Scholarly Paper

Weather's Effect on Construction Labor Productivity

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Abstract: Weather impacts construction worker productivity, both physiologically and psychologically. Weather's effect on productivity is therefore an important topic and has been the subject of a considerable amount of research for more than fifty years. However, it is observed that the results of previous studies lack consistency. In this paper, the Grimm and Wagner (G&W) and Thomas and Yiakoumis (T&Y) studies are compared, and they define productivity differently. So they cannot be directly compared. After normalizing for the different definitions, the regression curves for T&Y and G&W data are found to be reasonably close. The authors then combined the T&Y and G&W data to develop an improved regression relationship that should be used for studies and claims made about temperature's impact on productivity. In addition, peak productivities are found to probably be affected by the regional location of a worker. However, no evidence showed that heavier work such as mason work was more sensitive to temperature and humidity than other trades. Finally, T&Y's and G&W's data were studied for humidity's impact on productivity, and a new model for temperature and humidity's combined effect on productivity is presented. It explains a notable amount, but not all, of the productivity variation associated with the actual temperature and humidity data studied. This paper and its findings will help project managers plan and control their work more accurately and resolve disputes more readily. **DOI: 10.1061/(ASCE)LA.1943-4170.0000212.**

Introduction

Weather impacts construction worker productivity, both physiologically and psychologically (NECA 2004). Physiologically, individuals may suffer heat stress or stroke in hot weather, and experience tissue damage or loss of feeling in an extremity due to exposure during cold temperatures. Low temperatures may require workers to wear heavier, bulkier clothing (Hancher and Abd-Elkhalek 1998). High wind speeds may affect construction means and methods (e.g., limited crane use). Rains, snow, ice, and high wind speeds will also have an effect on productivity. All of this may affect a worker psychologically, to the point where he or she may become demoralized and less productive.

Weather's impact can cause loss of productivity (LOP). A contractor who incurs such may be able to recover for weather-related productivity losses, depending on contractual circumstances and customary practices. In such a claim the contractor may generally request extra financial compensation and possibly a time extension to the work. The success of such a claim will hinge on the specific contractual clauses and customary practices governing the project (Moselhi and El-Rayes 2002).

Weather's effect on productivity is therefore an important topic and has been the subject of a considerable amount of research for more than fifty years. One of the earliest studies was by Clapp (1966), who studied bad weather time versus temperature and rainfall for five sites. He found that bad weather impaired labor productivity on house construction in the United Kingdom. His work did not really define weather's impact in meaningful quantitative terms. Since then other important studies on this topic include Grimm and Wagner (1974), NECA (1974, 2004), and Thomas and Yiakoumis (1987). They all collected data from experimental or real projects and developed models to help contractors estimate the LOP due to weather. Grimm and Wagner (1974) and Thomas and Yiakoumis (1987) published the raw data in their papers.

Other researchers have subsequently cited the data from those earlier works. Examples include Brauer et al. (1984), Koehn and Brown (1985), and Srinavin and Mohamed (2003). However, these studies did not thoroughly explain how they normalized the data, leading to a question of whether the data were properly normalized.

The results of previous studies lack consistency. In this paper the Grimm and Wagner (G&W) and Thomas and Yiakoumis (T&Y) studies are compared, and they define productivity differently. This means that comparisons cannot be directly made. The authors introduce a way to normalize their data sets and compare their works properly. Geographical regions and labor trade impacts are also investigated.

The consequence of the work presented herein is a better model based on data from two previous weather studies, which will help contractors refine their bids and present and evaluate weather-based change impacts more accurately. Owners will have better information with which to evaluate such claims.

Review of Previous Studies and Legal Cases

Previous Weather-Related Construction LOP Legal Decisions

Adverse weather is considered one of the main factors causing delays and overruns on construction projects (Moselhi and El-Rayes 2002). Typically, there are three kinds of LOP cases related to weather:

1. Unexpected severe weather that a reasonable contractor cannot predict in its initial plan and estimate.[1] It is not the mere presence of bad weather per se, it is the presence of bad weather that could not have been reasonably foreseen (Ibbs and Razavi 2014). Unfavorable weather normally includes hot weather,[2] cold weather,[3] and excessive rain, wind, and flooding.[4] A claim

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based on unexpected severe weather can be rejected if the weather is deemed to be not unusually severe.[5] In addition, contracts generally support time extensions caused by unusually severe weather, but in some instances do not provide for equitable cost adjustments for such delays.[6]

2. The project schedule was moved to unfavorable weather time because of changes.[7] Contractors need to show that they did not undertake contract performance in unfavorable weather for their own reasons.[8] Another possible rejection reason is that the delay pushed as much or even more work into milder weather;[9] and
3. Unexpected work environment change. A typical example of this kind is when building windows and temporary heat were unexpectedly not provided during winter construction.[10]

Many cases did not specify the details of how loss was determined, but some of those cases did provide details regarding the LOP claimed and granted.

1. In *Luria Brothers & Company v. United States* the witness testified that the contractor had to work outside on trench excavations and foundation construction in winter weather. He estimated the loss to be 33.33, 25, and 20% for different time periods. The board allowed 20, 10, and 10%, respectively. Note that this project was based in Pennsylvania, which has more severe weather conditions than some other parts of the United States. Projects in more temperate regions will likely have less pronounced productivity losses due to weather.
2. In *Appeal of Pathman Construction Co.*, the performance of concrete and masonry work was delayed into a winter season because of a strike. The contractor requested 25% LOP, which was accepted by the board.
3. In *Appeal of Fruehauf Corporation*, the contractor was forced to work in the winter. It claimed for 50% LOP and 25% was allowed by the court.
4. In *Appeal of Hugh Brasington Contracting Co.*, the government failed to provide adequate heat. Half of the building was affected and 50% LOP was allowed for the affected part of the contractor's work.

From the four above legal cases and board decisions, it is clear that courts recognize that weather impacts productivity and a contractor can successfully lodge a claim if that claim is properly prepared and presented. Moreover, the courts generally granted around 25% LOP to these impacted contractors, which can be a substantial amount of money. Such LOP awards must be tempered with any contractual language. For instance, owners often require that schedules include number of adverse weather days in contracts that must be overcome before any time and productivity impact will be awarded. It is therefore important to have good, reliable models that explain weather's impact. Better models will provide courts and boards better evaluation tools.

Previous Weather Studies

Grimm and Wagner (1974) and the National Electrical Contractors Association (NECA 2004) conducted experiments to measure the productivity under different weather conditions. Grimm and Wagner (1974) collected and analyzed masonry productivity data from a series of experimental test stations, and published a contour graph showing the impact of temperature and humidity on the work's productivity ratio (PR herein after). Grimm and Wagner called it productivity, but it's a ratio of actual productivity divided by optimal productivity. The data were collected hourly and grouped according to temperature and humidity. Their original data were published in Johnson et al. (1972), and showed that productivity is very sensitive to temperature. The G&W study is reviewed in more detail later in this paper.

NECA (2004) collected productivity data from an experiment on installing test receptacles with the temperature and humidity controlled. However it only studied two electricians and did not consider learning curve effects. NECA did not provide the raw data. It only provided an inefficiency table with productivity normalized against different temperatures and humidity based on their data. No information has been provided as to how the optimal productivity and productivity percentages were calculated.

Clapp (1966) and Thomas and Yiakoumis (1987) also collected real project data. Clapp studied five semidetached home building sites in the United Kingdom and determined when construction work would stop given different temperature and rainfall levels. But these results were based on monthly temperature averages and work stoppages, not diminished productivity rates. Thomas and Yiakoumis (1987) developed a regression model using temperature and humidity to predict PR (in their work, they called it predicted efficiency). They studied masonry, steel work, and formwork. That study is also examined in more detail later in this paper.

Brauer et al. (1984), Koehn and Brown (1985), Srinavin and Mohamed (2003), and Moselhi et al (1997) developed models based on previously published data. Brauer et al. (1984) developed a diagram showing wet-bulb globe temperature (WBGT) versus PR with climate zone adjustment based on previously published data. Koehn and Brown (1985) developed a table showing productivity versus temperature and humidity. Abele (1986) presented a figure showing the relationship between temperature and productivity for both manual work and equipment work. This work focused on cold weather and was based on various previous studies from the construction industry and military (Lee 2007). They state their analysis is based on previously-published studies but do not identify those studies. Mosehi et al. (1997) developed an automatic decision support system named WEATHER. The system was designed to help the contractor make decisions based on weather information and possible effect. They calculated productivity loss based on existing models. Hancher and Abd-Elkhalek (1998) focused on adjustment factors (such as trades) and developed a figure showing productivity loss versus temperature and tables of multipliers with adjustment factors. Their model is, in general, based on NECA (1974). These studies did not thoroughly explain how they normalized the data, leading to a question of whether the data were properly normalized.

Besides the above studies, Kuipers (1977) developed an equation and a series of look-up tables for PR considering temperature, humidity, solar radiation, wind, clothing, etc. This model was based on the theory that the human being is a heat-producing organism operating in a thermal environment and a thermal imbalance (imbalance of heat production and heat loss) will cause inefficiency. The model is comprehensive in considering various factors related to weather conditions, work being performed, and human relations to the work environment. It is too complex to be used in a practical context, and it is based on a very small data set that is questionable to validate the model (Lee 2007).

Srinavin and Mohamed (2003) developed a model close to the Kuipers model, considering temperature, humidity, radiant temperature, wind velocity, the nature of construction task, and clothing based on previous data. They then tested the model with data collected from four construction sites in the northeast of Thailand. They concluded that their model worked better on light and moderate work than heavy work. However they did not explain their assumptions about unavailable data including wind, task type, clothing, metabolic rate, etc.

Of all the studies reviewed above, only the G&W study and the T&Y provided their source data. The availability of that source data

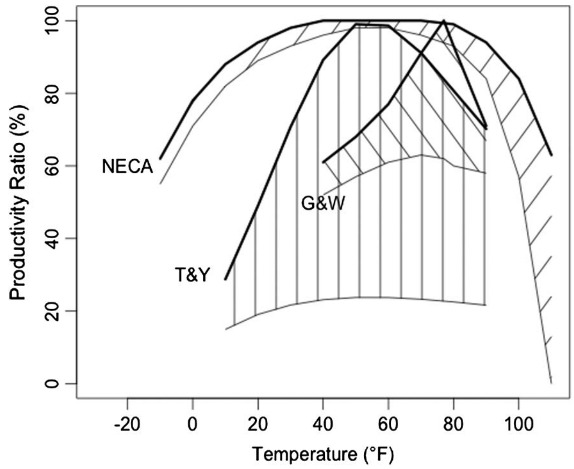

Fig. 1. Temperature versus productivity (data from NECA 1974; Thomas and Yiakoumis 1987; Grimm and Wagner 1974)

allowed us to conduct a meta-analysis, which is the subject of this paper.

Meta Analysis of Previous Temperature and Humidity Research

Grimm and Wagner (1974) and Thomas and Yiakoumis's (1987) estimates of temperature's impact on productivity are shown in Fig. 1. Even though the NECA (1974, 2004) studies did not provide raw data, that data is included in the figure because NECA's discussion of its findings is compelling. The other studies discussed previously are excluded because they did not explain how they normalized and processed their data.

The PR in Fig. 1 represents the ratio of actual productivity divided by optimal productivity. These prior works, however, have different definitions of optimal productivity, which will be discussed in detail in the next section of this paper. The hashed areas shown below the solid curves in Fig. 1 represent the range of each study's estimate of temperature's impact on productivity for different humidity levels. For example, Thomas reports 100% PR at 50°F and 0% humidity versus 25% PR at 50°F and 85% humidity.

Temperature versus Productivity by Previous Studies

The models shown in Fig. 1 have their peak PRs at different temperature ranges. G&W's optimal temperature was approximately 80°F, T&Y's was around 45°F, and NECA had a wider range, in general 40–80° range. The figure also reveals that NECA's model was less sensitive to temperature and G&W's model was more sensitive.

There are a number of different reasons why these models might differ so much, including (1) the various researchers might have collected data and performed their analyses differently (such as the data cleaning method, model selection, and model fitting method they used); (2) these research studies were conducted in different geographical regions, and laborers from different regions might have different productivity curves; and (3) the studies focused on different types of work (heavy manual work versus fine motor skill work). Different explanations are offered in the following subsections.

Possible Reason #1: Different Data Normalization

Upon detailed examination, these models were found to have been developed using different definitions of PR. Fig. 2(a) shows the PRs provided by G&W and T&Y, in raw original published form, not yet normalized with a common definition. Fig. 2(b) shows PRs after these source data were normalized. (That normalization will be explained later in this paper.) Before normalization, the PRs used by G&W are in general lower than T&Y's, with most PRs below 80%. T&Y's PRs varied from 25 to 175%, and many were larger than 100%. After normalization, the boxplots are closer together, meaning that the data are more in agreement than might have otherwise been suspected [Figs. 2(a and b)]. Statistical t-tests show that before normalization four of the five temperature pairs (G&W versus T&Y) are statistically significantly different. After normalization, none of the five pairs is statistically different. See Table 1, where the null hypothesis (H0: G&W and T&Y have the same average productivity ratios) is rejected at a 95% confidence level with a p-value < 0.05. The normalization process therefore confirms that the two sets of data are reasonably corroborative when adjusted for the differences in their original definitions.

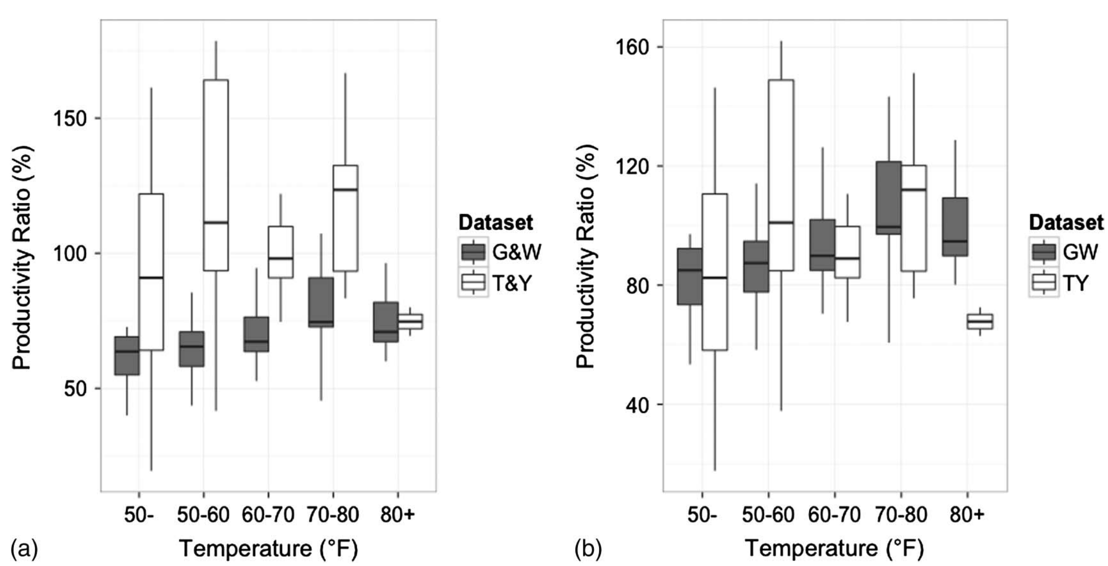

Fig. 2. Temperature versus productivity (data from Grimm and Wagner 1974; Thomas and Yiakoumis 1987): (a) unnormalized; (b) normalized

Table 1. Statistical p-Values for before versus after Normalization (Data from Grimm and Wagner 1974; Thomas and Yiakoumis 1987)

Normalization process	Below 50°	50–60	60–70	70–80	Above 80°
Before normalization	0.0001364	0.001954	0.003946	0.01263	0.9216
After normalization	0.9119	0.117	0.5739	0.7481	0.0716

The G&W curve was developed by computing the individual, actual productivity for a series of tasks and dividing such by the best actual productivity for those tasks overall. For example, if a mason installed three brick walls at a rate of 10 labor-hours, 15 labor-hours, and 20 labor-hours, the G&W values would be 1.0 (10/10), 0.67 (10/15), and 0.5 (10/20). T&Y, on the other hand, compared the actual productivity rate for each of these walls against the planned rate for each wall. If the mason planned to work at 15 h/wall, but actually spent 10, 15, and 20 h respectively, then the PRs would be 1.5 (15/10), 1 (15/15), and 0.75 (15/20) accordingly. Thus, the models are not directly comparable unless the underlying definitions are harmonized.

T&Y's definition relied on the contractor's estimate, using the planned rate in the denominator of the PR calculation. G&W's estimate, on the other hand, used the very best actual productivity experience in the denominator for all PR calculations. Thus the estimated productivity rate was not used in the PR calculation.

To use both data sets in a consistent way and get reasonable results, the raw data provided by each researcher to compute the average productivity achieved in the 50–80°F range was used as a weighting average. That average was used as the denominator in the normalized PR calculation. Then the actual productivity for all temperature ranges was divided by that average optimal value. The normalized PRs are shown in Fig. 2(b). From this a quadratic model was developed for each data set and the two data sets combined. The normalized data from the two data sets and the resulting regression lines are shown in Fig. 3.

The solid line represents a regression line based on combined data, and the dotted line represents a regression line based on T&Y and G&W respectively. The combined model is as follows:

$$\text{Estimated productivity ratio} = 23.92 + 2.07T - 0.014T^2 \qquad (1)$$

where T = temperature in °F.

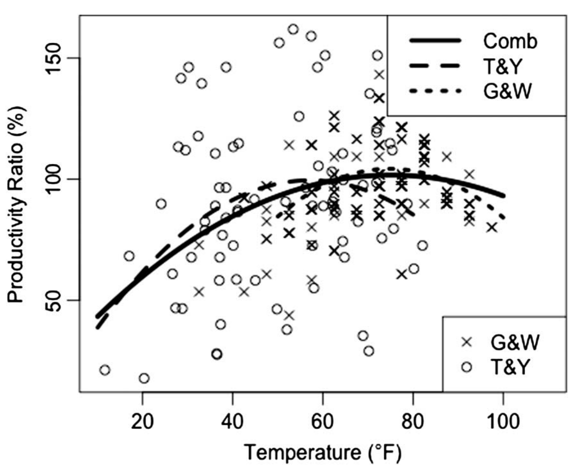

Fig. 3. Temperature versus productivity ratio with regression models

In the t-test for this model, all coefficients have p-values smaller than 0.05. The F-statistic is very close to 0. This means that the model is statistically significant and the probability that the temperature does not have an effect on productivity is almost 0%. The R^2, which is the statistical coefficient of determination, is only 0.1238, which means that only around 12% of the variation in the productivity can be explained by this model. Inspection of Fig. 3 shows large scatter in the original data, which substantiates the low R^2.

Based on the combined data set of T&Y and G&W, the authors conclude that the effect of temperature is significant, but it is only one factor among many other factors that will have an impact.

Possible Reason #2: Regional Differences

Another possible reason for why T&Y's PR peaks at a different temperature than G&W's is that those studies were performed in different geographical regions with different weather conditions. Optimal temperatures calculated by G&W and T&Y were 45°F and 80°F, and the average temperatures (based on NOAA 7:00 a.m. to 7:00 p.m. data) in Texas and Pennsylvania are 55 and 70°F. NECA's optimal temperature is 40–80°F, and the average temperature in that study was 60°F.

G&W's study was located in Texas whereas T&Y's data were collected from central Pennsylvania. Texas and Pennsylvania have quite different climates. Fig. 4 shows the distribution of hourly air temperature from 7:00 a.m. to 7:00 p.m. (NOAA 2015) for 2010. Those two curves are based on hourly NOAA data with 20 TX stations (data size: 94,576) and 7 PA stations (data size: 33,215) in 2010. The curves are kernel density estimates (kernel density estimation is a nonparametric way to estimate probability density function of a random variable).

Pennsylvania is generally cooler than Texas.

Fig. 4 also shows the PRs for the T&Y (Pennsylvania) and G&W (Texas) studies. The PR curves bear some relationship to the temperature curves. Though a convincingly-strong statistical relationship was not found, it does seems reasonable that a person's optimal productivity will be affect by their habitat basis. That is, people in Pennsylvania are probably acclimated to a cooler environment, and their peak productivity occurs at a cooler temperature than is the case for Texas workers.

Possible Reason #3: Different Trades

Lee (2007) summarized previous studies (including G&W and T&Y) on weather's effect on productivity and commented that the PR differences in those studies might come from different labor trades studied. Heavy, manual work is more tiring, and these works will suffer productivity degradation faster than workers performing

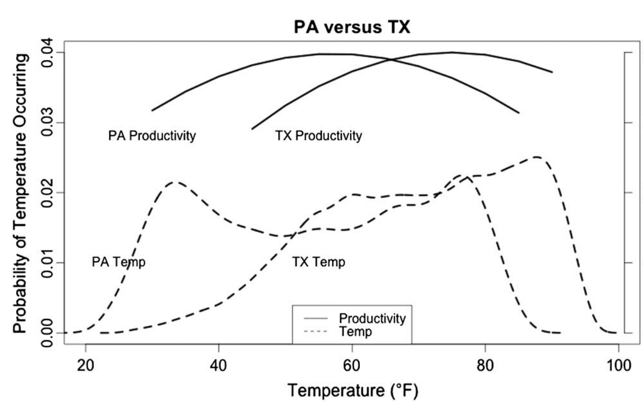

Fig. 4. PA versus TX: temperature and productivity (temperature probability based on data from NOAA 2015)

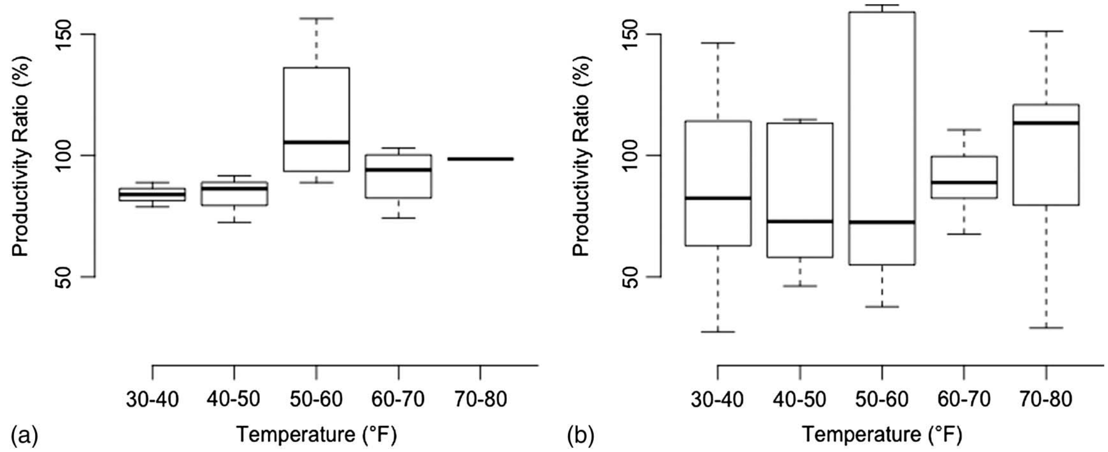

Fig. 5. Productivity of (a) masonry versus (b) other work (data from Thomas and Yiakoumis 1987)

lighter, less taxing work. The NECA data are from light work and the Grimm data are from heavy work, whereas Thomas combined relatively easy and hard work.

Thomas and Yiakoumis (1987) collected productivity data from three trades. Fig. 5 shows PR versus temperature for different trades. The G&W's data were not used here.

Fig. 5(a) shows that masonry PR is relatively constant across different temperatures, and is less variable than the formwork and structural steel work shown in Fig. 5(b). There is no evidence from this data set that the heavier work (masonry work) was more heavily affected. It is not clear from the Thomas study that masonry work was more labor-intensive than the forming and steel work. It is reasonable to believe that the planned productivity estimates account for the difference between heavy and light work. The data set is small, and further studies are needed for this topic.

Humidity's Effect

As indicated in Fig. 1, the T&Y, G&W, and NECA (2004) studies claim that productivity is affected by humidity as well as temperature. The NECA data were not available, but it was possible to normalize and analyze the T&Y and G&W data to evaluate humidity's impact on productivity. Fig. 6 shows the result, with 60% humidity being optimal. The T&Y regression line shows a steep downward pattern and diverges from the combined regression line

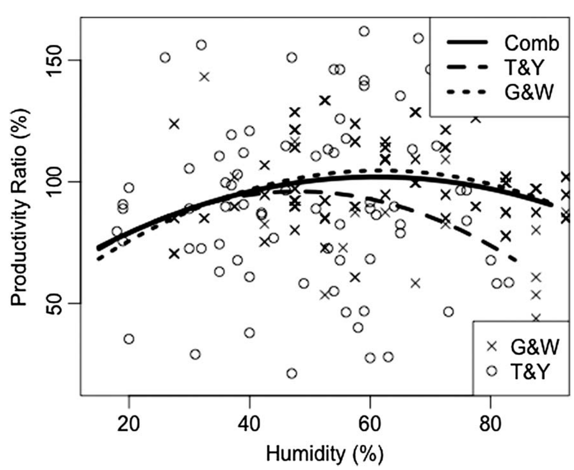

Fig. 6. Humidity versus productivity ratio with regression models

probably because of lack of data for higher humidity. In their original paper, T&Y acknowledged that their data only contained three data points at the high end of the relative humidity scale, and thus no definitive conclusions regarding higher values of humidity's effect can be drawn based on their work.

The statistical fit for these data are represented in Eq. (2):

$$\text{Estimated productivity ratio} = 51.02 + 1.67H - 0.014H^2 \quad (2)$$

where H = humidity in %.

Applying the t-test for this model all coefficients are determined to have p-values smaller than 0.05, and the F-statistic is very close to 0. That means the model is very significant and the probability that humidity does not affect productivity is close to 0. The R^2 is 0.05, which is smaller than the temperature equation, Eq. (1). This means that humidity is a contributor to productivity but less of a contributor than temperature because humidity's R^2 is less than temperature's R^2.

From this it can be concluded that humidity itself also has a significant effect on productivity, but its effect is smaller than temperature's. Because temperature and humidity might have an interactive effect on productivity, combining temperature and humidity's effect on productivity resulted in Eq. (3):

$$\begin{aligned}\text{Estimated productivity ratio} = {} & -27.02 + 2.38T - 0.022T^2 \\ & + 1.82H - 0.021H^2 + 0.011HT\end{aligned} \quad (3)$$

This model reflects temperature, humidity, and the two-way interaction between temperature and humidity's effect on PR. All coefficients are significant and R^2 is 0.2445 for this model, which means that this model can explain about one-quarter of the variations in data if the combination of temperature and humidity are considered.

Conclusions and Recommendations

In conclusion, previous studies on temperature and humidity's effect on productivity are not consistent in terms of their data definitions, so they cannot be directly compared. After normalizing for the different definitions, T&Y and G&W data are reasonably close as seen in Figs. 2(a and b). Though the curves do diverge somewhat at temperature range extremes, the researchers believe that they are generally close. These data were combined, and a new regression relationship, Eq. (1), was developed. It should be used for studies and claims made about temperature's impact on productivity. The authors have not found any other published study that addressed this issue and believe this work is a new contribution to the industry's understanding of productivity.

Next, the investigators found that peak productivities are probably affected by the regional location of a worker. The Pennsylvania workers in T&Y's study had a different peak PR than the Texas works in G&W's study. One possible reason for their difference is that their data were collected from different regions. No evidence showed that heavier work such as masonry work was more sensitive to temperature and humidity than other trades.

In addition, T&Y's and G&W's data were reviewed for humidity's impact on productivity, and found to be reasonably congruent. The combined humidity-productivity curve represented by Eq. (2) is based on normalized data from those two studies.

Finally, these normalized data were analyzed from a temperature and humidity perspective and a new combined temperature-humidity model was developed, as represented by Eq. (3). It explains a notable amount, but not all, of the productivity variation associated with the actual temperature and humidity data studied.

Reviewing these findings as a whole, the normalization and different analyses provide herein offer a better understanding of construction labor productivity. These studies and analyses can serve as supplementary techniques to quantify productivity loss and can help project managers plan and control their work more accurately and resolve disputes more readily. Harmonizing these studies allows for more reliable use of such. For instance, instead of asserting that temperature and weather conditions are abnormal (say, outside the 10-year average), normalizing and combining these studies provides enough data points to permit a more rigorous statistical analysis. Variations can now be measured in terms of standard deviations from normal expected conditions, and the probability of exceeding some particular temperature point or temperature range can be objectively described. Such information should not be used mechanistically though. Rather it should be used as a supplement to the judgment to an experienced analyst who has studied the project fully.

More research is needed to understand how productivity loss is affected by different geographical regions and by other weather types (snow, rain, wind). This paper provides a starting point for such future research.

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Endnotes

[1]See the Appeal of Zisken Construction Company, J.D.Hedin Construction Co. Inc. v. United States, Edge Construction Company v. United States, Appeal of Triad Mechanical Inc., Daewoo Engineering and Construction Co. v. United States.

[2]See Fru-Con Construction Corporation v. United States.

[3]See Appeal of E. B. Bush Construction, Luria Brothers & Company v. United States, Appeal of Fruehauf Corporation, Appeal of Excavation-construction Inc., Appeal of Pathman Construction Co., Appeal of Triad Mechanical Inc.

[4]See Appeal of Zisken Construction Company, J.D.Hedin Construction Co. Inc. v. United States, Appeal of International Builders of Florida Inc., Appeal of John E. Faucett, Appeal of Lamb Engineering and Construction Company, Daewoo Engineering and Construction Co., Ltd. v. United States.

[5]For example, in Appeal of Zisken Construction Company, the appeal was rejected because the weather was not unusually severe. The court noted that though "it rained more often than normal, the amount of each rainfall was below normal; there was a cold snap but there were 21 mild days which gave Zisken some advantages." See also Appeal of Fruehauf Corporation, Appeal of Community Heating and Plumbing Company, Appeal of Triad Mechanical Inc., Appeal of Lamb Engineering and Construction Company.

[6]For example, in Edge Construction Company v. United States, Edge was entitled to an extension of project time for weather-related delays, but the cost reimbursement was not supported.

[7]See Luria Brothers & Companys v. United, Appeal of International Builders of Florida Inc., Appeal of Fruehauf Corporation, Appeal of Essential Construction Co. and Himount Contractors Ltd., Joint Venture, Kit-San-Azusa v the United States, Appeal of Donohoe Construction Company, George Sollitt Construction Co. v. United States, Appeal of Pathman Construction, Appeal of Excavation-Construction Inc.

[8]For example, in Appeal of John E. Faucett, the plaintiff's claim was rejected because it voluntarily undertook contract performance during an anticipated period of normally heavy rainfall because of Faucett's desire to start work on another project immediately after the disrupted project would finish. See also Appeal of Fred A. Arnold, Inc.

[9]See Appeal of Excavation-Construction Inc., Appeal of J.A.Jones Construction Company.

[10]See Appeal of E. B. Bush Construction, Appeal of Acme Missiles & Construction Corporation, Appeal of Hugh Brasington Contracting Co.

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