MODELING, INVESTIGATING, AND QUANTIFICATION OF THE HOT WEATHER EFFECTS ON CONSTRUCTION PROJECTS IN OMAN

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ABSTRACT: The construction industry is recognized as one of the industries most exposed to climatic conditions. Construction projects are mainly executed in an outdoor environment and the activities are considered weather-sensitive. Severe weather conditions can directly affect the productivity and efficient operation of construction projects. In addition, the weather is known to be one of the main factors that decrease labour productivity in construction projects causing project delays, cost overruns, and contractual claims between contractors and clients. Oman has a hot climate with very high temperatures in summer, warm winters, and low annual rainfall. During extremely hot weather, labour productivity significantly decreases, as construction work may stop partially or completely, therefore, this paper investigates and quantifies the hot and humid weather effects in construction projects in Oman. A construction productivity model was developed using the work/rest schedule proposed by the National Institute for Occupational Safety and Health (NIOSH), USA. The daily weather temperature and relative humidity of Muscat were inputs into the model and the expected productivity in terms of working hours were the output of the model. The model was applied to case studies, which involved three completed construction projects under different testing scenarios in Muscat. Results indicate that implementing the influence of hot and humid weather can lead to an extension of 3–38% longer project duration compared to the planned duration.

Keywords: Construction; Heat stress; Productivity; Project duration; Modeling.

نمذجة وبحث تأثير الطقس الحار على مشاريع البناء في عمان

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الملخص: تعتبر صناعة البناء من أكثر الصناعات المعرضة للظروف المناخية ويتم تنفيذ مشاريع البناء بشكل أساسي في بيئة خارجية وتعتبر أنشطتها حساسة للطقس. يمكن أن تؤثر الظروف الجوية القاسية بشكل مباشر على إنتاجية وكفاءة عمليات مشاريع البناء، بالإضافة إلى ذلك ، من المعروف أن تأثيرات الطقس على صناعة البناء هي أحد العوامل الرئيسية التي تقلل من إنتاجية العمالة، مما يتسبب في تأخير المشروع ، وتجاوز التكاليف ، والمطالبات التعاقدية بين المقاولين وأصحاب المشروع. يعتبر مناخ عمان جاف وحار ويمتاز بدرجات حرارة عالية جدا في الصيف و دافئ شتاء، وأثناء الظواهر الجوية شديدة الحرارة قد تنخفض إنتاجية عمال البناء بشكل كبيرمما يؤدي إلى توقف أعمال البناء جزئيًا أو كليًا. تهدف هذه الورقة البحثية إلى نمذجة وبحث وقياس تأثيرات الطقس الحار والرطب في مشاريع البناء في عمان. تم تطوير نموذج إنتاجية البناء باستخدام جدول نسبة العمل إلى الراحة المقترح من المعهد الوطني للسلامة والصحة المهنية (NIOSH). تم استخدام درجة حرارة الطقس اليومية والرطوبة النسبية لمحافظة مسقط كمدخلات في النموذج وكانت الإنتاجية المتوقعة من حيث ساعات العمل هي ناتج النموذج. تم تطبيق النموذج في ثلاث مشاريع انشائية وفي ظل عدة سيناريوهات اختبار مختلفة. أشارت النتائج إلى أن تأثير الطقس الحار والرطب يمكن أن يؤدي إلى إطالة مدة المشروع بنسبة 3 إلى 38٪ مقارنة بالمدة المخطط لها.

الكلمات المفتاحية: التشييد؛ الإجهاد الحراري؛ الإنتاجية؛ مدة المشروع؛ النمذجة.

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1. INTRODUCTION

Construction projects are executed in an outdoor environment, most of its activities being conducted by workers outdoors (Al Shebani and Wedawattab, 2014) and therefore, are affected by various weather conditions (El-Rayes and Moselhi, 2001). Weather events such as extreme cold, heat, wind, snowfall or precipitation are recognized among the factors causing noticeable project delays, cost overruns, and contractual claims. It can significantly affect a project's schedule and produce significant deviations from the baseline schedule (Shahin, AbouRizk, and Mohamed, 2011; Ballesteros-Péreza, *et al.*, 2017).

The construction industry needs to take note of different weather conditions and improve their working environment to make it safer. Weather simulation can assist in optimizing the project's schedule to make it more robust in terms of weather impacts. Weather simulation models can be seen as extremely complicated random number generators that outputs resemble weather circumstances at a certain place (Kerkhove and Vanhoucke, 2017). The simulation models follow a pattern to construct the necessary models and quantify the impact of adverse weather conditions on actual operation projects: 1) Study of construction processes, 2) Understanding the effect of weather on those processes, 3) Identify the weather variables that influence the construction processes, 4) Search for weather information sources, 5) Choosing a modelling method, 6) Develop an appropriate tool that will generate weather variables, 7) apply the model to real projects to validate the developed model (Moselhi, Gong, and El-Rayes, 1997). Although the processes of constructing a model to allow integrating weather effect in construction projects planning and operations seem to be well addressed, however, it is a challenging process in terms of finding the correct data, and generalize the model to all construction projects. For example, productivity data for different construction trades must be available to model the construction operation and not all construction companies keep track of such data. The National Institute for Occupational Safety and Health (NIOSH) issues regulations and work guidelines regarding occupational exposure to high temperatures and hot environment. Such regulations can be used to construct a model to help predict weather variables that affect the performance of the construction operation and will allow predicting its negative impact on the duration of the construction project. Thus, this research will use the threshold limits values published by NIOSH in hot weather region like experienced in Oman.

The climate of Oman can be described as dry and hot with low annual rainfall, very high temperatures in summer and warm winters. During extremely hot weather conditions, labour efficiency may tremendously decrease, because construction work may stop partially or entirely. Moreover, workers have reduced working hours due to the Ministry of Manpower has issued a directive to all companies, especially construction firms in the country, to stop all outdoors activities between 12.30 pm and 3.30 pm, from June to August (Ministry of Manpower, 2008), when the weather is extremely hot and humid. The effect of such low productivity and shorter working hours during the hot summer months in Oman may cause construction delays and therefore, additional costs of the project. The consequence is a financial loss that must be borne by either the contractor, the client or both (Ballesteros-Péreza, et al., 2017). Therefore, this research aims to model, investigate, and quantify the effect of hot and humid weather on construction projects duration in Oman.

2. BACKGROUND

Extreme weather conditions can cause productivity to fall and delays in the project, especially in the construction industry, because most of its activities being managed by labours outdoors (Al Shebani and Wedawattab, 2014). Hot weather affects construction worker physiologically as well as psychologically. Physiologically, individuals may suffer heat stress or stroke in the hot weather. All of this may affect a worker psychologically; to the point where he or she wishes not to be exposed to the unpleasant working conditions and become demoralized and less productive (Ibbs and Sun, 2017; Koehn and Brown, 1985). Based on the findings of Yildirim *et al.* (2009), Grimm and Wagner (2009), and Thomas and Yiakoumis (1987), there is an inverse relationship between the increase in temperature and labour productivity. Previous studies showed that at a temperature between 100° - 110° F the quality of the work declined, also working at this range of high temperatures resulted in serious health hazards and low productivity (Koehn and Brown, 1985). Palmer and Creagh (2013), Grimm and Wagner (1974), and Thomas and Yiakoumis (1987) noted that an increase in humidity could also be adversely affecting labour productivity. Ibbs and Sun (2017) concluded that humidity has a critical effect on productivity, but its impact is smaller compared to that of temperature. Studies also indicate that temperatures above 110° F and below -10° F with humidity above 50% are intolerable, and it is difficult to achieve construction operations (Kohen and Brown, 1985).

Though extreme weather condition in construction projects is recognized as one of the factors causing the productivity to fall, producing noticeable project delays, cost overruns, waste of resources and contractual claims (Apipattanavis, *et al.*, 2010; Chan and Au, 2008; El-Rayes and Moselhi, 2001; Lee *et al.*, 2017), it is also reported to be one of the main factors that influence financial performance and business continuity (Moselhi, Gong, and El-Rayes, 1997; Al Shebani and Wedawattab, 2014; Guo, Chen, and Chiu, 2017).

Weather can affect a construction process in various ways; it can slow down the works by lowering the performance of construction labours and materials and can cause a temporary work stoppage, which therefore affects the plan and schedule of the project (Al Shebani and Wedawattab, 2014). Thus, understanding inclement weather influence on any construction project can reduce claims and arguments caused by delays (Apipattanavis, *et al.*, 2010; Chan and Au, 2008; Dytczak *et al.*, 2013).

Previous studies investigated the impact of inclement weather on construction activities and productivity. Moselhi *et al.* (1997) quantified the influence of weather conditions on daily construction activity; they developed an automated decision support system called WEATHER to study the impact of adverse weather conditions on the labour productivity and work-stoppage of construction operations. The developed WEATHER model estimates construction productivity as well as the duration of construction activities and weather patterns in different modes to improve the accuracy of the planning and scheduling. A mathematical study of weather by Koehn and Brown (1985) employed some non-linear equations to examine the effect of weather changes on the productivity rate. Their investigation suggests a clear relationship between overall construction performance and weather-related factors such as temperature and humidity it shows that at a temperature between 100° and 110° F the quality of the work declined, also working at this range of high temperatures resulted in serious health hazards and low productivity. Koehn and Brown (1985) found that construction productivity decreases rapidly at elevated temperatures, and there is an adverse relationship between construction productivity and humidity. The quantification of weather impacts on productivity was reported by the National Electrical Contractors Association (NECA) (Hanna, 2004). The research engaged two travelling electricians installing electrical boxes and duplex outlets while operating in an environment chamber that monitored the temperature and humidity. The study found that productivity levels differ depending on humidity and temperature. Grimm and Wagner (1974) studied the productivity in masonry construction over a period of nine months during the construction of 283 test walls and published a diagram showing the impact of temperature and humidity on the productivity. The research found a decline in productivity as temperature and relative humidity deviated. They reported that relative humidity had a much greater effect on productivity rate. Ahuja and Nandakumar (1985) and Kavanagah (1985) measured the impact of weather as a percentage in their construction modelling and analyzed how frequently weather resulted in decreased activity. AbouRizk and Wales (1997) research used a general regression neural network to study the relationship between weather variables and earthwork productivity. This study investigated three weather variables: precipitation, daily maximum temperature, and daily minimum temperature. It demonstrated the impact of these weather variables has on a project schedule by calculating the duration for the same project according to different start dates. The South Dakota Department of Transportation (Kenner, *et al.*, 1998) adopted a pragmatic solution by combining their construction records with weather records to calculate contract time and determine time extensions for adverse weather. Yildirim, Koyuncu, and Koyuncu (2009) findings showed a negative association between temperature increase and labour productivity level. Palmer and Creagh (2013) state that the rise in humidity due to climate change reduces labour productivity. Studies also indicate that temperatures above 110° F with humidity above 50% are intolerable and all useful work stops, therefore, it is difficult to achieve efficient construction operations (Arditi, 1985). Thomas *et al.* (1990) described the factor model for evaluating the productivity of labour-intensive construction activities. The validity of the factor model is demonstrated by considering the effect of temperature and relative humidity on productivity. Thomas *et al.* (1990) also noted that the increase in humidity could be adversely affecting labour productivity. Ibbs and Sun (2017) concluded that humidity has a critical effect on productivity, but its impact is smaller compared to that of temperature. Shahin *et al.* (2011) proposed a simulation model that quantify the effects of extreme weather events on construction projects and to assist in project planning and decision support. Miroslaw *et al.* (2013) presented a numerical procedure to identify the efficient construction project structure and a corresponding schedule. It addressed the impact of inclement weather conditions on technological operations. Marzoughi *et al.* (2018) developed a model using multivariate statistical techniques and an analytical network (ANP) method to assess the duration of project operations, taking into consideration the effect of weather.

3. HEAT STRESS

This section covers a brief introduction about heat stress in hot environments and present recommendations for workers exposed to heat and hot environments derived from the occupational exposure to heat and hot environments published by National Institute for Occupational Safety and Health (NIOSH) (NIOSH, 2018).

Total heat stress is controlled by the three factors, the heat generated in the body, the heat gained from the environment, and the heat lost to the environment from the body. Environmental and/ or metabolic heat stress results in physiological reactions (heat stress) to promote heat transfer from the body back to the surroundings to maintain core body temperature. Many of the heat exposure responses in the body are desirable and useful. However, at some level of heat stress, the compensatory mechanisms are no longer capable of keeping body temperature at the rate needed for normal body tasks. Consequently, there is an increase in the risk of heat-related illnesses, disorders, and other hazards.

Workers who are subjected to extreme heat or work in indoor or outdoor hot environments or even those involved in exhausting physical activity may be at risk for heat stress. Those at risk of heat stress include outdoor workers and workers in hot environments, for example, firefighters, bakery workers, farmers, construction labours, miners, boiler room workers, and factory workers. Outdoor labours are subjected to a great deal of exertional and environmental heat stress. The recommendations are intended to provide limits of heat stress so that heat-related illnesses and disorders are reduced.

NIOSH proposes that employers implement measures to protect the health of labours exposed to heat and hot environments. Employers need to monitor environmental heat and determine the metabolic heat produced by workers (e.g., light, moderate, or heavy work). Based on the increase in risk, additional modifications (e.g., worker health interventions, clothing, and personal protective equipment) may be required to shield workers from heat stress. In hot conditions, physiological monitoring and medical screening are suggested. Employers, supervisors and workers need to be trained to recognize symptoms of heat-related illness, adequate hydration, care and use of heat-protective garments and equipment, the impact of multiple heat-tolerance risk variables (e.g., drugs, alcohol, obesity, etc.), the significance of acclimatization, the significance of reporting symptoms and suitable first aid. Employers should have a plan to acclimatize a new employee because it has been shown that the lack of acclimatization is a significant factor associated with worker heat-related illness and death. NIOSH recommends that employers provide the means for adequate hydration and that their employees be encouraged to hydrate themselves with drinking water below 15 ° C (59 ° F) close to the work zone. Workers in heat less than 2 hours and involved in moderate work activities should drink 1 cup (8 oz.) of water every 15–20 minutes. Furthermore, employers should establish a work/rest schedule and provide a cool environment for employees to rest and recover (e.g., air-conditioned or shaded). These essentials are intended to protect the health of workers from heat stress or injuries in hot environments.

4. WORK-REST HOURS PREDICTION MODEL

This section describes the research methods that have been used for assessing the relationship between the high temperature (T) and relative humidity (RH) and the productivity of the labours. Two primary data were collected for this research. First, historical weather data for daily temperature and relative humidity in Muscat city were collected from the Public Authority for Civil Aviation (PACA) for the years from 2015 to 2018. The data received from PACA were not clean, with missing records and limited years; only from 2015 until 2018 while the data needed should be at least from 2008. Therefore, actual weather data from the National Oceanic and Atmospheric Administration (NOAA) was used.

The data from NOAA covered daily temperature in Muscat from 2001 until 2018. To cover the daily relative humidity for the years from 2001 to 2018; daily relative humidity received from PACA was repeated every two years, with an assumption that the relative humidity will not differ much within two years and it was observed that almost same relative humidity was repeating every two years.

The database was established using the daily temperature (mean, maximum and minimum) from NOAA and daily relative humidity (mean, maximum and minimum) from PACA. The temperature ranged from a low of 12.4 °C to a high of 47.5 °C, and the relative humidity was in the range of 5%-100%. It was observed that the temperature and relative humidity were extreme in the months from April to September while it is normal during the remaining months of the year. Therefore, weather data from April to September was considered in this research.

To maintain a healthy and safe working environment, the National Institute for Occupational Safety and Health (NIOSH) developed a work/rest schedule for workers. Table 1 shows the work and rests time per hour for a certain temperature and humidity to minimize the effect of heat on the labours. The workload category is expressed as worker’s metabolic heat production: light work = <180 kcal/hr; moderate work = 180–300 kcal/hr; heavy work = 300–415 kcal/hr; and very heavy work = >520 kcal/hr (NIOSH, 2018).

Table 1 is used for the quantification of weather effects on labourers' productivity in Table 2, which illustrates the percentage of rest per hour due to high temperature.

More tables that are comprehensive were developed for the considered months – April to September. Data were summarized for each month, and Most-likely case and pessimistic cases were defined for each workload category for the data analysis. The most likely case reflected the percentage of rest per hour for the mean adjusted temperature based on mean relative humidity while the pessimistic case is the percentage of rest per hour for the maximum adjusted temperature based on maximum relative humidity. These two cases were defined because they reflect the worst-case scenarios compared to other cases (e.g. minimum adjusted temperature based on minimum relative humidity).

The data was analyzed using EasyFit software to find out the best-fit probability distribution function that represents the probability of percentage of rest per hour the work may experience for each month. For each month; six probability distributions were found as follows:

- Light work: most likely and pessimistic
- Moderate work: most likely and pessimistic
- Heavy work: most likely and pessimistic

Randomly generating percentages for rest per hour in for a month will generate a full month affected by the weather condition, which is not logical and not valid. Therefore, the probability of occurrence of negative weather effect was calculated from the weather data set. Table 3 below illustrates the probability of occurrence of the affected days for each month; that was found using the following equation:

The probability of occurrence of an event is defined according to Eqn. (1):

$$P(E) = \frac{number\ of\ favorable\ outcomes}{number\ of\ possible\ outcomes} \quad (1)$$

Where the number of favourable outcomes is the percentage of rest per hour which is more than 0%, and the number of possible outcomes is the total number of days considered in the data. The probability of occurrence along with the probability of the percentage of expected rest to work were jointly used to generate the expected rest percentage for construction labours.

5. MODEL VALIDATION

The data needs to be statistically validated. A statistical comparison of the generated output for each month was carried out to ensure that the similarity between the historical data and the generated data is statistically adequate. The rest percentage prediction model was used to generate data for the expected percentages of rest construction labour may experience in months from April to September.

Table 1. Work/rest schedule for workers wearing normal clothing *(NIOSH, 2018)*.

Adjusted Temperature (C) †	Light work (minutes work/rest)	Moderate work (minutes work/rest)	Heavy work (minutes work/rest)
32.22	Normal	Normal	Normal
32.78	Normal	Normal	Normal
33.33	Normal	Normal	Normal
33.89	Normal	Normal	Normal
34.44	Normal	Normal	Normal
35	Normal	Normal	45/15
35.56	Normal	Normal	45/15
36.11	Normal	Normal	40/20
36.67	Normal	Normal	35/25
37.22	Normal	Normal	35/25
37.78	Normal	45/15	30/30
38.33	Normal	40/20	30/30
38.89	Normal	35/25	25/35
39.44	Normal	30/30	20/40
40	Normal	30/30	20/40
40.56	Normal	25/35	15/45
41.11	45/15	20/40	Caution
41.67	40/20	15/45	Caution
42.22	35/25	Caution	Caution
42.78	30/30	Caution	Caution
43.33	15/45	Caution	Caution
43.89	Caution	Caution	Caution
44.44	Caution	Caution	Caution

† Note: Adjust the temperature reading as follows before going to the temperature column in the table:
Full sun (no clouds): Add 13°F, Partly cloudy/overcast: Add 7° F
No shadows visible/work is in the shade or at night: no adjustment
Per relative humidity:
10%: Subtract 8° F, 20%: Subtract 4° F, 30%: No adjustment, 40%: Add 3° F, 50%: Add 6° F, 60%: Add 9° F
‡High levels of heat stress; consider rescheduling activities.

Table 2. Percentage of rest per hour for workers wearing normal work clothes.

Adjusted Temperature (C)	% Rest Per Hour		
	Light work	Moderate work	Heavy work
32.22	0	0	0
32.78	0	0	0
33.33	0	0	0
33.89	0	0	0
34.44	0	0	0
35	0	0	25
35.56	0	0	25
36.11	0	0	33.33
36.67	0	0	41.67
37.22	0	0	41.67
37.78	0	25	50
38.33	0	33.33	50
38.89	0	41.67	58.33
39.44	0	50	66.67
40	0	50	66.67
40.56	0	58.33	75
41.11	25	66.67	100
41.67	33.33	75	100
42.22	41.67	100	100
42.78	50	100	100
43.33	75	100	100
43.89	100	100	100
44.44	100	100	100

The number of generated instances was equal to the original data and statistical measures such as the mean, the variance, and the standard deviation were used to compare the generated data with the original data. Table 4 shows sample results for April. It can be seen that the generated data is reasonably replicating the real data except in the pessimistic scenario for moderate work, the data shows a large difference in the variance. The summary of the comparison between the generated data and the real data for other months is as follows: May: There is a big difference in the mean, variance and standard deviation between the generated and original data in the light work category for both scenarios (a most likely and pessimistic). In moderate work, for a pessimistic scenario, and in heavy work, a most likely scenario. While the pessimistic cases in both moderate work and heavy work, the data shows a large difference in the variance.

- June: In all work categories, for the most likely scenario; the data shows a noticeable difference in mean, variance and standard deviation. Also, a contrast was found in the mean and variance of the compared data in the pessimistic case in all work categories.
- July: The generated data is reasonably duplicating the real data in the heavy work, both scenarios and moderate work most likely cause. However, in the moderate work, scenario pessimistic; and both scenarios in light work, the data shows a big difference in the mean, variance and standard deviation.
- August: the mean, variance and standard deviation for the real and generated data were not consistent for the most likely scenario, in light and moderate work category. Also, the difference in variance was found to be large in the pessimistic scenario for light work. However, for the remaining scenarios, the data are in good agreement.
- September: The generated data replicates the real data fairly except in the moderate work, most likely scenario; which indicates a significant difference in the mean, variance and standard deviation.

This discrepancy found in the analyzed data can be because of the assumption that was made earlier. The collected data has two years of relative humidity records and an assumption that the relative humidity will not have a huge annual variance and therefore the two years relative humidity data can be replicated to cover the missing data.

6. APPLICATION OF THE MODEL IN REAL CONSTRUCTION PROJECTS

As described in the previous section, the construction productivity model will be applied in three real construction projects. The projects schedules were fed with four different weather effects testing scenarios. The testing scenarios are as follow:

- The first scenario (SC-1): The project activities are categorized as a moderate workload, and the weather conditions are most likely.
- The second scenario (SC-2): The project activities are categorized as moderate workload, and the weather conditions are pessimistic.
- The third scenario (SC-3): The project activities are categorized as heavy workload and the weather conditions are most likely.
- The fourth scenario (SC-4): The project activities are categorized as heavy workload, and the weather conditions are pessimistic.

These four testing scenarios were used because this research work is motivated to investigate and quantify the effect weather on construction project schedules and such objective can be reached if the projects were tested against the moderate and heavy type of construction work activities. Activities performed during the hot and humid season are targeted in this part of the study. In addition, it is hypothetically assumed that the original project schedule has no weather consideration in estimating the project activities durations. However, the usual practice is to extend the activity duration to count for unforeseen extreme weather conditions.

Table 3. Probabilities of occurrence of the affected days for each month.

Month	Percentage of Days Affected					
	Light work		Moderate work		Heavy work	
	Most likely	Pessimistic	Most likely	Pessimistic	Most likely	Pessimistic
April	0	10	6	38	26	72
May	11	47	41	31	72	93
June	16	44	48	76	84	92
July	7	20	21	47	66	86
August	1	14	10	35	44	76
September	0	11	7	37	37	76

Table 4. Comparing April generated data against the real data.

Workload category	Light work			Moderate work				Heavy work			
Scenario	Most-likely	Pessimistic		Most-likely		Pessimistic		Most-likely		Pessimistic	
Best Distribution function	Constant =0	Gamma		Frechet		Beta		Gamma		General Extreme Value	
Type of data		Real data	Generated data	Real data	Generated data	Real data	Generated data	Real data	Generated data	Real data	Generated data
Mean		4.42	4.42	1.92	1.53	19.96	12.18	8.96	8.26	37.00	24.68
Variance		213.33	225.34	67.60	52.95	859.53	363.09	265.70	267.42	997.62	936.88
Std. deviation		14.61	15.01	8.22	7.28	29.32	19.06	16.30	16.35	31.59	30.61

6.1 Project A

The construction of the project took 365 days. In this research, the construction part only was analyzed, which included; sub-structure works, super-structure works, and masonry works. The critical path of this part was identified, and its duration is 250 days.

Figure. 1 (a) shows the affected activities by the first testing scenario (SC1) applied to the construction schedule for project A. The increase in activity duration is shown in red font. For the remaining activities, the effect was negligible this is because of a lower percentage of rest per hour in a particular activity and because some of the activities are in October, November, December and January which are not considered in this research. The critical path duration for project A was increased by 41.5 days to reach a total of 291.5 days.

Figure. 1 (b) shows the construction activities affected by the second scenario. The affected activities are more than that of the first scenario. This increase in affected activities is due to the high percentage of rest per hour for the pessimistic scenario compared to the same moderate load work category.

It was observed that the critical path duration reaches a total of 307.5 days with an increase of 57.5 days.

The construction activities affected by the third testing scenario (SC3) for the project is shown in Fig. 1(c). It was observed that the critical path duration was increased by 60.5 days to reach a total of 310.5 days. The high duration of critical path compared to previous scenarios is because of the high percentage of rest per hour for heavy load category.

The construction activities affected by the fourth scenario is shown in Fig. 1(d). It was seen that the critical path duration is 344 days, with an increase of 94 days. This is the worst-case scenario in which the load category is heavy, and weather conditions are pessimistic. The percentage of rest per hours for this scenario is high. Thus the labour will take more rest in an hour during his work. As a result, the new duration for the affected activities is high compared to other scenarios.

In conclusion, for project A, it was found that the percentage increase in critical path duration for first, second, third and fourth scenarios are 17%, 23%, 24% and 38% respectively. The effect of hot weather was highest for the heavy load work and pessimistic weather conditions, and least for moderate workload category and most likely weather condition.

6.2 Project B

The project duration for project B is 423 days, started on 3rd April 2010 and completed on 31st May 2011, and the critical path duration of the construction part was 199 days.

The construction activities affected after applying the first scenario (SC1) is shown in Fig. 2(a). It was observed that the first four activities were affected by the hot weather, resulting in a shift in the start date of the remaining activities. Some of the activities were not affected by the weather conditions this is due to a lower percentage of rest per hour inactivity and because some of the activities are in October, November and December. The critical path duration was increased by eight days to reach a total of 207 days.

Figure 2(b) shows the construction activities affected by the second testing scenario (SC2); which is the moderate workload category and pessimistic weather condition. The affected activities more than that of the first scenario. This is a result of the high percentage of rest per hour for the pessimistic case compared to the same load work category, which is moderate. Consequently, the duration of the critical path was affected due to this increase in the duration of activities. It reached a total of 221 days with an escalation of 22 days.

For the third scenario (SC3), the output of the construction productivity model is shown in Fig. 2(c). It is shown that the hot weather affected the first seven activities, which increased in the duration of the critical path. The critical path duration for the construction part was increased by 18 days to reach a total of 217 days.

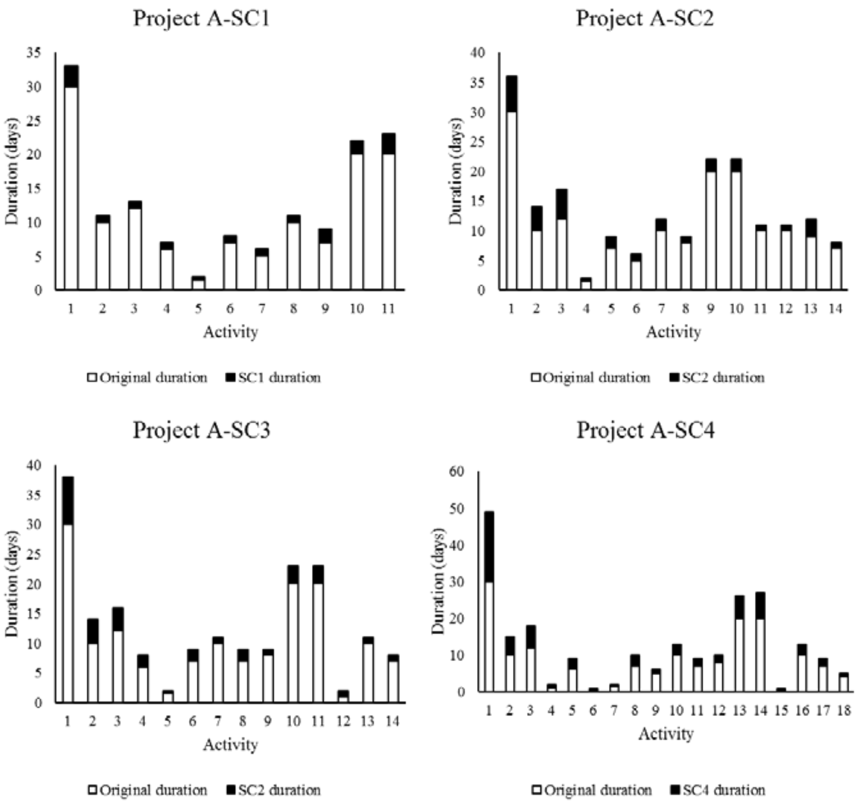

Figure. 1. Project A results after tested under four testing scenarios (SC1, SC2, SC3, and SC4); (a) Affected activities and their durations for SC1, (b) Affected activities and their durations for SC2, (c) Affected activities and their durations for SC3, (d) Affected activities and their durations for SC4.

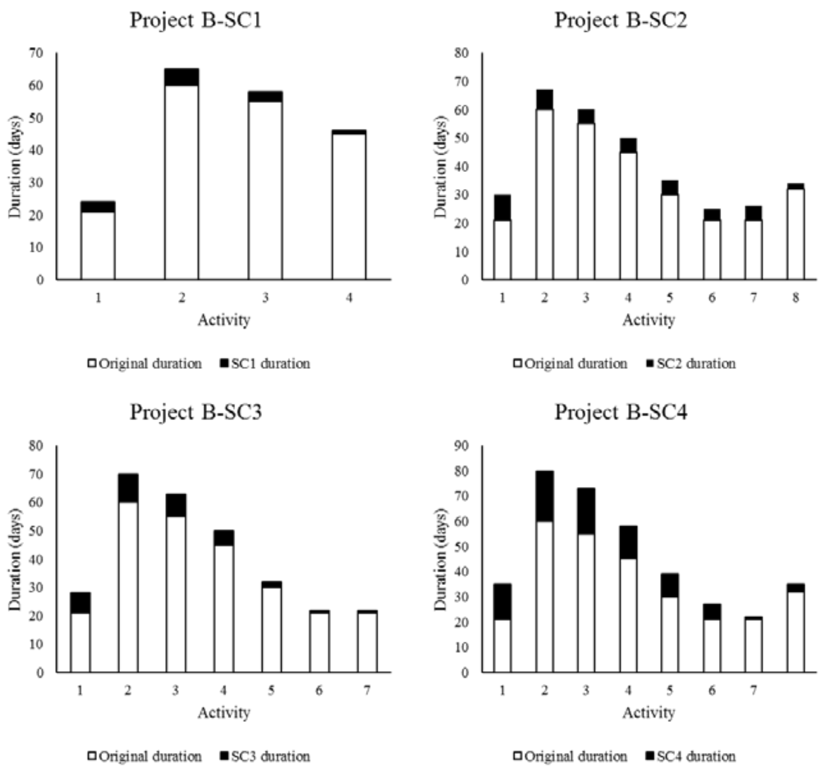

Figure. 2. Project B results after tested under four testing scenarios (SC1, SC2, SC3, and SC4); (a) Affected activities and their durations for SC1, (b) Affected activities and their durations for SC2, (c) Affected activities and their durations for SC3, (d) Affected activities and their durations for SC4.

affected by the fourth testing scenario (SC4). It is obvious from the graph that more activities are by the Figure. 2(d) shows the construction activities affected hot weather conditions. These observations are expected; since this scenario covering the heavy load work category and pessimistic weather conditions; in which the percentage of rest per hour is the highest. The labour will take more time resting per hour during his work, resulting in an extended duration to finish the work of the activity. It was seen that the critical path duration is 242 days, with an increase of 43 days from the duration of the original critical path.

In conclusion, the percentage increase in the critical path duration for the four scenarios was calculated. It was found that a 4% increase for the first scenario, 11% for the second scenario, 9% for the third scenario and 22% for the fourth scenario. The effect of hot weather was highest for the heavy load work and pessimistic weather conditions, and least for moderate workload category and most likely weather condition.

6.3 Project C

The construction duration of project C is 239 days; it was started on 24th June 2018 and accomplished on 28th February 2019. As followed in previous projects, the construction part was studied for this research which includes; sub-structure works and superstructure work. The duration of the critical path for the construction part is 150 days.

The construction activities affected after applying the first scenario is shown in Fig. 3(a). The graph shows that the hot weather affected three activities.

For some of the activities the weather conditions had no impact, this is due to the low percentage of rest per hour for the moderate and most likely scenarios and because some of the activities are in October, November, December and January, which are not considered in this analysis. The critical path duration was calculated and found to be 154 days; it was increased by four days compared to the original critical path duration.

Figure. 3 (b) shows the results for the second scenario; which is the moderate workload category and pessimistic weather condition. The hot weather conditions affected more activities compared to the first scenario. This is because of the high percentage of rest per hour for the pessimistic weather condition. Subsequently, the critical path duration was increased by five days. It reached a total of 155 days.

For the third scenario, the output of the construction productivity model is presented in Fig. 3(c). It shows that the critical path duration for the construction part was increased by eight days to reach a total of 158 days.

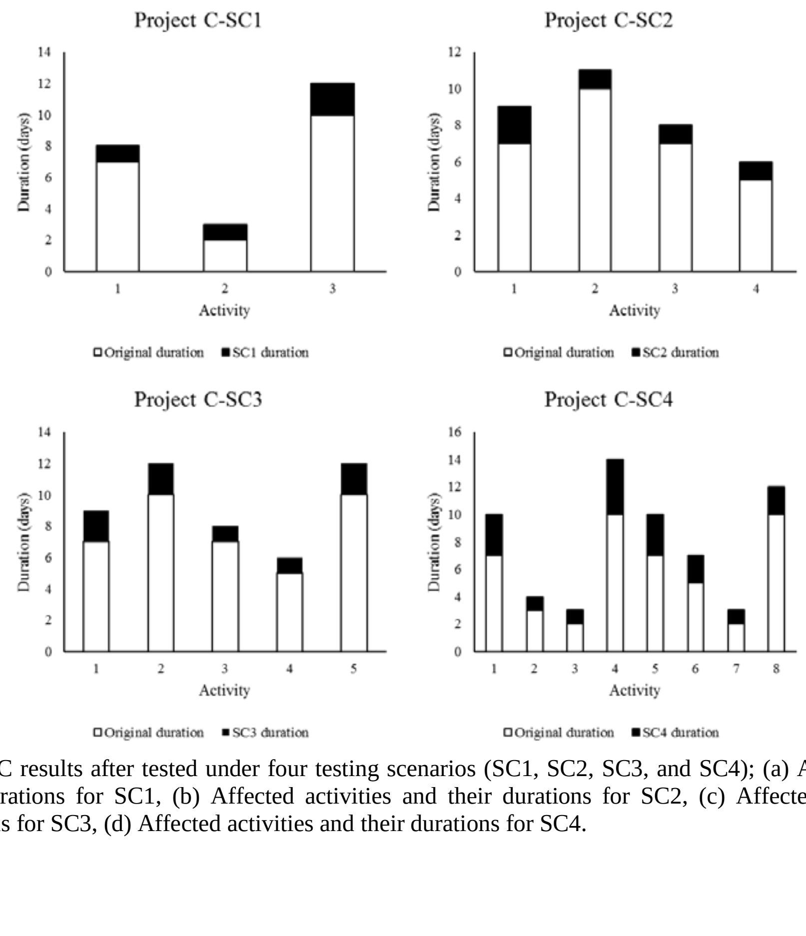

Figure. 3. Project C results after tested under four testing scenarios (SC1, SC2, SC3, and SC4); (a) Affected activities and their durations for SC1, (b) Affected activities and their durations for SC2, (c) Affected activities and their durations for SC3, (d) Affected activities and their durations for SC4.

The output of the construction productivity model for the fourth scenario is shown in Fig.3(d). More activities were impacted by the hot weather conditions. The graph shows that the first eight activities increased in their working duration, resulting in an extension of the critical path duration. This is predicted because this scenario is the worst scenario; where the percentage of rest per hour is high. It was seen that the new critical path duration for the construction part is 167 days with a rise of 17 days from the duration of the original critical path.

In conclusion, the percentage increase in critical path duration was calculated for the four scenarios. For the first and second scenarios, the increase was found to be equal to 3%, 5% for the third scenario and an increase of 11% was calculated for the fourth scenario. It was observed that the effect of extreme weather conditions was highest for the heavy load work and pessimistic weather conditions, and least for moderate workload category and most likely weather condition

CONCLUSION

In this study, a construction productivity model was developed using the daily temperature and relative humidity of Muscat, Oman from the years 2001 to 2018. The daily temperature and relative humidity were used to calculate the percentage of rest per hour rule presented by NIOSH. The generated data were validated statistically against the original data. The rest per hour model was able to satisfactory replicate the real data with some discrepancies. This result may be driven from the fact that the collected data had a simplification due to lack of data and only two years relative humidity records were used in the study. This is a limitation to the model and a future extension of this model will incorporate a large range of relative humidity and temperature records.

The construction productivity model was used to investigate and quantify the weather effects on project duration. It was applied to three completed construction projects. For each project, four weather testing scenarios were applied to investigate the impact of hot weather under different workloads on the project duration. The critical path duration was calculated for each scenario in each project and compared with the original critical path durations. The results showed an increase in the critical path duration for all three projects in all scenarios. It was found that 17%, 23%, 24% and 38% increase in critical path duration for project A, for SC-1, SC-2, SC-3 and SC-4, respectively. For project B the percentages were 4%, 11%, 9% and 22% for each scenario respectively. In addition, 3%, 3%, 5% and 11% increase in critical path duration for project C were found for the four presented scenarios.

CONFLICT OF INTEREST

Authors declare no conflicts of interest.

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