Quantifying the Impact of Schedule Compression on Labor Productivity for Mechanical and Sheet Metal Contractor

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Abstract: In a typical construction project, a contractor may often find that the time originally allotted to perform the work has been severely reduced. The reduction of time available to complete a project is commonly known throughout the construction industry as schedule compression. Schedule compression negatively impacts labor productivity and consequently becomes a source of dispute between owners and contractors. This paper examines how schedule compression affects construction labor productivity and provides a model quantifying the impact of schedule compression on labor productivity based on data collected from 66 mechanical and 37 sheet metal projects across the United States. The model can be used in a proactive manner to reduce productivity losses by managing the factors affecting productivity under the situation of schedule compression. Another useful application of the model is its use as a litigation avoidance tool after the completion of a project.

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Introduction

The construction industry is highly competitive and operates within a volatile market. Disputes often arise out of this environment, with one of the dominant factors in these disputes being time. Tensions between owners and contractors often escalate when the issue of time arises. Driving these tensions is the fact that time inevitably equals money. Time savings greatly improve profits, whereas a loss of time can lead to financial distress.

As a result, time conservation is a prime concern for both the owners and contractors on construction projects. If substantial losses of time are encountered during a project, late completion will become a significant issue. If a project is extended beyond the original completion date, the owner may lose business opportunities or income derived from use of the facility. Simultaneously, to the extent that the contractor is responsible for the delay, the contractor is often contractually bound to accelerate the work at his/her expense. Clearly, timely completion is one of the basic objectives of the construction project since it will prevent these negative impacts from hindering the contractor and owner. However, timely completion can often be accompanied by its own problems.

It is not uncommon for an owner to require the contractor to complete a project within a time frame less than normally needed or to require additional work to be completed within the original time frame (mandated acceleration). This case of reducing project duration is usually covered under the change order clause. However, unforeseeable circumstances such as different site conditions that are outside the control of the contractor may cause a reduction of the time available for completing the work. Besides the previous reasons, there are numerous other scenarios leading to schedule compression (Noyce and Hanna 1997; Horner and Talhouni 1995). For instance,

- To make up lost time due to a delay that occurred before or during the construction phase;
- When unanticipated weather conditions limit the available time for construction, especially for outdoor work and the contract shifts the risk of unusual weather conditions to the contractor; and
- When the income to be derived from the facility is estimated to outweigh the extra costs of schedule compression.

When these circumstances arise, the contractor is forced to find a way to speed up the work progress, or "compress the schedule" to finish the project by the completion date. By definition, when the contractor speeds the work up to compensate for the reduction in available time, the schedule is compressed.

Schedule compression, defined as a reduction from the normal experienced time or optimal time typical for the type and size of project being planned within a given set of circumstances (CII 1990), is a common problem on construction projects. According to previous studies, more than 90% of electrical contractors have experienced schedule compression of their original or normal

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project duration (Noyce and Hanna 1998). Oftentimes, a contractor is forced into schedule compression when numerous delays occur during project execution without the owner accordingly granting extra time. For example, on approximately three out of four construction projects, owners refuse to grant a time extension for delays (Leonard 1988). As these facts indicate, contractors frequently experience schedule compression during project implementation.

Problem Statement

It may seem that schedule compression would be an effective solution for time related construction problems. Unfortunately, schedule compression can negatively impact the contractor's labor productivity. Further, the occurrence of disputes and claims between owners and contractors arises when the labor productivity of the contractor is impacted due to compression of a project schedule. As labor costs often represent the largest percentage of total project cost, while also commonly being the most variable cost component, understanding how schedule compression affects construction labor productivity is crucial for increasing project performance, avoiding disputes, and maintaining sound financial status of a company.

Direct costs incurred during schedule compression can be easily tracked, so they are usually not disputable. The more significant cause of increased project costs due to schedule compression is lost labor productivity. This is one of the most prevalent types of damages found in construction claims. Contractors usually fail to provide evidence showing the work was accelerated, including a cause–effect relationship between the schedule compression and increased cost. Contractors need to prove the work was accelerated, and that additional costs and lost productivity were incurred as a result. Without demonstrating and quantifying damages, the additional cost of lost productivity cannot be compensated.

Objective

This study examines how schedule compression affects construction labor productivity. The primary objective of this study is to provide a model to quantify the impact of schedule compression on construction labor productivity.

Literature Review

Although many studies have been conducted on the issue of schedule compression, most of the studies deal with schedule compression as a trade-off between time and cost, with the objective of minimizing cost escalation while achieving schedule compression. Many mathematical and optimization models have been developed as a means of calculating the required compression of individual activities on the project schedule. However, these methods are quite complex in nature and provide little practical use on the project site due to their complexity (Noyce and Hanna 1998). Aside from the two ensuing studies, relatively little effort has been made to determine the effects of schedule compression on labor productivity.

Two significant qualitative studies on schedule compression were done by the Construction Industry Institute (CII 1990) and Noyce and Hanna (1997). CII released a practical and usable catalog of concepts and methods effectively used in industry to compress a schedule. They identified 94 different techniques for schedule compression applicable throughout all phases of the project cycle. However, their study results were more qualitative than quantitative. Although CII evaluated each technique's impact on cost, as well as on duration of the project, they failed to produce quantifiable results for the techniques provided. Their conclusion regarding the effect of such schedule compression methods on project performance is not empirical because it was derived from experts' personal experience and perception, rather than project records or direct observations of field operations.

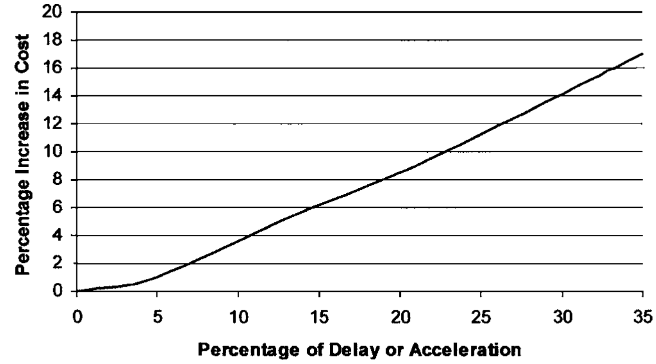

Fig. 1. Matthews curve (Heather 1989), reprinted with permission

Another comprehensive study on schedule compression was done by Noyce and Hanna (1997). They presented 29 different schedule compression concepts with seven subsections: Organization, materials, equipment and tools, information, labor, support service, and construction methods. They also provided descriptions, when to apply each technique, conditions for successful application, cautions, cost implications, and examples for each method they identified. Like the CII study, the results were qualitative rather than quantitative.

Horner and Talhouni (1995) analyzed previously published studies quantifying the effects of acceleration on productivity in order to see how the acceleration affected job site conditions and site operations. The job site factors affected by schedule compression included working hours, shift pattern, pay, absenteeism, size of labor force, congestion, source of labor, learning curve effect, quality, efficiency, and delay.

In 1967, the so-called Mathews curve was developed after evaluating a contractor's claim arising out of a freeway construction project in Seattle (Heather 1989). The rationale behind the Mathews curve is that if the work is either delayed or accelerated such that the contractor is required to perform substantially the same work in a different length of time, the cost will necessarily increase. In other words, if a project is delayed, accelerated, or disrupted, the amount of the delay or acceleration will also affect the unchanged work by an amount identified on the developed curve (Heather 1989). The Mathews curve is shown in Fig. 1. The model was empirically derived after studying industrial machinery, and assessing the life of the equipment.

Thomas (2000) analyzed how labor efficiency is affected by the disruption of work flow resulting from schedule acceleration. The study estimated productivity loss during schedule acceleration based on 250 weeks of data from three electrical projects, all which experienced schedule acceleration. It was found that inefficient work hours resulting from the uneven work flow, a common occurrence during schedule acceleration, is estimated in the range of 20–45%. However, his finding is hard to be generalized

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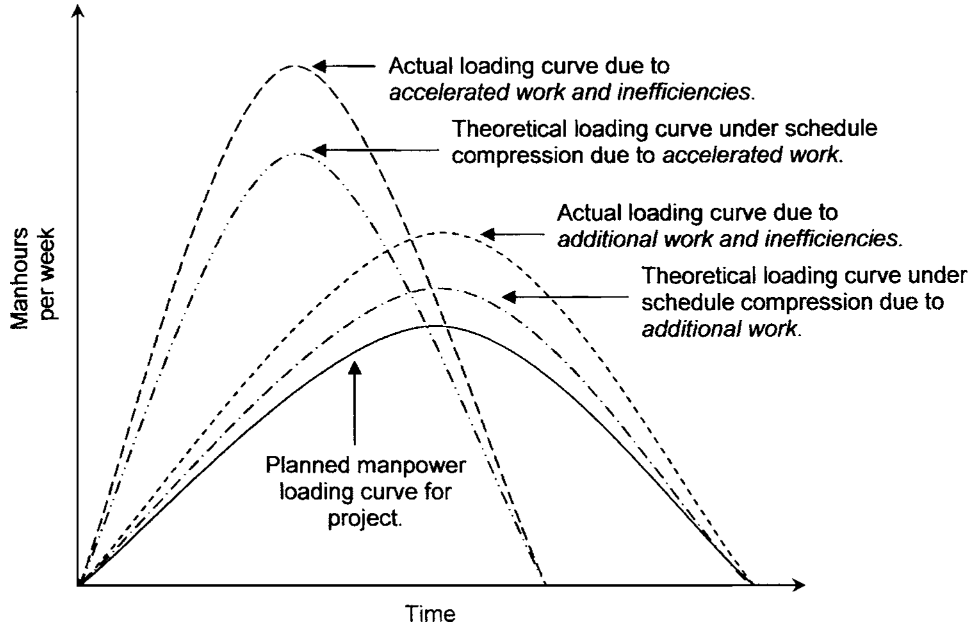

Fig. 2. Lost labor hours due to schedule compression

due to the uniqueness of each accelerated project and the small sample size (three projects).

Impact of Schedule Compression on Labor Productivity

Fig. 2 compares manpower loading graphs under two different schedule compression conditions. One case is when the construction period is shortened and the other case is when the contractor is asked to perform additional work within the original time frame. As can be seen in Fig. 2, manhours per week under schedule compression are much greater than during normal operation. The additional workhours are due to inefficiencies, as well as the manhours necessary to accelerate the work. This is because schedule compression affects labor productivity in various ways. For example, the planned sequence of activities and flow of resources, including labor, materials, equipment, and subcontractors, may be impacted. When this orderly plan is impacted by schedule compression, labor productivity can be seriously affected (Peles 1977; Borcherding et al. 1980; Marchman 1988; Long 1988; Haneiko and Henry 1991; Thomas and Raynar 1997). If more activities must be accomplished concurrently in a limited working space and more workers are added to achieve a certain percentage of completion, the jobsite cannot accommodate the number of workers or activities in some situations. This may cause congestion and a high density of workers, resulting in a productivity loss (U.S. Army 1979; Peles 1977; Marchman 1988; Long 1988). As the number of on-site workers increases in size, it is critical that a corresponding increase be made to the supervisory staff, materials, tools, and equipment. Dilution of supervision plus a shortage of materials, tools, and equipment can lead to a productivity loss (Peles 1977; Thomas and Raynar 1997). With a quickened pace, there is no chance to take advantage of the normal learning curve effect (Marchman 1988; Haneiko and Henry 1991). Besides the above reasons, there are many other ways that schedule compression may affect labor productivity. Fig. 3 illustrates how the labor productivity losses occur when schedule compression is present. The inputs are situations that require schedule compression. Influencing factors are those situations or conditions that lie outside of management's direction and can decrease labor productivity. Controlling factors represent conditions for successful application of schedule compression, and outputs are simply some of the possible results from schedule compression.

Data Collection

A data collection sheet was used in the acquisition of data for this study and consisted of two parts: (1) information on the contractors' background (company information and size) and (2) information describing a specific project that experienced schedule acceleration and compression. Data collection sheets were distributed to mechanical contractors and sheet metal contractors in the United States, with telephone and e-mail follow-up. In some cases, the study team visited contractors to gain a better understanding of the project utilized in this study. A variety of project factors were collected: project type, size, type of owner, project delivery method, contractor's role, type of contract, contractor's project management practice, productivity information, and project schedule, along with estimated and actual manpower loading graphs.

For this study, 66 mechanical and 37 sheet metal projects were analyzed. The project data were gathered from contractors of various sizes and geographic locations (continental United States). The value of construction put-in-place per year by these companies ranged from \$3.9 million to \$170 million, with a range of total manhours of direct labor per year (averaged over the last three years) from 9,690 to 1,977,300 manhours. To avoid location bias, which could occur with the use of contractors from only a certain region of the country, data were solicited on projects from contractors with headquarters in 20 states, with the projects located in 28 different states. The work entailed new construction (43%), addition or expansion construction (19%), renovation (19%), and combinations of these three (13%). Construction

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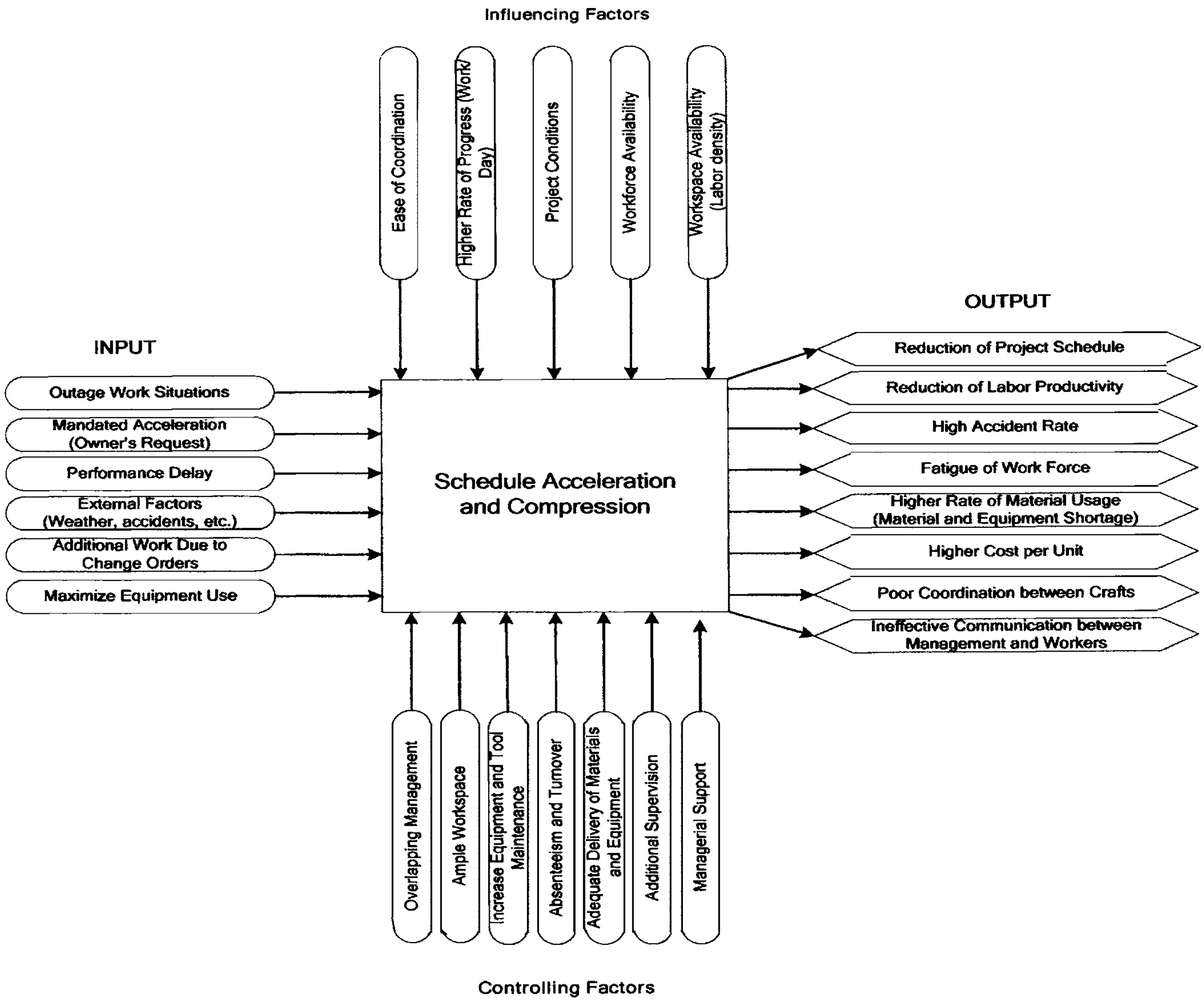

Fig. 3. Schematic structure of schedule compression

project types that compose the database are commercial (banks, retail, office buildings, etc.: 12%), institutional (hospitals and correctional facilities: 35%), industrial (manufacturing or process plants, paper mills, wastewater treatment plants, etc.: 38%), manufacturing (line, factory, etc.: 6%), residential (multiunit housing: 2%), and others (arenas, etc.: 8%). The types of work performed on these projects include heating, ventilating, and air conditioning (HVAC: 43%), plumbing (22%), process piping (24%), fire protection (4%), and others (7%).

Quantitative Definition of Schedule Compression

Although many studies have been conducted on schedule compression, the quantitative definition of schedule compression has not been clearly established. Before quantifying the impact of schedule compression on labor productivity, the quantitative definition of schedule compression needs to be established to determine whether a project has experienced schedule compression.

Normal Duration

The "normal duration" is the time required for completing a project with a normal crew size and normal weekly workhours for a certain type and size of project. Normal weekly workhours in the construction industry is generally considered to be 40 h, working eight hours per day and five days per week. However, there has been no firm rule to determine a normal crew size for a certain type and size of project. In this study, the average number of workers, based on project size, was considered as the normal crew size for a certain type and size of project. Thus, normal duration can be defined as follows:

$$\text{Normal duration} = \frac{\text{project size}}{\text{normal crew size} \times 40} \tag{1}$$

where, project size is in manhours by using actual total manhours consumed for the project. Using the data collected for this study, equations showing the relationship between average crew size and project size for mechanical projects and for sheet metal projects were developed as follows:

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- Mechanical work

$$\text{Log (average crew size)} = -1.03 + 0.455 \log(\text{project size}) + 0.380 \text{ industrial} \quad (2)$$

The variable industrial is assigned a value of one for industrial projects and zero for other project types, such as institutional or commercial.

- Sheet metal work

$$\text{Average crew size} = 1.587 + 2.7\text{E}^{-4}(\text{project size}) \quad (3)$$

From the normal (average) crew size obtained from Eqs. (2) and (3), the normal duration for a certain type and size of project can be calculated by using Eq. (1). Normal duration will be utilized later to determine schedule compression, including whether a project experienced schedule compression and how much of the duration was compressed. Using the collected data, regression analysis was used to determine the average crew size for a given project size. The R^2 values for the equations are 79.8% (mechanical contractors) and 89.4% (sheet metal contractors).

Percent Schedule Compression

Based on the fact that schedule compression occurs when a contractor is required to do a certain amount of work in a shorter period of time than the normal or optimal time typical for the type and size of a project, the quantitative definition of schedule compression may be determined. Quantitatively defined, schedule compression is the difference between normal project duration for a certain type and size of project and actual duration spent to complete the project.

To generalize the difference in time regardless of type and size of project, percent schedule compression *(% schedule compression)* was developed. Percent schedule compression can be used to determine if a project has experienced schedule compression during implementation of the project, while also indicating the amount of time compressed. Percent schedule compression avoids bias from: Project size, project duration, work hours per week due to different crew scheduling methods, the number of workers involved in the project, whether a time extension was granted or not, and if the project was initially compressed or poorly planned.

$$\%\ \text{schedule compression} = \frac{\text{normal duration} - \text{actual duration}}{\text{normal duration}} \quad (4)$$

Percent schedule compression can have both positive and negative values. A positive value means the project was compressed to the point that it was completed in less time than the normal duration. In other words, the project experienced schedule compression for reasons, such as a delay in the middle of project, a late start, additional work, or many change orders. A % schedule compression value of zero indicates the project was completed as normal, or enough time extensions were granted to accommodate the increased work scope or changed work. A negative % schedule compression value indicates more time was granted and used than needed, or the work scope was reduced while the project duration remained as planned.

Development of Quantification Model

Efficiency Loss

Efficiency is a commonly accepted method used to quantitatively calculate labor productivity. Efficiency is defined as the ratio between the actual labor hours expended to complete the project and the budgeted base hours (Hanna 2001). Loss of efficiency is defined as the difference between actual hours utilized and budgeted hours as a percent of total actual hours utilized.

Lost efficiency may result from a contractor's poor performance or the impact of productivity related factors such as overmanning, overtime, shift work, and work interruptions. The strength of this method is its representation of the direct effects, as well as the indirect effects, on productivity since actual labor hours are calculated after the completion of the project. To compare projects of varying size, percent lost efficiency (%lost eff) is defined as

$$\%\text{lost eff} = \frac{\text{total actual direct labor hours} - \text{budgeted direct labor hours}}{\text{total actual direct labor hours}} \times 100 \quad (5)$$

Predictor Variables

Percent schedule compression is a good indicator for determining whether the project schedule was compressed, as well as, how much the project schedule was compressed. Obviously, there are other factors that interact with the amount of schedule compression, such as project size and type, and also the contractor's project management. In addition, there are factors caused by schedule compression, including: Overtime, shift work, overmanning, crew size increases, work hour increases, and stacking of trades. These other factors amplify or mitigate the impact of schedule compression on labor productivity. Table 1 shows the variables tested. A definition of each factor was provided in column 2 and a description of how the variable was measured is given in Column 3.

Hypothesis Testing

Statistical testing was performed to see if each factor was related to productivity loss and if the relationship is statistically significant. The relationships between factors and productivity loss are shown in Table 2. The relationship with productivity loss is explained by the value of the Pearson correlation coefficient and *p* value. The higher the value of the Pearson correlation coefficient and the smaller the *p* value, the closer the relationship is between factors and %lost eff. There may be some degree of redundancy or overlap among variables. This correlation can result in one of the variables being in the model while the other variable(s) are not, although both of them have a significant relationship with productivity loss.

Model for Determining Loss of Labor Productivity due to Schedule Compression

Based on the variables in Table 1, a multiple regression analysis was performed against percent lost efficiency (%lost eff) to predict productivity loss caused by schedule compression. As previously defined, lost efficiency is the quantitative measure of all

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Table 1. Factors Tested

Terms and factors	Definition	Measurement
% schedule compression	(Normal duration−actual duration)/(normal duration)	Percent
Actual project duration	Actual duration in weeks to complete the project	Weeks
Schedule management	Was a CPM schedule created and regularly updated for this project?	0=no 1=yes
Manpower management	Was a manpower loading graph made and regularly updated for this project?	0=no 1=yes
Absenteeism	Ratio between the number of craftsmen that fail to appear for the work and the number of craftsmen employed on this project	1=0–5% 2=6–10% 3=11–20% 4=greater than 20%
Average manpower	Average number of craftsmen used for the project	Number
Construction type	Either renovation or all others, which include addition or expansion and new construction	0=all others 1=renovation
Contract budgeted work hours	Total estimated work hours that the contractor used to allocate labor resource	Work hour
Use of CPM	Was a critical path method of scheduling used?	0=no 1=yes
Actual average manpower/estimated average manpower	Ratio of actual average manpower to estimated average manpower	Ratio
Estimated manpower loading chart	Was an estimated manpower loading graph made for this project?	0=no 1=yes
Actual peak/avg. ratio/estimated peak/avg. ratio	Ratio of actual peak/average manpower to estimated peak/average manpower	Ratio
Actual peak/estimated peak	Ratio of actual peak manpower to estimated peak manpower	Ratio
Extension granted?	Was a schedule extension granted for this project?	0=no 1=yes
Extension requested?	Was a schedule extension requested for this project?	0=no 1=yes
Fixed end date	Was there a fixed end date for this project?	0=no 1=yes
Manpower shortage at the start	Was there a manpower shortage at the start of the project?	0=no 1=yes
Manpower shortage during	Was there a manpower shortage during the project?	0=no 1=yes
Mechanical or sheet metal	Project was either mechanical or sheet metal	0=sheet metal 1=mechanical
% beneficial occupancy	Percent of project executed on an operating unit	Percent
Overmanning	Was overmanning experienced on this job?	0=no 1=yes
% overtime	Total overtime work hours divided by total estimated work hours	Percent
Owner type	Was the owner private or public	0=public 1=private
Manpower at peak	Peak number of craftsmen used for the project	Number
Peak/average manpower	Ratio of peak manpower to average manpower	Ratio
Percent extended	Percent extended is calculated by subtracting the original duration from the actual duration and dividing by the original duration	Percent
Percent of PM's time	Percent of the project manager's time spent on this project	Percent
Progress tracking 1	Did you track progress by actual installed quantities?	0=no 1=yes
Progress tracking 2	Did you track progress by actual work hours?	0=no 1=yes
Progress tracking 3	Did you track progress by earned value?	0=no 1=yes
Productivity tracking	Was productivity tracked on this project?	0=no 1=yes
Project manager's experience 1	As a project manager, total number of projects of this construction type	Number
Project manager's experience 2	Total years employed as a project manager	Years
Project manager's experience 3	Total years employed by this company	Years
Project manager's experience 4	Total years employed in the construction industry	Years
Project size	Actual work hours utilized at completion of the project	Work hours
Project type	Either industrial or all others, which include commercial, institutional, residential, etc.	0=otherwise 1=industrial
% shift work	Total shift work hours divided by total estimated work hours	Percent
Update CPM	Was the CPM schedule updated during construction	0=no 1=yes
Update manpower loading	Was the manpower loading graph updated based on actual hours and new estimates?	0=no 1=yes
% change order due to schedule compression	Percentage of change order hours due to schedule compression	Percent

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Table 2. Relationships between Factors and Percent Loss Efficiency

Factor	Pearson correlation	P value	Interpretation (on average . . .)
Actual peak/estimated peak	0.398	0.020	As the ratio of actual peak manpower to estimated peak manpower increases, the productivity loss increases.
Actual average manpower/estimated average manpower	0.351	0.042	As the ratio of actual average manpower to estimated average manpower increases, the productivity loss increases.
% schedule compression	0.306	0.078	As the amount of time compressed increases, the productivity loss increases.
% overtime	0.312	0.078	As the amount of overtime work hour increases, the productivity loss increases.
% beneficial occupancy	0.295	0.091	As the percent of project executed on an operating unit increases, the productivity loss increases.
Schedule management	−0.295	0.091	If the contractor does not create CPM schedule and regularly update the project schedule, a higher productivity loss is likely on the project.

lost work hours as a result of schedule compression. %lost eff was expressed as a percentage of the total actual manhours expended on the project. This was done to provide a measure that was specific to each project.

The final model contains eight variables. The regression equation to predict the impact of schedule compression on labor productivity is as follows:

$$\begin{aligned}
&\text{Productivity loss caused by schedule compression}\\
&\quad = -0.0723 + 0.417\%\ \text{schedule compression}\\
&\qquad - 0.00252\ \text{actual manpower at peak}\\
&\qquad + 0.0591\ \text{ratio of actual and estimated manpower at peak}\\
&\qquad - 0.0474\ \text{schedule management} + 0.193\ \text{industrial}\\
&\qquad + 0.102\%\ \text{beneficial occupancy}\\
&\qquad + 0.594\%\ \text{change order for schedule compression}\\
&\qquad + 0.00239\ \text{actual project duration}
\end{aligned} \tag{6}$$

Statistical Analysis of Final Model

The R^2 value for the final model equation is 76.8%, with an adjusted R^2 of 68.7%. Table 3 shows the result of the statistical analysis of the final model. The p value of the regression analysis was less than 0.001, and p values for predictors in Table 3 were also statistically significant, indicating a relatively strong regression model.

Table 4 gives the calculations and applicable range of each of the independent factors included in the final quantification model.

Table 3. Statistical Analysis of Final Model

Predictor	Coefficient	P value
Constant	−0.07233	0.292
% schedule compression	0.41705	<0.001
Actual manpower at peak	−0.00252	<0.001
Ratio of actual and estimated manpower at peak	0.05911	<0.001
Schedule management?	−0.04737	0.090
Industrial?	0.19307	<0.001
% beneficial occupancy	0.10211	0.062
% change order for schedule compression	0.59380	<0.001
Actual project duration	0.00239	0.001

It should be noted that the final model is not valid for a project containing a factor that is not within the applicable range. Projects that contain variables that are not within the parameters of the model should not be used with the final model to predict productivity loss due to schedule compression.

Validation of Final Model

Cross Validation

The model was validated through cross validation. For cross validation, the data were divided randomly into five subsets. The model was refit using four subsets, and then the prediction accuracy was determined with the remaining subset. This process was repeated for all five subsets. The result shows three out of every four projects fell within ±10% of the actual value.

Validation for Project Type, Size, and Duration

Validation of the final model was also performed to see if there is any bias due to type of work, project size, and project duration. The data used to develop the final model were regrouped into sheet metal projects and mechanical projects, and then the predicted value of %lost eff was compared with actual %lost eff. The average deviation of sheet metal projects was −1% and that of mechanical projects was +1%. This meant the final model can be used on both types of work.

The projects were grouped into three groups based on project size to see if the final model can work on different sizes of projects. The first group included projects with actual manhours less than 20,000 hours. The second group contained projects with actual manhours ranging between 20,000 and 100,000 manhours. The last group represented projects with a project size greater than 100,000 manhours. The predicted productivity loss obtained from the final model was compared with actual productivity loss. According to the test results, the average deviations of small project, medium project, and large project were +1, −1, and +2%, respectively. This confirmed there is no apparent bias in project size when using the final model.

The same process was performed for different project durations. The projects were grouped into three groups based on project duration. The first group included projects where the actual duration was shorter than a half-year (26 weeks). The second group contained projects having an actual duration between a half-year and one year. The third group represented projects with

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Table 4. Calculation and Applicable Range of Factors Included in the Final Model

Predictor	Calculation	Applicable range
Constant	1	
% schedule compression	(Normal duration − actual duration)/(normal duration)	0.01–0.89
Actual manpower at peak	Number of sheet metal (or mechanical) workers at peak	10–90
Ratio of actual and estimated manpower at peak	(Actual manpower at peak)/(estimated manpower at peak)	1–4.53
Schedule management?	Was a CPM schedule created and regularly updated for this project? 0=no, 1=yes	0 or 1
Industrial?	Either industrial or all others, which include commercial, institutional, residential, etc. (0=others 1=industrial)	0 or 1
% beneficial occupancy	(Total workhours executed on an operating unit)/(total workhours)	0–1
% change order for schedule compression	(Total change order hours for schedule compression)/(total change order hours)	0–0.4
Actual project duration	Actual project duration in weeks	2–84

project durations longer than one year. The test results indicated the average deviations of short project, medium project, and long project to be +1, 0, and 0%, respectively. This confirmed there is no apparent bias in project duration when using the final model.

Example Application

A sheet metal contractor in Wisconsin claimed compensation for lost productivity caused by schedule compression. The sheet metal contractor entered into a contract to fabricate and install the HVAC systems for a project in another state. The project was estimated to take 10,000 manhours and 52 weeks. During the project, the owner asked the sheet metal contractor to fabricate and install an HVAC system for one additional floor, requiring an additional 1,500 manhours that was not included at the time of the contract. The contractor requested a time extension for the additional work, but the owner refused to grant more time. Further, as the owner required that his company be able to operate during construction, the contractor was required to execute the project while the facility was operating for the last 20% of construction duration. Throughout the project, the contractor updated its CPM schedule for this project on a biweekly basis, while also regularly updating its manpower loading chart for the project. From the analysis of the manpower loading chart, it was found that an average of 6.3 sheet metal workers were employed daily during the project, with a peak of 14 sheet metal workers. This peak value is 1.5 times the contractor's estimated manpower at peak. The contractor also implemented overtime work to meet the project deadline. As a result, the contractor completed the project on time, including the additional work. A total of 14,000 manhours were spent on this project, including 900 overtime manhours.

The contractor asked the owner to pay for 14,000 manhours of work, but the owner refused this request. The owner did not want to pay more than 11,500 hours (10,000 original manhours and 1,500 manhours for additional work). Therefore, the owner did not want to pay for the lost manhours caused by the schedule compression, despite the contract documents' allowance of fair and just payment for change order and change conditions. In addition, the owner demanded demonstration of a cause–effect relationship.

Step 1: Determining Schedule Compression

The first step should be to determine if this project experienced schedule compression or not, and whether the cause of schedule compression came from the owner instead of the contractor. If the owner and contractor agree that the project schedule was compressed either at the start of project or during the construction, they should proceed to the next step. If the owner and contractor fail to agree, the quantitative definition of schedule compression in Eqs. (1) and (4) should be used. If actual project duration is longer than normal duration for a project, neither of the models from the current study would be applied.

For the example case, by using Eq. (3), normal crew size for the sheet metal project of 14,000 manhours can be calculated as 5.38 workers. Consequently, the normal duration for this project would be 65 weeks, which is longer than the actual project duration of 52 weeks. Hence, it is determined that this project experienced schedule compression by 20.1%

$$\text{Normal duration for the example case} = \frac{14{,}000}{5.38 \times 40} = 65 \text{ weeks}$$

$$\%\ \text{Schedule compression of example case} = \frac{65-52}{65} = 0.201(\text{or } 20.1\ \%)$$

Step 2: Quantifying Productivity Loss

In the absence of project data that can show that schedule compression affected the entire project and which can be used to negotiate with the owner on compensation for the productivity losses, the quantification model in this study would be applied to quantify the impact of schedule compression on productivity. The productivity loss calculated from Eq. (6) can be a starting point for negotiations between the owner and contractor. Eq. (6) gives 15.97% as the productivity loss due to schedule compression for the example project. Therefore, the lost manhours caused by schedule compression are: $14{,}000 \times 0.1597 = 2{,}236$ manhours. Detailed calculations of the quantification model are provided in Table 5.

Study Limitations

Off-project costs may accrue when contractors are forced to reallocate resources from other projects to a project that is experiencing schedule compression. Further, the commitment schedule compression puts on a certain project will tie up important resource and hence limit the company's ability to undertake other

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Table 5. Input and Output of Example Case for Quantifying Productivity Loss

Predictor	Coefficient	Value	Product
Constant	−0.07233	1.00	−0.07233
% schedule compression	0.41705	0.20	0.08381
Actual manpower at peak	−0.00252	15.00	−0.03779
Ratio of actual and estimated manpower at peak	0.05911	1.50	0.08867
Schedule management?	−0.04737	1.00	−0.04737
Industrial?	0.19307	0.00	0.00000
% beneficial occupancy	0.10211	0.20	0.02042
% change order for schedule compression	0.59380	0.00	0.00000
Actual project duration	0.00239	52.00	0.12431
		% loss eff	0.15972

work. Consequently, the loss of productivity, or even profit, from a secondary project is not considered in the analysis of the losses accrued by an impacted project under the Delta approach (Hanna 2001). This study is limited to mechanical and sheet metal projects with lump sum contracts and a traditional project delivery system.

Conclusions

It is clear from this study's findings that various scenarios leading to schedule compression exist, and that these scenarios negatively affect labor productivity. This research can assist labor-intensive specialty trades not only in understanding the impact of schedule compression on labor productivity, but also practically calculating productivity loss and labor cost. The model developed through this research can be used in a proactive manner to reduce productivity loss due to schedule compression by managing the factors affecting productivity under the situation of schedule compression. Another useful application of the model is its use as an antilitigation tool after completion of a project. For dispute resolution, the values for percent lost efficiency obtained from the model can be used as the basis of negotiation between contractors and owners.

Recommendations

Interaction with industry professionals during the data collection, analysis of case projects, and development of the quantification models revealed certain practices that can be used to both reduce productivity losses and improve the performance of labor during schedule compression. The recommendations provided in this section may either keep a project from being impacted by schedule compression all together, or mitigate the impact of schedule compression on labor productivity when applicable. Following these recommendations will help to encourage an increase in both project and company profitability.

Selection of Schedule Compression Methods

Among overtime, overmanning, and shift work, there is no superior choice for schedule compression. However, there are some criteria that can determine the schedule compression method that would best fit the project situation. These criteria include the availability of good supervision, work force, contract terms, site conditions, length of acceleration, etc. For example, if there is not enough supervision or work force, overtime may be the best option. Furthermore, if a contract specifies overtime premium and shift differential, overtime and shift work may be the better choice than overmanning. Additionally, if a site space will not accommodate additional crews, shift work or overtime work would again be used in order to avoid a congestion problem. If there are a limited number of qualified and motivated craftsmen available, use overtime. However, if craftsmen who are well-versed with shift work are available, this method should be used. Last, if long-term acceleration is anticipated, preferable options may be hiring more workers (potential overmanning) or having multiple work shifts.

Best Practices and Appropriate Use of Scheduling Compression Techniques

Preconstruction Planning

Time constraints, and material, equipment, and labor availability should all be identified during preconstruction planning to adequately establish a realistic project schedule and manpower consumption. These precautions will help to avoid unplanned schedule compression and manpower shortage during the project. Further, it is recommended that strong communication with all parties involved in the project be established, and to encourage their involvement at early stages of the project execution plan.

Project Schedule Management

Develop a realistic schedule, including anticipated weather delays, early in the project and update regularly. Provide a certain period of time as a "buffer" to absorb unanticipated delay events (weather, etc.) for each key milestone. As the project progresses, do more detailed planning by using short-interval scheduling such as a 3-week schedule.

Project Progress Tracking

Monitor progress daily or weekly instead of biweekly or monthly. Issue status reports regularly, and improve communication with other contractors, construction managers, and owners.

Manpower Management

Record manpower data, and monitor productivity and absenteeism for detrimental trends. Develop efficiency at recognizing the effect of inefficient labor.

Awareness of Availability of Adequately Skilled Labor

Hastily seeking more workers may introduce less productive workers. Consequently, the quality of the work may suffer. To ensure adequately skilled workers are available, and to avoid manpower shortages during the project, reappraise labor requirements as the project goes on, and assess company or local manpower availability from time to time.

Be Selective on the Work Assigned to a Second Shift

By assigning completely different tasks to the second or third shift, shift operations are greatly improved. These tasks should be totally independent from the tasks performed by the previous shift, including different materials and tools. In addition, it is recommended that a second shift be used only for a well-defined and relatively small scope of work that requires minimal engineering and design support. This rational is necessary due to the

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difficulties in managing a shift schedule and the limited off site support during second and third shift work. A smaller scope will facilitate coordination, planning, and supervision of the second shift. Material requirements should be minimal, since most supply stores are closed during the working hours of second and third shifts.

Overlapping Management

Overlapping of supervision is needed to ensure smooth handovers between shift groups. This overlap helps to avoid low productivity and rework between shifts, and to improve coordination by letting workers know what has been completed by the previous crews. This can be accomplished by requiring the foreman of the first shift to stay 1–2 h longer, and the foreman of the second shift to arrive 1–2 h earlier.

Innovative Crew Scheduling

Using innovative crew scheduling such as four 10-h days can be very useful, since variable shift arrangements can increase production and improve productivity. However, special arrangements generally are not effective in short-term accelerations; and therefore, should be implemented only in long term acceleration situations.

Keep the Shift Schedule Regular and Predictable

Workers should know their schedule well ahead of time, so they can plan their rest, child care, recreation, and contact with family and friends. This will help the workers keep upbeat attitudes. Further, irregular schedules contribute to accidents by producing fatigue from sleep loss.

Small Overtime Durations

Short durations of overtime have a reduced effect on productivity in comparison to extended overtime usage. If used for short, intermittent durations, overtime efficiency loss can be curtailed. Therefore, utilize spot overtime rather than extended duration overtime on crafts or tasks on the critical path.

Enough Supervision

As crew size increases, the subsequent dilution of supervision may result in a poor quality of work. Add more foremen and supervisors as the work force is increased to provide timely answers to engineering questions and request for clarification.

Managerial Support

Working overtime or implementing multiple shift work eliminates some of a worker's time with his family and time for social relationships. An overtime premium and shift differential does not always compensate for this loss. Additional compensation should be given to workers to increase efficiency and company relations.

Avoid Congestion

When adding more crews is necessary, add more crews only within the work space allowed. Since available working space in a construction site changes day to day, the project manager should keep his or her eyes on the net work space on site. When the site is very congested, shift work can be most effective.

Avoid Material, Tool, and Equipment Shortage

As the crew size increases and overtime workhours increase, corresponding material, tool, and equipment increases should be provided at the same rate of increase. Assigning a material control coordinator to the project and increasing the inventory of spare parts, hand tools, and expendables may reduce material, tool, and equipment shortages.

Minimize Workhours On-Site by Using Modular and Preassembled Components

When large numbers of components can be preassembled, it is a good idea to do as much work as possible in the shop, rather than in the field. As a result, productivity is enhanced by eliminating "assembling" inference by other trades, weather problems, and job-site congestion.

Sufficient Amount of Artificial Lighting

When working under a second shift schedule, safety will be greatly improved by providing a sufficient amount of artificial lighting.

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