box of scheduling work activities beyond the prescribed working hours. Evidence from the world's hottest regions (e.g., Middle East, Africa) indicates that construction workers commence work at 5:00 am and finish work at 3:00 pm (Porritt et al. 2011). Construction workers can beat the heat by starting earlier to avoid some extreme conditions which may occur at certain times of a day. Previous research indicates that meteorological parameters [wet bulb globe temperature (WBGT) and air pollution index (API)] are influential to determine the maximum work duration (heat tolerance time, HTT) (Chan et al. 2012a; Chan et al. 2013). The purpose of this paper is to develop and apply the established MCS-based algorithm to evaluate the impact of different start and finish times on direct-work rates and health hazard. The ultimate aim is to identify an optimal work pattern which may maximize the direct-work rates and minimize health hazard due to heat stress.

Cumulative Strain (CS)

Cumulative strain (CS) is defined as total inner feeling of overall exertion (e.g., physical effort, stress and fatigue) to the task. Ratings of perceived exertion, defined as the intensity of subjective effort, stress, discomfort felt during physical activity (Coquart et al. 2009; Foster et al. 2001), was used as a yardstick to measure workers' strain in this study. A multiple regression equation of RPE with ten determining factors was constructed as Eq. (1) (Chan et al. 2012a). The CS that a construction worker reaches exhaustion can be estimated based on the RPE equation.

$$RPE=-5.43+0.11WBGT+1.40T+0.10API+0.06A-0.07PBF+2.28ADH+0.50SH+0.14EC+0.16RE-0.01RHR \quad (1)$$

where WBGT is wet bulb globe temperature (°C); T is work duration (hour); API is air pollution index; A is age; PBF is percentage of body fat (%); RHR is resting heart rate; ADH is alcohol drinking habit ("none"= 0, "occasionally"= 1, "usually"= 2), SH is smoking habit ("none"= 0, "occasionally"= 1, "usually"= 2); EC is energy consumption; and RE is respiratory exchange.

Developed MCS-based Algorithm

An optimized schedule involves scheduling work-rest frequency, rest duration, and timing of rest breaks (Hise et al. 2009). The calculation of optimal work-rest schedule is illustrated in Figure 1. Two goals were addressed in the optimization process when such schedules are designed. These goals include maximizing the direct-work rates and minimizing the workers' strain during working at heat exposure. Monte Carlo simulation technique is used to account for the uncertainties and variations of meteorological and physiological parameters during summer time in Hong Kong. It estimates the maximum work duration that workers can work without endangering their health hence prevents the occurrence of heat stress on construction site. Scenario analysis is employed to determine the number of breaks of different durations to find out which work-rest pattern may yield the highest DT and lowest CS. On the basis of work-to-exhaustion-then-take-a-rest principle, an optimized work-rest schedule that maximizes the direct-work rates and at the same time safeguards the health and safety of construction workers is developed.

(Please insert Figure 1 here)

Timing of Rest Breaks

Earlier research work has developed a heat stress model to compute the maximum work duration (Heat Tolerance Time, HTT) that a construction worker could work continuously without endangering his/her health (Chan et al. 2012a). Based upon 281 sets of synchronized meteorological and physiological data collected from construction workers in four different construction sites between July and September 2010, physiological, work-related, environmental and personal parameters were measured to construct a HTT model (Chan et al. 2012a). Having been verified and validated against virgin data, the HTT model was found to be statistical acceptable (Chan et al. 2012a; Yi and Chan 2013b). HTT is defined as the duration that a construction worker can work continuously without endangering their health (voluntary exhaustion). HTTs of construction workers are different due to their own personal characteristics (e.g., age, alcohol drinking habit, smoking habit, percentage of body fat, resting heart rate) and work environment (API and WBGT). Different HTTs in construction workforce imply that resting time may be required at varied moments for different construction workers. For scheduling purpose, it is necessary to unify the work-rest pattern. Hence, the mode HTT that appears most often in a set of HTTs was taken as the desired timing of rest breaks and was subsequently used as reference values to determine the work-rest frequency and rest durations.

Rest Durations

Chan et al. (2012b) determined how long construction workers should be allowed to recover in hot weather after working to exhaustion. It was found that on average that a construction worker could achieve 58% energetic recovery in 5 min; 68% in 10 min; 78% in 15 min; 84% in 20 min; 88% in 25 min; 92% in 30 min; 93% in 35 min; and 94% recovery in 40 min (Chan et al. 2012b). In general, the longer they have the resting period, the better the recovery of their strength although the rate of recovery has a diminishing effect with increased recovery time. Henning et al. (1989) demonstrated that the degree of recovery was proportionate to the length of the rest break taken. The subsequent heat tolerance time/RPE of a construction worker would be reduced by the same degree of recovery if s/he was not allowed adequate rest time to achieve full recovery.

Work-Rest Frequency

Scenario analysis was employed to determine the number of breaks of different durations to find out which work-rest pattern would yield the highest DT and lowest CS. Each scenario represented a coherent view of a possible meteorological and physiological state. The RPE increases with the work duration in each scenario since other HTT variables were kept constant in a meteorological and physiological state. The CS that a construction worker reaches exhaustion can be computed as Eq. (2).

$$\mathrm{CS}_{ij} = \begin{cases} \int_0^{HTT_{ij}} (\alpha t + \beta) dt & (\mathrm{j} = 1) \\ 7 * (1 - \text{Rate of revoevry}_k) + \int_0^{HTT_{ij}} (\alpha t + \beta) dt & (\mathrm{j} > 1) \end{cases} \quad (2)$$

where CS_{ij} is the j^{th} cumulative RPE that the construction rebar worker reaches exhaustion in scenario *i*; HTT_{ij} is the j^{th} work duration that the construction worker reaches exhaustion in scenario i (h); α = 1.40; β = 0.11WBGT + 0.10API + 0.06A - 0.07PBF + 2.28ADH + 0.50SH + 0.14EC + 0.16RE - 0.01RHR; Rate of recovery $_k$ is the corresponding recovery rate after taking a rest of R_k (i.e. 5 min, 10 min, 15 min, 20 min, 25 min, 30 min, 35 min, 40 min).

The scheduling mechanism of work-to-exhaustion-then-take-a-rest principle is shown in Figure 2. On the basis of the work-to-exhaustion-then-take-a-rest principle, the calculation of the number of breaks, DT and CS for each scenario was conducted. After testing these scenarios, the average number of breaks was determined and then the average DT and CS were estimated. The calculations of CS for each scenario and the average CS after testing for *m* scenarios are described as Eqs. (3) and (4) respectively.

$$CS_i = \sum_{j=0}^{n_i} CS_{ij} \quad (3)$$

$$\text{Average } CS = \frac{1}{m}\sum_{i=0}^{m} CS_i \quad (4)$$

where CS_{ij} is the j^{th} cumulative RPE that the construction rebar worker reaches exhaustion in scenario *i*; n_i is the number of breaks for rebar worker in scenario *i*; *m* is number of various scenarios (meteorological and physiological state).

(Please insert Figure 2 here)

Work Patterns

The traditional work pattern in Hong Kong is from 8:00 am to 6:00 pm with one hour lunch break between 12:00 pm and 1:00 pm. The HKCA's pilot scheme is from 7:45 am to 6:15 pm with a 1.5 hour lunch break. A common element in both work patterns is the total working hours of 9-h. Therefore, work patterns were generated to be in line with the common work arrangement of 9-h working hours and one hour lunch break per day. In the light of Employment Standards Act which specifies that no employee should work more than 5 consecutive hours without a meal break (Ministry of Labour 1995), three work arrangements were considered to develop these work patterns: (a) 4 h in the morning session and 5 h in the afternoon session; (b) 4.5 h in the morning session and 4.5 h in the afternoon session; and (c) 5 h in the morning session and 4 h in the afternoon session. The earliest start time and the latest end time for these work patterns were set to 6:00 am and 7:00 pm respectively as the daylight hours of Hong Kong summer time (between June and September) are between 6:00 am and 7:00 pm (Hong Kong Observatory 2011). Based on the start-early-and-finish-early principle, twenty-one additional work patterns were proposed and are listed in Figure 3. The methodology employed to optimize work-rest schedule in different work patterns is summarized in Figure 3. The optimization algorithm was applied in the HKCA's pilot scheme, the traditional pattern and 21 proposed work patterns respectively to compare and identify which pattern would yield the highest productive time of construction workers. Monte Carlo simulation was conducted to these 23 work patterns to determine the time of resting. Scenario analysis was further applied to find out which work-rest pattern would yield the highest DT. Except for the HKCA's pilot scheme and the traditional work pattern where the duration and timing of breaks are fixed, construction workers in other work patterns would be allowed to take a break if they have reached exhaustion, to ensure that their health and safety would not be undermined.

(Please insert Figure 3 here)

Monte-Carlo Simulation

Distribution Fitting of Meteorological Variables

The nature of uncertainty and variability is expressed in the form of a probability distribution, which gives both the range of values that the variable could take and the likelihood of occurrence of each value within the range (Sari et al. 2009). Generally, the distribution and its parameters are previously unknown and need to be estimated from the available information about the random nature of the meteorological variables (WBGT and API) in different work patterns. WBGT was invented more than 50 years ago and is now the most widely used index to assess heat stress (Budd 2008). It was invented and first used during the 50s as an imaginative and successful campaign to control heat illness in training camps of the United States Army and Marine Corps (Yaglou and Minard 1957). The main strengths of WBGT are its consideration of the effects of the sun and wind, which are the two crucial components of outdoor climate, as well as those of air temperature and humidity (American College of Sports Medicine 2007). WBGT was captured by a heat stress monitor (QUESTemp°36, Oconomowoc, Wisconsin, United States). The heat stress monitor measures four environmental parameters simultaneously at 1 minute interval: ambient or dry bulb temperature, natural wet bulb temperature, globe temperature, relative humidity from which the corresponding WBGT index can be computed. The API is based on the level of 6 atmospheric pollutants, namely sulfur dioxide (SO_2), nitrogen dioxide (NO_2), respirable suspended particulates, carbon monoxide (CO), ozone (O_3), lead (P_b) and is measured and updated hourly by the Hong Kong Environmental

Protection Department into a single number (Environmental Protection Department 2007).

Expanded distribution curve for WBGT was constructed from 819 sets of meteorological data collected from seven different construction sites between July and September of 2010-2012 in Hong Kong (281 in 2010, 411 in 2011, and 127 in 2012), whereas the distribution curve for API was obtained by referring to the summer record (July-September 2010-2013) broadcasted by the Environmental Protection Department. Crystal Ball™ (a widely applied Monte Carlo simulation tool) performs a mathematical fit to determine the set of parameters for each distribution that best describes the characteristics of the selected data. It judges the quality of each fit using one of several standard goodness-of-fit tests, and then chooses the distribution with the highest-ranking fit to represent the selected data. Distribution curve for WBGT and API were constructed for each work pattern.

Simulation of HTT

Distribution curves for non-meteorological HTT variables (i.e., age, smoking and alcohol drinking habits, resting heart rate, percentage of body fat, energy consumption, respiratory exchange) were constructed by referring to historical data. HTT is set to range from 0 to 4 / 4.5 / 5 hour according to the work time for construction workers in Hong Kong. A simulation of 100,000 iterations with a 95% confidence interval for each HTT variable was performed with the Crystal Ball™ to model a variety of outcome values.

Evaluation of HKCA's Pilot Scheme, Traditional Work Pattern and Other Proposed Work Patterns

Based on the optimization algorithm developed by Yi and Chan (2013a), Monte Carlo simulation is used to compute the HTT probability distribution in a given work pattern. HTT is set to range from 0 to 4.25 / 4.75 hour between 7:45 am - 12:00 pm in the morning and between 1:30 pm - 6:15 pm in the afternoon respectively for the pilot scheme. Similar assessments are done for the traditional work pattern, i.e. start work at 8:00 am, and finish work at 6:00 pm, with one hour lunch break between 12:00 pm and 1:00 pm, and other proposed work patterns as shown in Figure 3. Crystal Ball™, simulation software, which sorted and matched all the resulting values of HTT with corresponding values of HTT variables, was used to compute the simulation. The work-rest pattern of each scenario (a possible meteorological and physiological state) can be derived by the scheduling mechanism. Since voluntary exhaustion (heat tolerance) is a state of self-awareness when one starts to feel a general inability to physically continue to perform due to consumption of all energy stored (World of Sports Science 2012), the work duration/RPE beyond HTT is considered as non-DT and 7 respectively. The DT for each scenario and the average DT after testing for m iterations can be computed by Eq. (5) and Eq. (6) respectively. The CS for each scenario and the average CS after testing for m iterations can be computed by Eq. (7) and Eq. (8) respectively.

$$DT_{ij}\,(h) = \begin{cases} RT_j - ST_{j-1} & HTT_{ij} > RT_j - ST_{j-1} \quad (j \geq 1) \\ HTT_{ij} & HTT_{ij} \leq RT_j - ST_{j-1} \quad (j \geq 1) \end{cases} \tag{5}$$

$$\text{Average DT (h)} = \frac{1}{m}\sum_{i=1}^{m}\left(\sum_{j=1}^{n} DT_{ij}\right) \tag{6}$$

where DT_{ij} is the direct-work time of the construction worker before j^{th} timing of rest breaks in i^{th} iteration (hour); RT_j is the j^{th} timing of rest breaks set in the work-rest schedule; ST_{j-1} s the $j\text{-}1^{th}$ timing of start time set in the work-rest schedule; HTT_{ij} is the work duration that the construction worker reaches exhaustion before j^{th} timing of rest breaks in i^{th} iteration (hour); *m* is number of iterations by Monte Carlo methods; *n* is the number of rest breaks in the work-rest schedule.

$$
\mathrm{CS}_{ij} = \begin{cases} \int_0^{\mathrm{RTj\ -\ ST\ j-1}} (\alpha t + \beta) dt + 7 * (HTT_{ij} - RT_j - ST_{j-1}) & HTT_{ij} > RT_j - ST_{j-1} \cap \mathrm{j} = 1 \\ \int_0^{\mathrm{RTj\ -\ ST\ j-1}} (\alpha t + \beta) dt + 7 * (HTT_{ij} - RT_j - ST_{j-1}) + 7 * (1 - \text{Rate of revoevry}_{\ k}) & HTT_{ij} > RT_j - ST_{j-1} \cap \mathrm{j} > 1 \\ \int_0^{HTT_{ij}} (\alpha t + \beta) dt & HTT_{ij} \leq RT_j - ST_{j-1} \cap \mathrm{j} > 1 \\ \int_0^{HTT_{ij}} (\alpha t + \beta) dt) + 7 * (1 - \text{Rate of revoevry}_{\ k}) & HTT_{ij} \leq RT_j - ST_{j-1} \cap \mathrm{j} > 1 \end{cases} \tag{7}
$$

$$
\text{Average CS} = \frac{1}{\mathrm{m}} \sum_{\mathrm{i}=1}^{\mathrm{m}} (\sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{CS_{ij}}) \tag{8}
$$

where CS_{ij} is the j^{th} cumulative RPE that the construction rebar worker reaches exhaustion in scenario i; $\mathrm{RT_j}$ is the j^{th} timing of rest breaks set in the work-rest schedule; $\mathrm{ST_{j-1}}$ s the $j\text{-}1^{th}$ timing of start time set in the work-rest schedule; HTT_{ij} is the j^{th} work duration that the construction worker reaches exhaustion in scenario i (h); α = 1.40; β = 0.11WBGT + 0.10API + 0.06A - 0.07PBF + 2.28ADH + 0.50SH + 0.14EC + 0.16RE - 0.01RHR; Rate of recovery $_k$ is the corresponding recovery rate after taking a rest of R_k (i.e. 5 min, 10 min, 15 min, 20 min, 25 min, 30 min, 35 min, 40 min).

Statistical Analysis

A descriptive statistical analysis on the meteorological parameters and HTT in 23 work patterns was conducted. One-way analysis of variance (ANOVA) and was employed to identify variables (i.e., length of work session, beginning of work session, end of work session, rest duration, timing of rest breaks) that would significantly affect the DT, DR and CS. Direct-work rate (DR) is defined as the percentage of DT with respect to total working hours daily and is expressed mathematically as Eq. (9). All statistical analyses were performed at a level of 95% statistical significance ($p < 0.05$). These analyses were performed using software program SPSS 17.0.

$$\text{DR (\%)} = \text{DT (hour) / Total working hours daily} \tag{9}$$

where DR is direct-work rate (%); and DT is direct-work time (hour).

Results

The simulated (Mean ± Standard Deviation) meteorological data in each work pattern are listed in Table 1. The mode HTT, rest duration, work-rest frequency, DT, DR and CS in each work pattern are summarized in Table 2.

(Please insert Table 1&2 here)

HTT in Different Work Patterns

The simulated HTTs after disregarding the extreme values (those falling beyond 95% confidence level) are shown in Table 2. It can be seen in each work arrangement (i.e. 4 h in the morning session and 5 h in the afternoon session; 4.5 h in the morning session and 4.5 h in the afternoon session; 5 h in the morning session and 4 h in the afternoon session) the mode HTT increases in the morning session, but deceases in the afternoon session. The change of the mode HTT in different work patterns lies in the variation of meteorological parameters (WBGT and API) as illustrated in Table 1. It is noted in Table 1 and 2 that the longest HTT reaches 2.58 h in work pattern 1 between 6:00 am and 10:00 am in the morning session (WBGT = 25.9 ± 1.0°C; API = 33.7 ± 8.0), while the shortest HTT reduces to 1.84 h in work pattern 15 between 12:00 pm and 4:00 pm in the afternoon session (WBGT = 33.7 ± 1.7°C; API = 36.8 ± 7.4). The HTT of the pilot scheme (work pattern 22) reaches 2.17 h between 7:45 am and 12:00 pm in the morning and reaches 2.03 h between 1:30 pm and 6:15 pm in the afternoon, which is longer than that of traditional work pattern (work pattern 23), 2.11 h between 8:00 am and 12:00 pm in the morning and 2.01 h between 1:00 pm and 6:00 pm in the afternoon.

Rest Time in Different Work Patterns

Table 2 shows the break time and number of breaks in each work pattern. It can be seen in each work arrangement that the total rest time (rest duration multiply number of breaks) increases with the mode HTT. It is also found that the longer the work duration is required in a work session, the longer rest time would be required. It is indicated that the shortest rest time (a 5 minute break) is required in work pattern 1 between 6:00 am and 10:00 am (HTT = 2.58 h) or in work pattern 2 between 6:30 am and 10:30 am (HTT = 2.53 h), while the longest rest time (two 25-minute break) is required in work pattern 1 between 11:00 am and 4:00 pm (HTT = 1.91 h) or in work pattern 2 between 11:30 am and 4:30 pm (HTT = 1. 89 h). The pilot scheme (work pattern 22a) has a 15 min break in the morning and a 15 min break in the afternoon, which is shorter than the computed rest time of 20 min in the morning and 30 min in the afternoon (work pattern 22b). The traditional work pattern (work pattern 23) only has a 30 min break in the afternoon, and none in the morning, however, the computed rest times is 15 min in the morning and 40 min in the afternoon (work pattern 5). Both the pilot scheme and the traditional work pattern do not provide adequate rest times to the construction workers and may endanger their health.

Optimal Work-Rest Schedule in Different Work Patterns

The DT and CS of the pilot scheme is 7.61 h (3.70 h in the morning and 3.91 h in the afternoon) and 51.1 (24.7 in the morning and 26.4 in the afternoon) respectively, which is better off than that of the traditional work pattern, 6.93 h (3.01 h in the morning and 3.92 h in the afternoon) and 54.3 (29.8 in the morning and 24.5 in the afternoon). A remarkable DT improvement of 9.9% and CS alleviation of 5.9% is achieved by the pilot scheme. Further DT improvements and CS alleviation can be made (DT of 7.73 h and CS of 46.9 for work pattern 22b and DT of 7.69 h and CS of 46.9 for work pattern 5) if adequate rest times are allowed as computed by the optimization algorithm. Nevertheless, when compared with other work patterns proposed in this paper, the pilot scheme has not achieved the optimized result yet.

It can be seen from Table 2 that three optimized patterns could yield the highest DT of 7.90 h: (1) work pattern 11 (7:30 am-12:00 pm in the morning session and 1:00 pm-5:30 pm in the afternoon session); (2) work pattern 15 (6:00 am-11:00 am in the morning session and 12:00 pm-4:00 pm in the afternoon session); and (3) work pattern 17 (7:00 am-12:00 pm in the morning session and 1:00 pm-5:00 pm in the afternoon session). The average CS of 46.6 arises in work pattern 11 and work pattern 17 is less than that of work pattern 15. Both work pattern 11 and work pattern 17 achieve maximum daily DT and could better safeguard construction workers' health and safety. Significant difference ($p < 0.05$) was found in DT and DR in different work sessions (Table 3-4). It was found DT increases with the length of work sessions while the DR decreases with the length of work sessions. It can be seen in Table 3 that 5 hour work session reaches the highest DT (4.07 h), followed by 4.5 hour work session (3.91 h) and 4 hour work session (3.65 h). Average DR was 4.24% higher for 4 hour work session in comparison with the 4.5 hour work session, and 9.75% higher than the average DR for 5 hour work session (Table 4).

(Please insert Table 3&4 here)

Discussion

HTT

International Organization for Standardization and Occupational health and safety agencies (e.g., American Conference of Governmental Industrial Hygienists, National Institute for Occupational Safety and Health) provide useful guidelines to individuals when being exposed to heat stress (NIOSH 1986; American Conference of Government Industrial Hygienists 2000; ISO 7933 1989; ISO 7243 2003). A common element in the evaluation of heat tolerance time is the use of WBGT. However, earlier studies and these OHS requirements on work limits at heat exposure fail to consider the personal characteristics, which would underestimate or overestimate the personal heat tolerance time. Age, weight, degree of physical fitness, use of alcohol or drugs, and a variety of medical conditions such as hypertension may affect a person's sensitivity to heat (Chan 2012a; Chan et al. 2013; Rowlinson et al. 2013). The heat stress model developed by Chan et al. (2012a) could determine the heat tolerance time (HTT) of construction workers by keeping certain parameters constant. Tucker et al. (2003) demonstrated that the injury and accident risk more than doubled over 2 hour of continuous work. Japan Society for Occupational Health (2005) has established similar occupational exposure limits for heat stroke, and advocates that workers should work for no more than two hours. Our findings provide convincing evidence to the timing of rest breaks for construction workers in hot and humid environment.

Rest Time

Recovery can play a considerable role to the well-being of construction workers (Maxwell et al. 2008). Similar findings have also been reported by other researchers for rest break studies. Tiwari and Gite (2006) opined that the duration of rest pauses should be at least 15 min to avoid excessive discomfort for physical demanding workers. Morioka et al. (2006) demonstrated that a 20 min break schedule could improve discomfort ratings for outdoor workers on construction site. Longer break is recommended in this study due to the insufferable environment of high temperature and humidity with low wind speed. Construction workers have to undertake outdoor physical work and often in confined spaces. Physically demanding works combined with the exposure to high temperature, humidity, solar radiation and poor air ventilation can further increase the physical stress of construction workers.

Improving labor productivity and maintaining occupational health and safety are major concerns in many industries. To reduce physiological strain as well as to improve productivity, administration of a suitable rest break schedule is considered as an effective solution (Tiwari and Gite 2006). Evidence from a range of industrial settings appears to suggest that fatigue can benefit from relatively frequent short breaks (Tucker 2003). A number of studies have called for more frequent and shorter breaks for light repetitive work (Dababneh et al. 2001). However, some studies have suggested that frequent breaks may cause task interruptions, which may cause direct-work rates to drop (Henning et al. 1997). The more frequent the breaks are, the more chances are for task interruptions (Awwad et al. 2001). Our findings of proposing a 20 min break schedule at mid-morning and a 30 min break schedule at mid-afternoon achieve maximum DT and DR.

Job Rotation

Although long work hours increase DT, it results in the loss of DR and fatigue because construction laborers have to perform complex, dynamic and fast-paced work in hot and humid environment. An analysis of aggregated data showed an exponential increase of accident risk from 8 up to 16 hours at work (Nachreiner 2001). However, construction workers in Hong Kong are always required to work for more than 9 hours daily. Job rotation is regarded as a control for fatigue. Jonsson (1998) asserted that this strategy is ideal for construction because it is especially useful for dynamic tasks that require variations in muscular load. Furthermore, job rotation reduces errors and increases direct-work rates (Ortega 2001). Hence, it is recommended that contractors could implement an appropriate job rotation plan for construction workers in hot seasons. Developing a proper job rotation plan involves determining which jobs to include, the rotation sequence and the proper rotation interval (Tharmaphornphilas and Norman 2004). Further research on planning job rotation in hot and humid environment should be launched.

Practical Application to the Construction Industry

Two optimized patterns could yield the highest DT of 7.90 h with a low CS of 46.6 (Table 2): (1) work pattern 11 (7:30 am-12:00 pm in the morning session and 1:00 pm-5:30 pm in the afternoon session); and (2) work pattern 17 (7:00 am-12:00 am in the morning session and 1-:00 pm-5:00 pm in the afternoon session). Further considerations need to be examined to determine which work pattern provides a better outcome. As in many densely populated cities around the world, noise is a significant environmental problem in Hong Kong (Fung and Lee 2011). In order to restrict and reduce the nuisance caused by environmental noise, the Hong Kong government manages construction noise under the Noise Control Ordinance. Execution of general construction work using powered mechanical equipment during the restricted hours (i.e. between 7:00 pm and 7:00 am or at any time on a general holiday) is prohibited under the Ordinance in Hong Kong unless a valid Construction Noise Permit is in force (Environmental Protection Department 2006), hence making work before 7:00 am difficult, if not impossible. Furthermore, if workers were to start work at 6:00am, they might need to wake up much earlier to allow for the travelling time to work. This might affect workers' social life and create further hardship and affect their willingness to work in the industry, it is therefore proposed that the 7:30 am-5:30 pm roster is a better option to achieve maximum DT/DR and minimize the likelihood of heat-related injuries to the workers. Under this work pattern, they will start work at 7:30 am and have a 20 min break at 9:40 am and continue work until 12:00 pm. They will have 1 hour lunch break at 12:00 pm and resume work at 1:00 pm. They will have another 30 min break at 3:00 pm and continue work until 5:30 pm.

A remarkable DT improvement of 9.9% and CS alleviation of 5.9% is achieved by the pilot scheme. Nevertheless, it is yet to achieve the optimal result. The optimal work-rest schedule which yields a DT of 7.90 h and a CS of 46.6 is to start work at 7:30 am and have a 20 min break at 9:40 am and continue work until 12:00 pm. Workers will have 1 hour lunch break at 12:00 pm and resume work at 1:00 pm. They will have another 30 min break at 3:00 pm and continue work until 5:30 pm. The optimal work-rest schedule can achieve a substantial DT improvement of 14.0% and CS alleviation of 14.2% when compared with the traditional work pattern.

Strengths and Limitations

Extreme hot environments are prevalent in numerous occupational settings, outdoors or in hot indoor environments. Such extreme conditions are commonly encountered in many occupational settings such as steel and iron manufacturing, glass factories, mining, textiles, ceramics, food canneries, construction, and farm work. Guidelines/recommendations on working in hot weather are by and large some "dos and don'ts" and are not based on scientific measurements. A better approach in deriving scientific algorithm to detect impending attacks of heat stress is urgently needed. The current study has contributed in providing an objective and scientific mechanism to optimize work-rest schedule in hot and humid environment. The methodology (see Figure 2) could be applied in different types of climates and for different industries to design an appropriate work-rest schedule for productivity improvement as well as accidents reduction. HTT and recovery rate could be determined by measuring the physiological conditions of workers and environmental parameters of workplace. The optimal work-rest schedule could be accordingly simulated on the basis of scheduling mechanism (work-to-exhaustion-then-take-a-rest).

Construction engineering and management research examines real-world means and methods in an effort to improve the effectiveness and efficiency of the industry (Lucko and Rojas 2010).This study illustrates how MCS technique can be applied in construction management research to achieve an optimized solution for construction workers. The current study has expanded and contributed in optimizing work-rest schedule for construction workers against hot and humid climate in the following manners.

- **Sophisticated algorithm** — Based on the early studies of Yi and Chan (2013a) which provides an objective and scientific mechanism to optimize work-rest schedule, a MCS-based algorithm is improved by taking the workers' cumulative strain into consideration. This improvement achieves a better balance between direct-work rates in the construction industry and workers' health and safety hazards against hot and humid climate. The enhanced algorithm is further developed to evaluate work pattern in practice. The current study applies the developed algorithms to evaluate the HKCA's pilot scheme and traditional work pattern.

- **Practical approach** — Earlier research work optimized work-rest schedule based on a prescribed work pattern (8:00 am -12:00 pm in the morning and 1:00 pm-5:00 pm in the afternoon). Further enhancement has been achieved by thinking outside the box of scheduling work activities beyond the prescribed working hours (e.g., starting work earlier to avoid some extreme conditions). The current study proposed 21 work patterns in line with the common work arrangement of 9-h working hours and one hour lunch break, and identified an ideal work pattern which may maximize the productive time of construction workers and minimize the health hazard due to heat stress.
- **Precise simulation** — Monte Carlo simulation is a computerized tool for modeling a stochastic process where the input data are randomly determined by certain statistical distributions (Kroese et al. 2011). In such a simulation, the computer generates large sets of outputs after running a large number of iterations with random inputs. Larger numbers of simulations can avoid bias in the statistical sense. High precision can be achieved by increasing the number of iterations in a simulation (Kroese et al. 2011). In order to obtain high accuracy for the mode HTTs, a simulation of 100,000 iterations was performed in the current study as compared to 10,000 iterations in the previous study.

The limitation of the study is the single sample source and the limited sample size. In this study, participants were mainly steel bar bender and fixers since bar bending and fixing is recognized as one of the most hazardous trades in the construction industry. Their physical abilities may be different from other trades of construction workers. Further research work should be done to increase the sample size and to replicate the experimentation to different trades to detect the effect of job nature on HTT. Instead of assessing the construction productivity as a whole, this study focused on the crew time utilization which is a part of construction productivity measurement. Further research on construction labor productivity measured by hourly output (using a labor hour as the input unit and the physical quantity of the completed work as output) in hot and humid environments is envisaged to be conducted in future. Last but not least, certain construction tasks such as concrete pours would carry on for over 5 hours. Studies on certain construction tasks (e.g., concrete pours) which have to go beyond 5 hours are definitely worth pursuing and will be subjects for future studies.

Conclusions

The nature of the Hong Kong construction industry is inherently complex and demanding. The meteorological environment of hot and humid summer of Hong Kong is hazardous to construction workers. Construction workers have to undertake physically demanding activities in these hot and humid conditions. Working in such an environment poses a significant challenge to their health and safety. In addition to these demanding environmental conditions, the business environment of the construction industry in Hong Kong is highly competitive. Construction workers are frequently asked to work for long and irregular hours, which are detrimental to worker's comfort, health, and productivity. To balance crew time utilization with workers' health and safety in a hot and humid environment, a schedule with direct-work rate of 87.8% is identified as the ideal work pattern for construction workers. Under this work pattern, construction workers will start work at 7:30 am and have a 20 min break at 9:40 am and continue work until 12:00 pm. They will have 1 hour lunch break at 12:00 pm and resume work at 1:00 pm. They will have another 30 min break at 3:00 pm and continue work until 5:30 pm. The proposed work pattern will enable the industry to produce solid guidelines for working in hot weather which may maximize the productive time of construction workers and at the same time minimize the health hazard due to heat stress.

Workers in different industries/regions may have different degrees of susceptibility to heat stress. An industry by industry specific study would better reflect the real situation. Since this study applies specifically to the construction industry, more work is needed to further investigate other industries and to other climates/seasons to provide a holistic view in future. This would be of tremendous value in better improving labor productivity and safeguarding workers' occupational health and safety.

Acknowledgements

This project is funded by two grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (RGC Project No. PolyU510409 and No. PolyU5107/11E). The research team is indebted to the technical support from technicians of the Hong Kong Polytechnic University and the Hong Kong Institute of Education. In particular, the participation of volunteers in this experimental study is gratefully acknowledged. This paper forms part of the research project titled "Experimental research on health and safety measures for working in hot weather", from which other deliverables will be produced with different objectives/scopes but sharing common background and methodology. The authors also wish to acknowledge the contributions of other team members including Prof Francis Wong, Dr Michael Yam, Dr Daniel Chan, Dr Edmond Lam, Prof Joanne Chung, Dr Del Wong, Prof Esmond Mok, Dr Geoffrey Shea, Dr Min Wu, Prof Herbert Biggs, Dr Donald Dingsdag, Dr YP Guo, Miss Alice Guan and Miss Jackie Yang.

References

American College of Sports Medicine. (2007). “Exertional heat illness during training and competition.” *Medicine and Science in Sports and Exercise*, 39 (3), 556-572.

American Conference of Government Industrial Hygienists. (2000). *Thermal Stress. In: Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposures Indices*, ACGIH. Cincinnati, OH.

Apple Daily. (2007). “Worker died from heat stroke in golf course (in Chinese).” <http://www1.hk.apple.nextmedia.com/template/apple/art_main.php?iss_id=20070724&sec_id=4104&art_id=7359016> (24 July 2007).

Apple Daily. (2010). “Worker died from heat stroke in a falling accident (in Chinese).” <http://hk.apple.nextmedia.com/realtime/art_main.php?iss_id=20100918andsec_id=6996647andart_id=14465015> (19 September 2010).

Awwad, J., Dababneh, A.J., Swanson, N., and Shell, R.L. (2001). “Impact of added rest breaks on the productivity and well being of workers.” *Ergonomics*, 44, 2, 164-174.

Budd, G.M. (2008). “Wet-bulb globe temperature (WBGT)–its history and its limitations.” *Journal of Science and Medicine in Sport*, 11, 1, 20-32.

Bureau of Labor Statistics. (2006). Fatal workplace injuries in 2006: a collection of data and analysis. <http://www.bls.gov/iif/cfoibulletin2006.htm> (12 June 2009).

Chan, A.P.C., Yam, M.C.H., Chung, J.W.Y., and Yi, W. (2012a). “Developing a heat stress model for construction workers. *Journal of Facilities Management*, 10, 1, 59-74.

Chan, A.P.C., Yi, W., Wong, D.P., Yam, M.C.H., and Chan, D.W.M. (2012b). “Determining an optimal recovery time for construction rebar workers after working to exhaustion in a hot and humid environment.” *Building and Environment*, 58, 163-171.

Chan, A.P.C., Yi, W., Chan, D.W.M., and Wong, D.P. (2013). “Using the thermal work limit (TWL) as an environmental determinant of heat stress for construction workers.” *Journal of Management in Engineering*, 29, 4, 414-423.

Choudhry, R.M., and Fang, D. (2008). “Why operatives engage in unsafe work behaviors: Investigating factors on construction sites.” *Safety Science*, 46, 566−584.

Construction Industry Council. (2008). *Guidelines on site safety measures for working in hot weather*, Publication No.2. Version 1. <http://www.hkcic.org/files/eng/documents/Publications/Working_in_hot_weather.pdf>

Coquart, J.B., Legrand, R., Robin, S., Duhamel, A., Matran, R., and Garcin, M. (2009). “Influence of successive bouts of fatiguing exercise on perceptual and physiological markers during an incremental exercise test.” *Psychophysiology*, 46(1), 209-216.

Dababneh, A.J., Swanson, N., and Shell, R.L. (2001). “Impact of added rest breaks on the productivity and well being of workers.” *Ergonomics*, 44, 2, 164-174.

Department of Health, HKSAR Government (2010). “Preventive measures against heat stroke and sun burn.” < http://www.dh.gov.hk/english/press/2010/100706-3.html> (6 July 2010).

Environmental Protection Department. (2006). *Noise from construction sites*. A concise to the noise control ordinance, ninth edition.

Environmental Protection Department. (2007). “API and air monitoring background information” < http://www.epd-asg.gov.hk/english/backgd/calcu.html>

European Foundation for the Improvement of Living and Working Conditions. (2011). “Workers prone to stress and burnt-out at work.” <http://www.eurofound.europa.eu/ewco/surveyreports/LU1012011D/LU1012011D.pdf>

Foster, C., Florhaug, J.A., Franklin, J., Gottschall, L., Hrovatin, L.A., Parker, S., Doleshal P., and Dodge, C. (2001). “A new approach to monitoring exercise training.” *Journal of Strength and Conditioning Research*, 15(1), 109-115.

Fung, Y.W., and Lee, W.L. (2011). “Identifying a common parameter for assessing the impact of traffic-induced noise and air pollutions on residential premises in Hong Kong.” *Habitat International*, 35, 2, 231-237.

Gouett, M.C., Haas, C.T., Goodrum, P.M., and Caldas, C.H. (2011). Activity analysis for direct-work rate improvement in construction. Journal of Construction and Engineering and Management, 137, 12, 1117-1124.

Henning, R.A., Sauter, S., Salvendy, G., and Krieg, E. (1989). Microbreak length, performance and stress in a data entry task. *Ergonomics*, 32, 855-864.

Henning, R., Pierre, J., Kissel, G., Sullivan, A., and Alteras-Webb, S. (1997). “Frequent short rest breaks from computer work: effects on productivity and well being at two field sites.” *Ergonomics*, 40, 78-91.

Hise, M., Hsiao, W.T., Cheng, T.M., and Chen, H.C. (2009). “A model used in creating a work-rest schedule for laborers.” *Automation in Construction*, 18, 6, 762-769.

Hong Kong Observatory. (2011). “2011 times of sunrise/sunset, moonrise/moonset and tidal predictions.” < http://www.weather.gov.hk/prtver/pdf/docs/gts/astron2011/sunrise_main_e.pdf>

Hong Kong Wen Wei Po. (2011). “Pilot scheme is implemented for construction rebar workers (in Chinese).” <http://trans.wenweipo.com/gb/paper.wenweipo.com/2011/08/19/HK1108190031.htm>(19 Aug 2011).

International Labour Organisation (ILO). (2007). <http://www.ilo.org/global/lang--en/index.htm> (25 Oct

2007).

International Labour Organisation (ILO). (2013). Labour Force Surveys. <http://www.ilo.org/dyn/lfsurvey/lfsurvey.home> (8 May 2013)

ISO 7243. (2003). *Hot Environments—Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)*. Geneva: International Standards Organization.

ISO 7933. (1989). *Hot Environments-Analytical Determination and Interpretation of Thermal Stress Using Calculation of Required Sweat Rate, 1st ed*. International Organization of Standard, Geneva, Switzerland.

Japan Society for Occupational Health. (2005). "Recommendation of occupational exposure limits (2005-2006)." *Journal of Occupational Health*, 47, 354-370.

Jonsson, H. (1998). "Ernst Westerlund: A Swedish doctor of occupation." *Occupational Therapy International*, 5, 155-171.

Konz, S. (1998). "Work/rest: Part II: The scientific basis (knowledge base) for the guide." *International Journal of Industrial Ergonomics*, 22, 73-99.

Kroese, D.P., Taimre, T., and Botev, Z.I. (2011). *Handbook of Monte Carlo Methods*, Wiley Series in Probability and Statistics. New York: John Wiley and Sons.

Maloney, W.F. (1990) Framework for analysis of performance. *Journal of Construction Engineering and Management*, 116(3), 399–415.Labour Department. (2010). "Prevention of Heat Stroke at Work in a Hot Environment." <http://www.labour.gov.hk/eng/news/PreventionOfHeatStrokeAtWork.htm> (29 October 2010).

Luber, G, and McGeehin, M. (2008). "Climate change and extreme heat events." *American Journal of Preventive Medicine*, 35, 5, 429-435.

Lucko, G., and Rojas, E.M. "Research validation: challenges and opportunities in the construction domain." *Journal of Construction Engineering and Management*, 136, 1, 127-135.

Lundgren, K., Kuklane, K., Gao, C., and Holmer, I. (2013). "Effects of heat stress on working populations when facing climate change." *Industrial Health*, 51, 3-15.

Maxwell, N.S., Castle, P.C., and Spencer, M. (2008). "Effect of recovery intensity on peak power output and the development of heat strain during intermittent sprint exercise while under heat stress." *Journal of Science and Medicine in Sport*, 11, 5, 491-499.

Ministry of Labour. (1995). *British Columbia Employment Standards Act and Regulations.* <http://www.labour.gov.bc.ca/esb/igm/esa-part-4/igm-esa-s-32.htm>

Morioka, I., Miyai, N., and Miyashita, K. (2006). "Hot environment and health problems of outdoor workers at a construction site." *Industrial Health*, 44, 474-480.

Nachreiner, F. (2001). "Time on task effects on safety." *Journal of Human Ergology*, 30, 1-2, 97-102.

Ortega, J. (2001). "Job rotation as a learning mechanism." *Management Science*, 47, 10, 1361-1370.

Porritt, S., Shao, L., Cropper, P., and Goodier, C. (2011). "Adapting dwellings for heat waves." *Sustainable Cities and Society*, 1, 81–90.

Rowlinson, S., Jia, A.Y., Li, B., and Ju, C.C. (2013). "Management of climatic heat stress risk in construction: a review of practices, methodologies, and future research." *Accident Analysis and Prevention*. DOI: http://dx.doi.org/doi:10.1016/j.aap.2013.08.011. (Accepted on 9 August 2013).

Sari, M., Selcuk, A., Karpuz, C., and Duzgun, H. (2009). "Stochastic modeling of accident risks associated with an underground coal mine in Turkey." *Safety Science*, 47, 78-87.

Sonmez, R., and Rowings, J.E. (1998). "Construction labor productivity modeling with neural networks." *Journal of Construction Engineering and Management*, 124(6), 498-504.

Tang, H. (2001). *Construct for excellence*. Rep. of the Construction Industry Review Committee, The Government of the Hong Kong Special Administrative Region, Hong Kong.

Tharmaphornphilas, W. and Norman, B. (2004). "A quantitative method for determining proper job rotation intervals." *Annals of Operations Research*, 128(1-4), 251-266.

Tiwari, P.S., and Gite, L.P. (2006). "Evaluation of work-rest schedules during operation of a rotary power tiller." I*nternational Journal of Industrial Ergonomics*, 36, 3, 203-210.

Tucker, P. (2003). "The impact of rest breaks upon accident risk, fatigue and performance: a review." *Work and Stress*, 17, 2, 123-137.

Tucker, P., Folkard, S., and Macdonald, I. (2003). "Rest breaks and accident risk." *Lancet*, 361, 680.

Washington State Department of Labor and Industries (WSDLI) (2008). "Outdoor heat exposure. concise explanatory statement." Economic analyses. Heat-related illness small business economic impact statement. < http://www.lni.wa.gov/rules/AO06/40/0640CES.pdf>

World of Sports Science. (2012) "Exhaustion." <http://www.faqs.org/sports-science/Dr-Fo/Exhaustion.html>.

Yaglou, C.P. and Minard, D. (1957). "Control of heat casualties at military training centers." *Archives of Industrial Health*, 16, 4, 302–316.

Yi, J., Kim, Y., Kim, K., and Koo, B. (2012). "A suggested color scheme for reducing perception-related accidents on construction work sites." *Accident Analysis & Prevention*, 48, 185-192.

Yi, W., and Chan, A.P.C. (2013a). "Optimizing work-rest schedule for construction rebar workers in hot and humid environment." *Building and Environment*, 61, 104-113.

Yi, W., and Chan, A.P.C. (2013b). "Which environmental indicator is the best in predicting the effects of heat stress on construction workers?" *Journal of Management in Engineering*. Posted ahead of print 9

Jan 2014. doi: 10.1061/(ASCE)ME.1943-5479.0000284.

Yi, W., and Chan, A.P.C. (2014). "Critical review of labor productivity research in construction journals." *Journal of Management in Engineering*, 30(2), 214-225.

Yip, B., and Rowlinson, S. (2009). "Job burnout among construction engineers working within consulting and contracting organizations." *Journal of Construction Engineering and Management*, 25, 3, 122-130.

Table 1 Statistics (Mean ± Standard Deviation) on meteorological data in different work patterns

Work pattern	Morning session	WBGT (°C)	API	Afternoon session	WBGT (°C)	API
1	6:00am-10:00am	25.9±1.0	33.7±8.0	11:00am -4:00pm	32.6±1.8	36.2±7.3
2	6:30am-10:30am	26.3±1.0	33.8±8.4	11:30am -4:30pm	33.0±1.9	36.5±7.9
3	7:00am-11:00am	27.0±1.2	34.1±8.3	12:00pm -5:00pm	32.3±2.4	37.5±6.8
4	7:30am-11:30am	27.7±1.3	34.2±8.2	12:30am -5:30pm	31.8±2.4	37.6±6.9
5	8:00am-12:00pm	28.9±1.3	34.3±9.4	1:00pm -6:00pm	30.9±2.5	37.8±7.1
6	8:30am-12:30pm	30.5±1.3	34.8±8.6	1:30pm -6:30pm	30.4±2.6	37.4±8.0
7	9:00am-1:00pm	31.7±1.3	35.0±7.3	2:00pm -7:00pm	29.9±2.6	37.1±8.4
8	6:00am -10:30am	26.2±1.1	33.7±8.0	11:30am -4:00pm	33.0±1.7	36.3±7.5
9	6:30am -11:00am	26.6±1.1	34.0±8.3	12:00pm -4:30pm	33.4±1.8	36.8±8.3
10	7:00am -11:30am	27.3±1.2	34.2±8.3	12:30pm -5:00pm	32.4±2.3	37.5±6.9
11	7:30am -12:00pm	28.3±1.3	34.3±9.5	1:00pm -5:30pm	31.9±2.3	37.6±7.1
12	8:00am -12:30 pm	29.5±1.4	34.6±9.4	1:30pm -6:00pm	30.6±2.4	37.8±7.7
13	8:30am -1:00pm	31.2±1.4	34.8±8.7	2:00pm -6:30pm	30.2±2.4	37.6±8.2
14	9:00am -1:30pm	32.1±1.4	35.2±8.2	2:30pm -7:00pm	29.6±2.3	37.2±8.1
15	6:00am -11:00am	26.3±1.5	33.8±8.4	12:00pm -4:00pm	33.7±1.7	36.8±7.4
16	6:30am -11:30am	26.6±1.5	34.1±8.4	12:30am -4:30pm	33.5±1.7	37.2±6.9
17	7:00am -12:00pm	27.9±1.5	34.2±9.6	1:00pm -5:00pm	32.2±2.1	37.6±6.9
18	7:30am -12:30pm	28.5±1.4	34.4±9.6	1:30pm -5:30pm	31.3±2.0	37.5±7.0
19	8:00am -1:00pm	30.3±1.3	34.7±9.0	2:00pm -6:00pm	30.5±2.2	37.5±8.0
20	8:30am -1:30pm	31.1±1.3	34.9±8.8	2:30pm - 6:30pm	30.1±2.4	37.3±7.5
21	9:00am - 2:00pm	32.3±1.3	35.4±8.4	3:00pm -7:00pm	29.2±1.9	37.0±8.1
22	7:45am - 12:00pm	28.7±1.3	34.3±9.4	1:30pm -6:15pm	30.5±2.4	37.6±7.9
23	8:00am-12:00pm	28.9±1.3	34.3±9.4	1:00pm -6:00pm	30.9±2.5	37.8±7.2

Note: Work pattern 1-7 is 4h in the morning session and 5h in the afternoon session; Work pattern 8-14 is 4.5h in the morning session and 4.5h in the afternoon session; Work pattern 15-21 is 5h in the morning session and 4h in the afternoon session; Work pattern 22 is HKCA's pilot scheme; Work pattern 23 is the traditional work pattern.

Table 2 Optimal work-rest schedule in different work patterns

Work pattern	Morning session	Mode HTT (hour)	Break time (min)	Nr	DT (hour)	CS	Afternoon session	Mode HTT (hour)	Break time (min)	Nr	DWT (hour)	CS	Total DT (hour)	DR (%)	Total CS
1	6:00am-10:00am	2.58	5	1	3.87	28.5	11:00am-4:00pm	1.91	25	2	3.85	23.1	7.72	85.8	51.6
2	6:30am-10:30am	2.53	5	1	3.85	28.3	11:30am-4:30pm	1.89	25	2	3.81	23.0	7.66	85.1	51.3
3	7:00am-11:00am	2.35	10	1	3.76	26.0	12:00pm-5:00pm	1.94	20	2	3.88	24.4	7.64	84.9	50.4
4	7:30am-11:30am	2.24	10	1	3.73	25.6	12:30am-5:30pm	1.96	20	2	3.92	24.5	7.65	85.0	50.1
5	8:00am-12:00pm	2.11	15	1	3.69	23.5	1:00pm-6:00pm	2.02	40	1	4.00	23.4	7.69	85.4	46.9
6	8:30am-12:30pm	2.04	20	1	3.66	22.1	1:30pm-6:30pm	2.05	35	1	4.09	23.8	7.75	86.1	45.9
7	9:00am-1:00pm	1.99	20	1	3.58	21.9	2:00pm-7:00pm	2.11	30	1	4.19	24.4	7.77	86.3	46.3
8	6:00am-10:30am	2.56	10	1	4.21	29.0	11:30am-4:00pm	1.87	40	1	3.63	20.8	7.84	87.1	49.8
9	6:30am-11:00am	2.47	15	1	4.18	26.8	12:00pm - 4:30pm	1.86	20	2	3.53	22.1	7.70	85.6	48.9
10	7:00am-11:30am	2.29	15	1	4.11	26.2	12:30pm - 5:00pm	1.95	30	1	3.77	22.0	7.88	87.6	48.2
11	**7:30am-12:00pm**	**2.18**	**20**	**1**	**4.09**	**24.5**	**1:00pm - 5:30pm**	**2.00**	**30**	**1**	**3.81**	**22.1**	**7.90**	**87.8**	**46.6**
12	8:00am-12:30pm	2.07	25	1	3.98	23.3	1:30pm - 6:00pm	2.03	25	1	3.92	23.1	7.89	87.7	46.4
13	8:30am-12:30pm	2.01	25	1	3.89	23.1	2:00pm - 6:30pm	2.08	25	1	3.98	23.3	7.87	87.4	46.4
14	9:00am-1:00pm	1.95	35	1	3.76	21.5	2:30pm -7:00pm	2.13	20	1	4.00	24.4	7.76	86.2	45.9
15	**6:00am-11:00am**	**2.50**	**20**	**1**	**4.55**	**27.5**	**12:00pm-4:00pm**	**1.84**	**35**	**1**	**3.35**	**19.1**	**7.90**	**87.8**	**46.9**

16	6:30am-11:30am	2.31	25	1	4.40	26.1	12:30am-4:30pm	1.88	35	1	3.39	19.4	7.79	86.6	45.5
17	**7:00am-12:00pm**	**2.21**	**30**	**1**	**4.31**	**24.7**	**1:00pm-5:00pm**	**1.99**	**20**	**1**	**3.59**	**21.9**	**7.90**	**87.8**	**46.6**
18	7:30am-12:30pm	2.11	30	1	4.17	24.4	1:30pm-5:30pm	2.00	20	1	3.61	21.9	7.78	86.4	46.3
19	8:00am-1:00pm	2.06	35	1	4.10	23.8	2:00pm-6:00pm	2.04	20	1	3.65	22.0	7.75	86.1	45.8
20	8:30am-1:30pm	2.03	40	1	3.97	23.2	2:30pm-6:30pm	2.09	15	1	3.69	23.4	7.66	85.1	46.6
21	9:00am-2:00pm	1.94	20	2	3.86	24.4	3:00pm-7:00pm	2.14	15	1	3.72	23.5	7.58	84.2	47.9
22a	7:45am-12:00pm	2.17	15	1	3.70	24.7	1:30pm-6:15pm	2.03	15	1	3.91	26.4	7.61	84.6	51.1
22b	7:45am-12:00pm	2.17	20	1	3.74	23.6	1:30pm-6:15pm	2.03	30	1	3.99	23.3	7.73	85.9	46.9
23	8:00am-12:00pm	2.11	0	0	3.01	29.8	1:00pm - 6:00pm	2.01	30	1	3.92	24.5	6.93	77.0	54.3

Note: Nr is number of breaks; DT is direct-work time (hour); DR is direct-work rate (%); CS is cumulative strain; Work pattern 1-7 is 4h in the morning session and 5h in the afternoon session; Work pattern 8-14 is 4.5h in the morning session and 4.5h in the afternoon session; Work pattern 15-21 is 5h in the morning session and 4h in the afternoon session; Work pattern 22a is HKCA's pilot scheme and work pattern 22b is an improved pattern derived from the optimization algorithm (7:45 am-12:00 pm in the morning and 1:30 pm - 6:15 pm in the afternoon); Work pattern 23 is the traditional work pattern and work pattern 5 is an improved pattern derived from the optimization algorithm (8:00 am -12:00 pm in the morning and 1:00 pm -6:00 pm in the afternoon

Table 3 ANOVA test of direct-work time in different work sessions

Work sessions (hour)	Direct–work time (hour)		F	Sig
	Mean	St. Dev.		
4	3.65	0.15	17.206	.000
4.5	3.91	0.20		
5	4.07	0.22		

Table 4 ANOVA test of direct-work rate in different work sessions

Work sessions (hour)	Direct-work rate (%)		F	Sig
	Mean	St. Dev.		
4	91.32	3.68	18.753	.000
4.5	87.08	4.46		
5	81.57	4.49		

Figure 1
Click here to download Figure: figure1.pdf

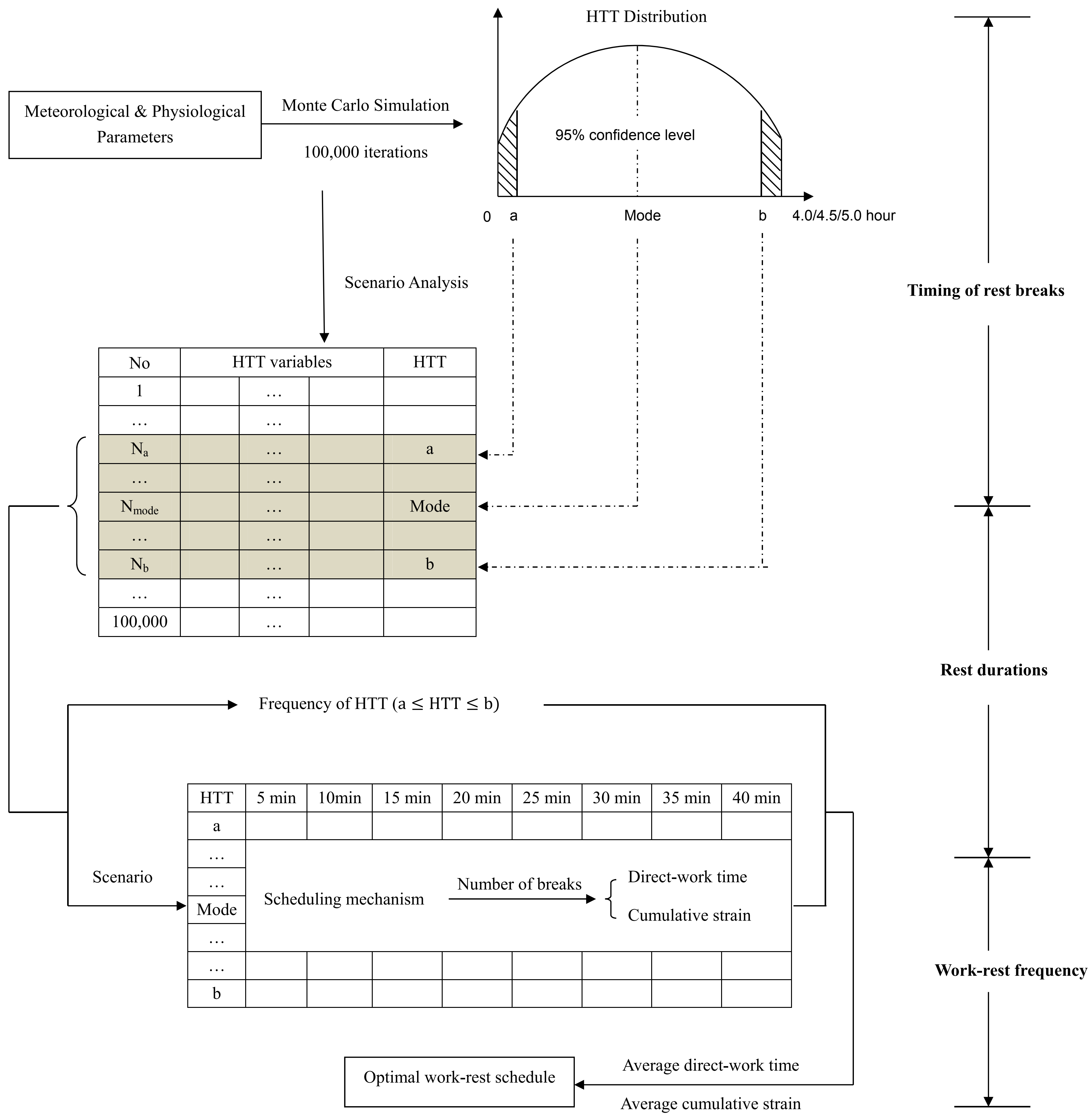

Figure 2
Click here to download Figure: figure2.pdf

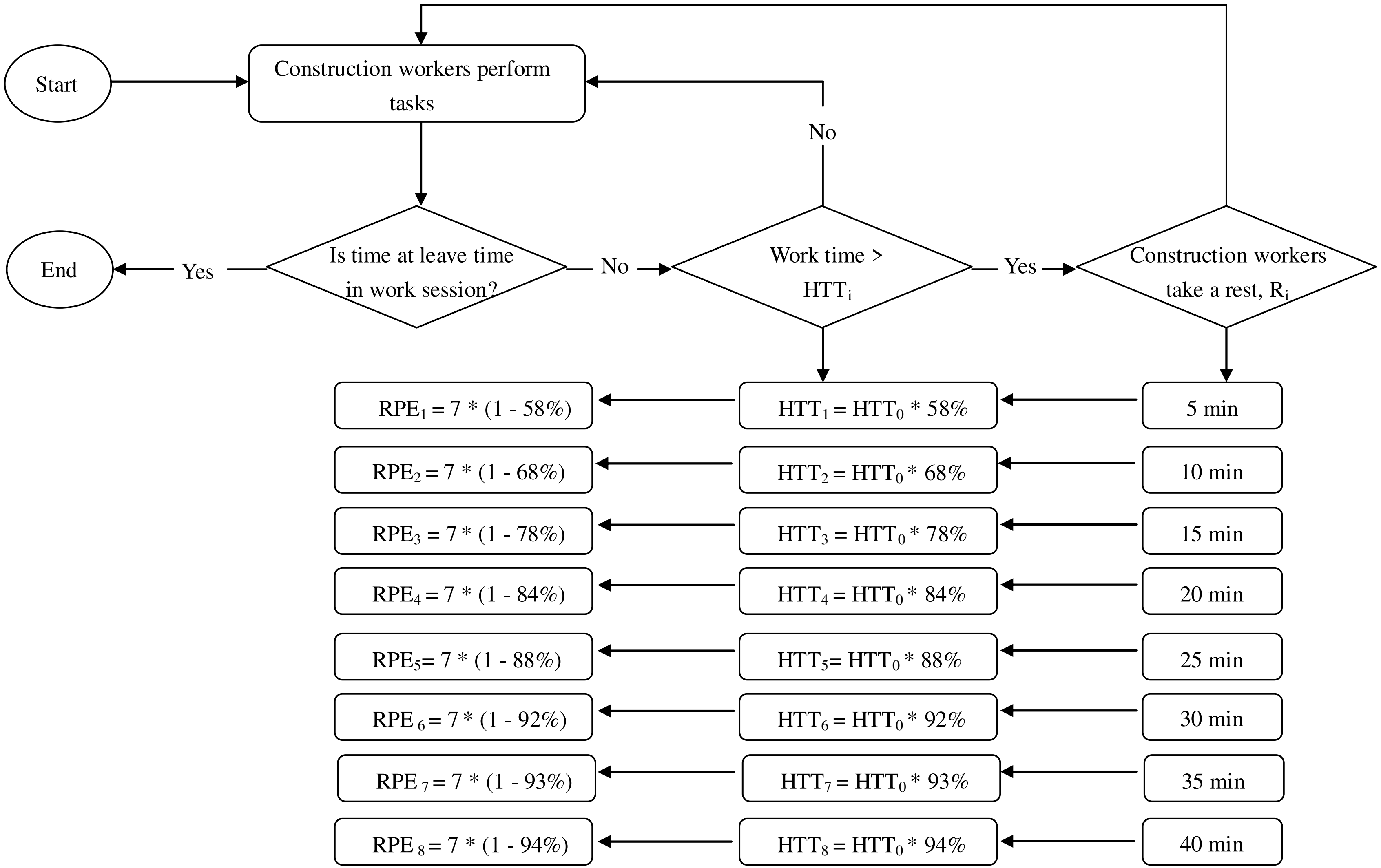

Figure 3
Click here to download Figure: figure3.pdf

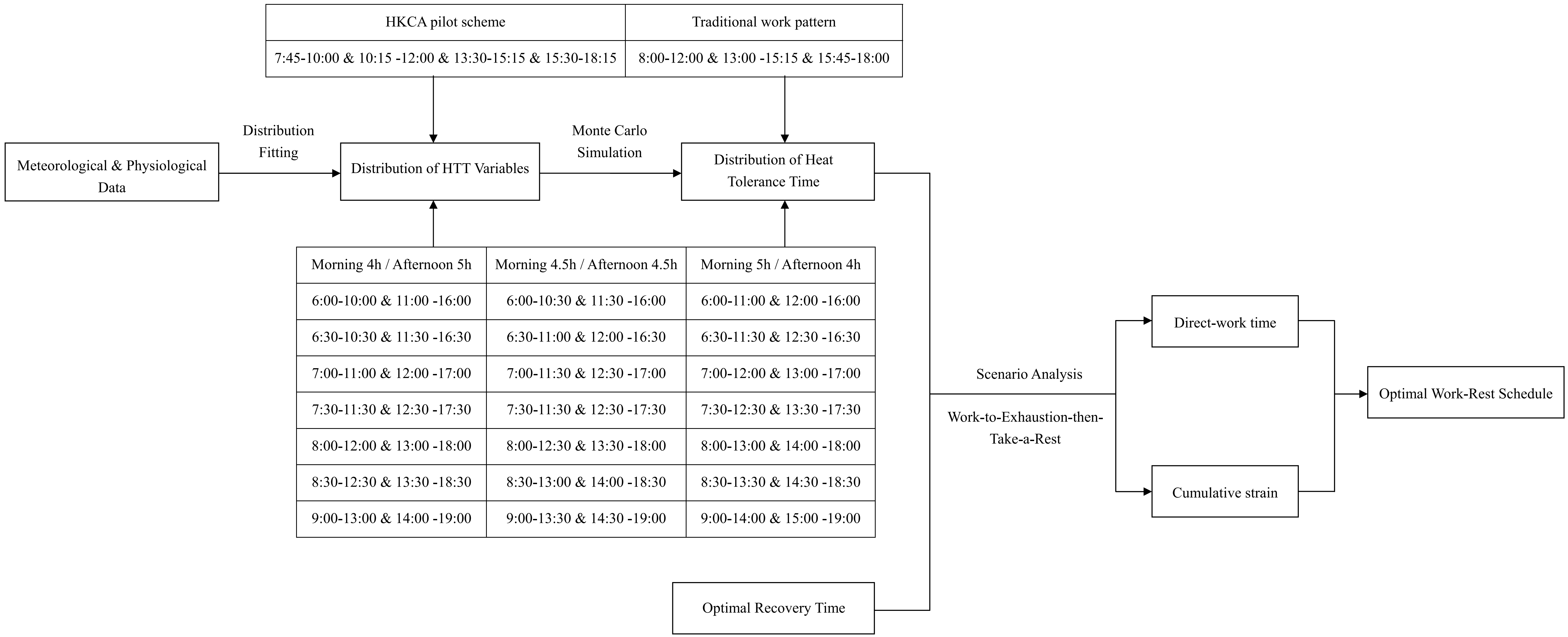

Figure Caption List

Fig. 1 Calculation of optimized work-rest schedule

Fig. 2 Scheduling mechanism

Fig. 3 Flowchart of optimizing work-rest schedule in different work patterns