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ENGINEERING MANAGEMENT THEORIES AND METHODOLOGIES

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Schedule Compression Impact on Construction Project Safety

Abstract Many construction projects are met with stringent timelines or the threat of exorbitant liquidated damages. In addition, construction schedulers are frequently forced to incorporate aggressive schedule compression techniques. As already discussed by previous researchers, these schedule compression techniques have direct impacts on project productivity and quality defects. Researchers have also pointed out that schedule compression will affect safety incidents such as Occupational Safety & Health Administration recordable injuries and near misses over long project durations. However, most of the existing studies treated safety as a subcategory of project productivity and project quality, and minimal research has been done to directly quantify the effect of schedule compression on safety at the project level. Therefore, in this research, we conducted a survey and statistical analysis to investigate the relationship between schedule compression and safety in construction projects. We interviewed various members of the Houston construction community from both industrial and non-industrial roles. Statistical analysis was used to identify factors that have significant impacts on the occurrence of safety incidents at an industry specific level.

Keywords: construction safety, schedule compression, overtime, work shift, Hurdle model

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1 Introduction

According to the United States Occupational Safety and Health Administration (OSHA), the construction industry is a high hazard industry that is extremely dynamic in nature (OSHA, 2013). Construction work can encompass a wide range of fields, from small residential home building projects to commercial developments and industrial projects over extensive durations. During the construction of these projects, regardless of size, workers are exposed to an abundance of hazards. According to OSHA, some of the most common hazards that workers are exposed to are falling from rooftops, unguarded machinery, being struck by heavy construction equipment, electrocutions, silica dust, and asbestos (OSHA, 2013). Not only can these hazards lead to injuries, they could inevitably lead to death.

As OSHA stated, there were 796 construction workers killed on the job in the year 2013 (OSHA, 2013). To mitigate these issues, most client companies require contractors and subcontractors to formulate safety management plans to prevent workers from being injured. Although safety is a priority to all parties involved, it is not uncommon that safety and other construction management practices take a backseat to schedule when faced with liquidated damages and lost profits. Even before submitting their initial bids, the contractors usually find themselves faced with limited durations to complete their tasks to meet the client expectations of having their facilities up and operational. Most clients will write provisions into their contracts that will hold the contractors to an aggressive completion date, as a necessary means to clear themselves of the liability of lost profits or prevention of occupancy. Due to these time constraints, contractors are usually forced to instate aggressive scheduling techniques to reduce the time needed to complete certain construction activities. This reduction in time is known as schedule compression.

According to the Construction Industry Institute (CII), schedule compression is used for the purposes of (1) reducing total design construct time; (2) accelerating a schedule for owner convenience; and (3) making up for lost time after falling behind schedule (CII, *n.d.*). To achieve schedule compression, contractors use various different compression methods, which generally consist of, but are not limited to, mandatory contractor overtime, over-manning on critical activities, working critical activities out of sequence, and instating shift work.

There is rich literature in regards to the connection between schedule compression and construction productivity and quality (see Table 1). Existing research has quantified the relationship between schedule compression and these variables, and considered safety to be a subcategory of both. In addition, the relationship between safety and schedule compression has been explored from the perspective of other industries that were not construction. Exploring this relationship from the construction project point of view is crucial for individuals considering the usage of schedule compression on their project. Obtaining the data and testing for statistical significance will assist in providing a framework to industry practitioners, and will strive to encourage them to consider safety as an independent variable of productivity and quality.

1.1 Definitions of schedule compression

Schedule compression is defined as the shortening of the required time to accomplish one or more engineering, procurement, construction or startup tasks. Four most common schedule compression techniques are analyzed in this research, which include overtime, overmanning, shift work, and working activities out of sequence. The following definitions from CII (*n.d.*) are used in this research.

- Overtime- any time worked over 40 h for a project craft worker.
- Over-manning- adding manpower to the budgeted workforce size.
- Shift Work- any work done after the primary workforce has completed work for the day.
- Out of Sequence Activities- any work that is done outside the scope of baseline scheduled activities for the sake of accelerating the work.

1.2 Relationship between schedule compression, productivity and quality in construction industry

Previous research results show that schedule compression leads to a decrease in productivity in most circumstances. For example, Thomas (1992) conducted a study in regards to the effects of labor productivity when scheduled overtime was required. Many different projects were studied in the construction and manufacturing industry, which showed a consistency of productivity loss when schedule overtime was utilized. The study revealed that after 3 weeks straight of overtime, the productivity began to diminish. Noyce and Hanna (1998) conducted a survey of 1,250 professionals to rank-order the most effective methodologies of both planned and unplanned schedule compression. The authors found that scheduled overtime and overstaffing caused a significant increase in costs, and a moderate decrease in productivity. Hanna, Taylor, and Sullivan (2005c) studied the effects of extended duration overtime (hours worked beyond a 40-h schedule) in labor heavy fields on productivity (the ratio between total input of resources and total output of product). The authors concluded that a decrease in productivity does occur when the number of hours worked per week increases or the project duration increases. Chang, Hanna, Lackney, and Sullivan (2005) developed a model to quantify the impact of schedule compression on labor productivity. Survey results were collected from 66 mechanical projects and 37 sheet metal projects in the United States. The analysis results showed that if schedule is compressed by x%, the total man-hour will increase by roughly $x/2$%. Hanna, Chang, Sullivan, & Lackney (2005b) investigated the relationship between shift work and labor efficiency. The authors concluded that shift work has the potential to be both beneficial and detrimental to the labor productivity of construction projects. The authors determined that small amounts of shift work are ideal, while large amounts may lead to detriments. Hanna, Chang, Lackney, and Sullivan (2005a) examined the impacts of over-manning on construction labor productivity. The results presented a

Table 1

Previous Studies of Schedule Compression's Effect on Safety, Quality and Productivity

	Construction productivity	Construction quality	Construction safety	Safety in other industries
General schedule compression	Chang, Hanna, Lackney, and Sullivan (2005); Nepal, Park, and Son (2006)	Nepal, Park, and Son (2006)		
Overtime	Thomas (1992); Noyce and Hanna (1998); Hanna, Taylor, and Sullivan (2005c)		Dong (2005)	Duchon and Smith (1993); Caruso, Hitchcock, Dick, Russo, and Schmit (2004); Kawada and Ooya (2005)
Workshift	Hanna, Chang, Sullivan, and Lackney (2005b); Folkard and Tucker (2003);		Folkard and Tucker (2003)	Rosa (1995); Dembe, Erickson, Delbos, and Banks (2006)
Overmanning	Noyce and Hanna (1998); Hanna, Chang, Lackney, and Sullivan (2005a)			

0% to 41% productivity loss depending on the level of over-manning and the peak project manpower.

Existing research also found that schedule pressure has adverse impact on construction quality. Nepal, Park, and Son (2006) conducted a study to determine the effects of schedule pressure on construction performance, and focused on potential tradeoffs in regards to scheduling. The authors determined that due to schedule pressure, constructors will cut corners on productivity and quality to remain on schedule, and that this has the potential to erase the benefit of using schedule compression methods. The analysis revealed that utilizing schedule pressure had an adverse effect upon productivity and quality, and working out of sequence, work defects, cutting corners, and losing motivation to work were the primary reasons.

These studies discussed above displayed a quantified relationship between various schedule compression techniques and both productivity and quality from the perspective of the construction industry. It is logical to assume that as both productivity and quality decrease, there is an inherent impact on the safety of the worker. This potential impact further strengthens the necessity of further research and the application of quantification methods to display the relationship between schedule compression and safety in the construction industry.

1.3 Relationship between schedule compression and safety in other industries

Previous researchers have found that there was a negative correlation between overtime and safety in various industries. For example, Duchon and Smith (1993) studied the possible risks added for accidents and health in the usage of extended workdays in various different industries (regular shift lengths of 10 to 12 h, while still maintaining a 40-h workweek). The authors concluded that in industries where there was a high risk of accidents, special consideration should be made before the usage of extended workdays is implemented. Caruso, Hitchcock, Dick, Russo, and Schmit (2004) summarized 75 recently published scientific findings on the relationship between overtime and extended work shifts on worker health and safety. These studies examined the relationship between long work hours, illness, injuries, health behaviors and overall worker performance. They found that 16 studies addressed overtime as a negative factor on health, which include preterm birth, unhealthy weight gain, increased alcohol consumption, increased smoking, and poor neurophysiological performance. Kawada and Ooya (2005) conducted a survey questionnaire to determine the relationship between workload and health complaints based on dose–response type questions. This questionnaire was then issued to 109 male workers at a car manufacturing facility in Japan. The authors concluded that workload showed a significant association with health complaints in regards to overtime.

Studies also found that work shifts have negative impact on the safety of workers. For example, Rosa (1995) identified work shifts and fatigue as a possible culprit of increases in accident rates in industries such as nursing, shipping, and mining. Dembe, Erickson, Delbos, and Banks (2006) conducted a study to analyze various forms of non-standard shift work, such as night and evening shifts, and to determine if these types of working environments enhanced the risk of injuries or illnesses on the workers. The authors found that workers with non-standard shift schedules had a higher risk of injuries or illnesses compared with conventional non-shift workers. The authors also determined that non-standard shift schedules were not riskier because of the job type or characteristic of the employees, but rather because of fatigue, sleepiness, stress and other physiologic variables.

These indications of negative correlations between work schedule and safety are a primary indicator that further research is necessary to quantify and further demonstrate the relationship, especially from a construction industry perspective.

1.4 Relationship between schedule compression and safety in the construction industry

Limited research has been conducted to quantify the relationship between schedule compression techniques and safety. Existing efforts focus on the effect of schedule compression on an individual worker's performance instead of on a project level perspective. For example, Folkard and Tucker (2003) reviewed previous literature of shift work's effect on both workers' safety and productivity. The results showed that safety risks grew from the morning through the night shift, and that successive nights worked also increase risks to safety. The authors determined that safety and productivity are truly reduced on night shifts. Dong (2005) examined various types of work scheduling techniques in construction, such as overtime, to determine if there was a possible connection between work hours and safety incidents. The author analyzed data from the National Longitudinal Survey of Youth, 1,979 cohort (NLSY79), which was based on people of various age, race, sex and industry over a number of years. Odds ratios were utilized to determine the risk of work-related injuries between construction workers and non-construction workers. The study revealed that construction workers began their days earlier, worked longer days, worked fewer weeks per year, were forced to work more than one job, traveled more frequently to work and changed jobs more frequently than non-construction workers. The author determined that overtime almost doubles construction workers' risk of getting injury (odds ratio ≈ 2).

Other research considered safety as a subcategory of productivity or quality when evaluating the impact of schedule compression methods. For example, Nepal, Park, and Son (2006)'s analysis of schedule compression on construction performance, stated that schedule pressure may have a negative effect on safety performance, but they believed it is related to work rate, quality, and productivity, and therefore did not consider it as an independent variable.

2 Methodology

2.1 Data collection

A survey questionnaire was developed and distributed to construction professionals in different construction sectors in Houston. The survey was conducted from September of 2014 to October of 2014, for which 52 responses were collected. Project data collected by the survey included the following information:

The overall project type and size.

If the project had any OSHA recordable injuries.

If schedule compression techniques were used (Overtime, Shift Work, etc.).

The type of compression techniques utilized and if safety mitigation exists in the form of safety management plans, drug testing, etc.

2.2 Descriptive statistics

As shown in Table 2, the respondents to the survey were primarily from the non-industrial sector (34) and followed by the industrial sector (18). The data obtained from the survey had a wide variety of project sizes per project type. The average project size by man hours is 882,384 and 527,528 for industrial and non-industrial projects respectively. The data was analyzed to determine if the respondents had experienced some form of schedule compression, which includes overtime, shift work, overmanning, and working activities out of sequence. As shown in Table 2, a medium percentage of non-industrial respondents (42%), and a large percentage of industrial respondents (67%) experienced schedule compression in the collected data set. Table 2 also shows the average OSHA recordable injuries for each project type in the collected data. The result is quite consistent with the numbers from the Bureau of Labor Statistics (BLS), which found that for the State of Texas the average industrial recordable cases were 2.1 per project (Bureau of Labor Statistics, 2012). This suggests that projects with schedule compression have a higher rate of OSHA recordable injuries. Moreover, it was found that 63.8% of the non-industrial responses and 79.6% of industrial respondents had some form of safety mitigation on their project.

2.3 Hurdle model regression analysis

In the past, count data models such as Poisson and logit models have been used in construction safety analysis. For example, Dong (2005) used logit regression to analyze the effect of overtime on construction workers' injuries. The author correlated the extent of overtime with the presence of injuries. The results concluded that overtime greatly increases the risk of injuries. Chua and Goh (2005) and Jablonowski (2014) used Poisson distribution in their research to model construction incident occurrences. However, it was found that many empirical data sets exhibit more zero observations than what a Poisson model would allow (Greene, 2011). In this research, a sample of 52 projects was surveyed and 37 of them had zero injuries, which clearly indicates the presence of excess zeros. Therefore, a Hurdle model, where zero and nonzero observations are treated separately is used in this research to determine a quantitative relationship between a set of explanatory variables (see Table 3) and the number of OSHA recordable injuries.

In a Hurdel model, the zero and nonzero observations are modeled under two approaches. The difference between zero and nonzero is modeled by a binary choice model, e.g., a logit regression model. The probability function of having zero injury is

$$f(y_i = 0|x_i,\ \alpha) = \frac{1}{1 + e^{x_i' \alpha}} \tag{1}$$

where, y_i = the number of injuries of the ith project; x_i = vector of explanatory variables of the ith project; α = vector of parameters to be estimated.

Therefore, the probability function of nonzeros can be written as

Table 2
Descriptive Statistics

	Industrial projects	Non-industrial projects
Number of responses	18	34
Average man-hour	882,384	527,528
Percentage of usage of schedule compression	67%	42%
Average OSHA recordables	2.3	0.7
Percentage of usage of safety mitigation	79.6%	63.8%

Table 3

Variables Used for Regression Analysis

Variables	Abbreviation
Number of OSHA recordables	Rec
Project type (1 for industrial project and 0 for nonindustrial project)	PrTyp
Project size (Manhours)	PrSiz
Overtime (1 if overtime is used in the project and 0 if otherwise)	OT
Hours per week (Based on 40 h workweek)	HrsPW
Overtime duration (Total weeks of overtime)	OTDur
Shift work (1 if shift work is used in the project and 0 if otherwise)	SW
Shift work weeks (Total weeks of shiftwork)	SWeek
Overmanning (1 if overmanning is used in the project and 0 if otherwise)	OvrM
Out of sequence (1 if out of sequence activities are used in the project and 0 if otherwise)	OutSeq
Minimum worker experience level (1 if minimum worker experience is required and 0 if otherwise)	MinExp
High turnover rate (1 if there is a high turnover rate and 0 if otherwise)	HTOr
Safety management program (1 if there is a safety management program and 0 if otherwise)	SMP
Drug testing program (1 if a drug testing program exists and 0 if otherwise)	DTP
Safety incentive program (1 if a safety incentive program exists and 0 if otherwise)	SIP
Safety audits / Inspections (1 if safety audits or inspections are used and 0 if otherwise)	SAI

$$f(y_i > 0|x_i,\ \alpha) = 1 - f(y_i = 0|x_i,\alpha) = \frac{e^{x_i'\alpha}}{1 + e^{x_i'\alpha}} \quad (2)$$

Furthermore, for those nonzero observations, the probability of a given number y_i is assumed to follow a zero-truncated Poisson process with the probability function

$$f(y_i|x_i,\ \beta,\ y_i > 0) = \frac{\lambda_i^{y_i}}{(e^{\lambda_i} - 1)y_i!},\ y_i = 1,2,\ldots \quad (3)$$

where, λ_i = the Poisson parameter and can be linked to explanatory variables as $\lambda_i = \exp(x_i'\beta)$; β = vector of parameters to be estimated.

The above function is truncated to represent the nonzero observations so that their probabilities are proportionated and their sum is equal to one. Let $\theta = (\alpha,\ \beta)$, the probability function of the Hurdle model can be expressed as

$$f(y_i|x_i,\theta) = \begin{cases} \dfrac{1}{1 + e^{x_i'\alpha}},\ y_i = 0 \\ \dfrac{e^{x_i'\alpha}}{1 + e^{x_i'\alpha}} \dfrac{\left(e^{x_i'\beta}\right)^{yi}}{\left(e^{e^{x_i'\beta}} - 1\right)y_i\,!},\ y_i = 1,2,\ldots \end{cases} \quad (4)$$

The log odds of the probability of a project with OSHA recordable can be expressed as

$$\log\left(\frac{f(y_i > 0|x_i,\theta)}{f(y_i = 0|x_i,\theta)}\right) = x_i'\alpha \quad (5)$$

The likelihood function of all n observations is

$$L(\theta,\ \tilde{y}) = \prod_{i=1}^{n} f(y_i|x_i,\ \theta) = \prod_{i=1}^{n} \frac{1}{1 + e^{x_i'\alpha}} \frac{\left(e^{x_i'\beta}\right)^{yi}}{\left(e^{e^{x_i'\beta}} - 1\right)y_i!} \quad (6)$$

Let $l(\theta,y_i) = \ln\Big(f(y_i|x_i,\theta)\Big)$, the log-likelihood function is as follows

$$l(\theta,\tilde{y}) = \sum_{i=1}^{n} l(\theta,y_i) \quad (7)$$

The estimate of parameter θ can be obtained by solving

$$\tilde{\theta} = \arg\ \max_{e\in\theta} l(\theta,\tilde{y}) \quad (8)$$

through numerical method, e.g., BHHH algorithm (Berndt, Hall, B. H., Hall, R. E., & Hausman, 1974). In the BHHH algorithm, the following equation is solved iteratively until convergence.

$$\hat{\theta}_k = \hat{\theta}_{k-1} + J^{-1}\left(\hat{\theta}_{k-1},\tilde{y}\right) S\left(\hat{\theta}_{k-1},\tilde{y}\right) \quad (9)$$

where, $S\left(\hat{\theta}_{k-1},\tilde{y}\right) = \sum_{i=1}^{n} S\left(\hat{\theta}_{k-1},y_i\right)$; $J\left(\hat{\theta}_{k-1},\tilde{y}\right) = \sum_{i=1}^{n} S\left(\hat{\theta}_{k-1},y_i\right) S\left(\hat{\theta}_{k-1},y_i'\right), S\left(\hat{\theta}_{k-1},y_i\right) = \frac{\partial l(\theta,y_i)}{\partial\theta}\Big|_{\theta=\hat{\theta}_{k-1}}$.

In this research the Akaike Information Criterion (AIC) was used to decide which variables should be included in the model. The AIC statistic is designed to measure the relative Kullback-Leibler information lost when a model is used to approximate the true model (Akaike, 1974). The AIC statistic of a choosing model can be calculated as

$$AIC = \sum_{i=1}^{n} l\left(\hat{\theta}, y_i\right) - p \quad (10)$$

where p is the number of explanatory variables in the model. Once the parameters are estimated, their significance was tested using the Wald test.

2.4 Estimation results

Table 4 shows the result of the Hurdle model estimation results. The effects of project type, project size and overtime duration on the number of injuries are all positive and statistically significant. The estimation results further reinforce the information obtained from the descriptive statistics. Considering the complexity of industrial type projects versus that of non-industrial projects, it is logical that injuries would be more prevalent in the industrial area when coupled with schedule compression techniques. It could also be inferred from the data that although overtime and shift work were present on the project, it was the duration of these activities that could facilitate OSHA recordable injuries on the project. It could be possible that as the workers continue long shifts for long periods of time, there is an increase in fatigue or other factors that would compromise their safety on the project. Considering the variables of overmanning and out of sequence activities, they appeared to have little bearing on the overall occurrence of OSHA recordable injuries. This could have been remedied by asking the respondents for additional quantitative measures such as total duration or total number of workers required for the overmanning activities, and total duration or total quantity of activities worked out of sequence. It could be inferred that without quantitative measures, these variables are not accurately represented, which were not recognized to the linkage to OSHA recordable injuries.

The logit regression results suggest that for an industrial project the risk (or odds ratio) of having an OSHA recordable (versus zero OSHA recordable) is 18.6 times higher than non-industrial projects. The result also show that overtime will increase the risk of having an OSHA recordable by a factor of 1.5, which is similar to the risk obtained by Dong (2005). In that paper, however, the risk is calculated for individual workers instead of at a project level. Moreover, having required the minimal experience level for workers, versus not required, reduce the odds of having an OSHA recordable by a factor of 0.115.

3 Conclusions

In this research, a survey was sent to various members of the construction community in Houston. Questions in the survey were designed to obtain project specific information such as project type and project size. In addition, questions were also developed to obtain information about the schedule compression techniques, and their usage on the projects, as well as information about safety mitigation practices on the projects.

The survey results show that a trend existed by the project type and size plus the usage of schedule compression techniques and safety incidents. The majority of industrial responses were greater in size than the majority of other projects. In addition to this, the responses that were industrial showed a larger usage of schedule compression techniques than the majority of residential and commercial responses.

A Hurdle model analysis shows that the number of OSHA recordable tends to be higher for industrial projects and for larger projects. Moreover, the duration of overtime was found to have statistically significant impact on the number of safety incidents. It could be inferred, as discovered in the literature review, that the workers who were exposed to long durations of overtime experienced fatigue and other health related concerns, which led to these safety-related incidents. However, shiftwork, overmanning and out of sequence activities did not appear to have much

Table 4

Hurdle Model Results

Variable	Poisson model		Logit model		
	Estimate	*P*-value	Estimate	*P*-value	Odds ratio
Intercept	-5.728×10^{0}	0.0001	-2.920×10^{0}	0.0247	0.0540
PrTyp	2.594×10^{0}	6.340×10^{-7}	2.921×10^{0}	0.0220	18.5679
PrSiz	6.371×10^{-7}	2.780×10^{-6}	1.240×10^{-6}	0.0527	1.0000
OT	1.954×10^{0}	0.5501	4.271×10^{-1}	0.0456	1.5328
HrsPW	9.127×10^{-2}	0.3272	4.165×10^{-2}	0.6411	1.0425
OTDur	4.836×10^{-3}	0.0028	3.637×10^{-3}	0.8724	1.1359
OutSeq	8.370×10^{-1}	0.5730	7.470×10^{-1}	0.5173	2.1107
MinExp	-9.179×10^{-1}	0.1610	-2.166×10^{0}	0.0428	0.1146

effect on the outcome of safety incidents. Although safety mitigation practices showed an abundance of usage on an industry specific level, they did not appear to diminish the number of incidents. The binary part of the regression identified that minimum worker experience level assisted in reducing the risk of having injuries.

In future studies, it would be beneficial to determine the optimal level of overtime and shift work duration, and to determine at what level problems will arise. This information had been tested on productivity factors in the past, so it is crucial to obtain this information about safety from a construction point of view. In regards to the minimal linkage between overmanning and out of sequence work, the author suggests that quantitative information be obtained to test the variables such as the durations of both. In addition, further information in regards to safety mitigation methods needs to be obtained. Specific information from respondents in regards to safety management planning for schedule compression may prove useful to display a mitigation of safety incidents. In other words, the safety program may be present but may not be prepared for schedule compression, further leading to safety incidents.

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