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Proving Engineering Productivity Loss

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ABSTRACT—The measured mile/baseline method has been widely accepted to quantify labor productivity loss, but it has not been successfully used in engineering productivity because of the challenges in engineering productivity measurement and the determination of productivity benchmark. This paper presents a series of procedures based on the measured mile/baseline method to quantify engineering productivity loss from a project specific perspective. A case study on the piping discipline in a large scale process plant project is used to illustrate the calculation. The paper also includes a proposed approach, the two mile method, to quantify engineering productivity loss using data for similar work, but different complexity.

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Introduction

Proving or quantifying lost productivity is one of the most contentious and controversial areas in construction claims and disputes. It is a task that usually involves processing data for completed work and corresponding work hours, calculating productivity, establishing baseline, causation study, and measuring productivity loss.

Although there may exist various methods to quantify productivity loss, the measured mile/baseline method by far is the most widely accepted for computing lost productivity in the construction industry. The original measured mile method determines the benchmark of the productivity achieved on identical activities in the same project. The productivity achieved on unimpacted sections was compared to the productivity achieved in sections where the work is known to be impacted. Responsibility for the difference in productivity is then assigned to the impacting party. Since it is not always possible to segregate an unimpacted area of work, the measured mile calculation has subsequently broadened to a baseline method. The baseline method also compares similar work activities, yet it allows for the comparison of lightly impacted areas to more heavily impacted areas. The lightly impacted portion is defined as the baseline set and although the baseline productivity rate may still contain lost productivity, it would allow the claimant to measure the productivity loss in the heavily impacted areas, and assign that loss to the responsible parties. In this paper, the authors use the broad meaning of “measured mile method,” and do not differentiate it from the baseline method.

During the course of design and construction, changes and the ripple effect of multiple changes are one of the most important causes for engineering productivity loss. It is usually difficult to discretely quantify the productivity loss caused by cumulative impacts of multiple changes. Despite wide application and acceptance in proving labor productivity loss, the measured mile/baseline method has not been successfully applied to engineering productivity.

The challenges lie in engineering productivity measurement and the determination of project specific productivity benchmarks. In this paper, the procedures specifically for measured mile/baseline calculation of engineering productivity are developed and the implementation is demonstrated by a case study, which proves that engineering productivity loss can be successfully quantified if the proposed procedures are followed to correctly measure productivity and determine the measured mile or baseline.

To overcome the difficulties of finding engineering work at exactly the same complexity in a project, a broader approach, called the two mile method, is proposed to calculate engineering productivity loss based on the data from similar areas (segments, systems, components, units ...) with different complexity by establishing a linear relationship between productivity and complexity. This paper not only contributes to the literature on engineering productivity loss calculation, also its practical significance is substantiated by offering viable approaches to quantify engineering productivity loss in litigation proceedings. Although this paper only focuses on the quantification of engineering productivity loss, the importance of cause and effect analysis, and responsibility allocation should not be ignored.

Productivity can be measured as the ratio between the units of work accomplished (output) and the units of time or efforts expended (input). In the literature, two inverse definitions were used: input/output, and output/input. In this paper, productivity is defined as the ratio of input to output, but the choice is a matter of personal preference.

Measured Mile/Baseline Method and its Application in Construction

Although the measured mile method has been widely used since 1986, the core fundamental of measured mile analysis originated much before that. In 1951, the measured mile method was successfully used in Maryland Sanitary Mfg. Co. v. US [20]. Researchers and professionals have developed and proposed systematic procedures for measured mile or baseline calculation [6, 12, 21, 22]. The general steps to perform measured mile/baseline calculation include processing data for production input and output, identification of units representing the completed work, computing the productivity by time periods or work sections, identification of measured mile or baseline, and using the difference between the impacted productivity and the measured mile/baseline to calculate productivity loss and damages.

A systematic procedure for measured mile calculation as a method was introduced by Zink [21, 22]. The measured mile method compares the productivity in an unimpacted period of time with productivity in an impacted period of time in the same project. The procedures Zink proposed include the following.

- Plot the actual labor worker-hours expended versus corresponding percentage of completion for the work;
- Exclude the first and last 10% from the analysis; and,
- Identify a linear or near linear portion showing the most efficient rate of progress in the 80% of the curve as the measured mile.

The measured mile method, as originally proposed, requires that the portion of work used to calculate the measured mile must be free or essentially free of disruptions and continuous in time, which limits its application. In order to address the weaknesses in the measured mile method, Thomas and his collaborators introduced the baseline concept [12, 13, 15, 16, 17, 18, 19]. Thomas defined that a baseline period is a period of time when the best productivity is achieved, but its baseline procedure requires the baseline to be selected from the reporting periods with highest production [19]. The baseline period is not required to a continuous, unimpacted time frame, while the measured mile period has to be a consecutive set of time periods. The steps to determine a baseline proposed by Thomas and his collaborators can be summarized as follows.

- Determine the total number of reporting periods;
- The size of the baseline subset, n , is 10% of the total number of reporting periods and should not be less than 5;
- The contents of the baseline subset are the n reporting periods that have the highest production or output; and,
- The baseline is the median of productivity value in each reporting period or the quotient of total production divided by total input in the baseline subset.

In the attempt to overcome the shortcomings of having subjective percentage used in selecting the measured mile or baseline, Ibbs and Liu proposed a statistical clustering method to separate the productivity data into different groups [6]. The average value for the group with the best productivity would serve as the measured mile or baseline. Although Ibbs and Liu's method could select the best baseline based on the available data, and was claimed to be more objective and neutral, the baseline selected by Ibbs and Liu's method may include data points that does not represent the best-sustained productivity.

Zink's measured mile method requires that the measured mile needs to be in a period with a linear or near linear relationship between the expended labor hours and percent of work complete, which implies that the level of productivity should maintain in the period that is disruption free or nearly so. The assumption behind the baseline method proposed by Thomas for selecting the reporting periods with the highest production or output as the baseline period can be understood as that the disruption impact per output unit is relatively lower in the periods in which best production is achieved. Ibbs and Liu's method employs a statistical clustering technique to segregate the periods with best productivity from all the others and uses the average as the baseline productivity, which implies that the baseline period is not necessarily continuous. In terms of baseline selection, Ibbs and Liu's method may include unstained productivity data point into the baseline set, because no productivity of a reporting period outside the baseline period can be better than that in the baseline period when relying on this technique. Zink and Thomas's procedures appear to seek the best-sustained productivity, and as a result, the reporting period with the highest productivity if not sustained would appear outside the measured mile/baseline set.

Despite the differences among various procedures, the core of measured mile/baseline method is a comparison of productivity in an unimpacted or lightly impacted area with the productivity of similar work in an impacted area. The comparison relies on an unbiased baseline representing the best sustained productivity.

Engineering Productivity Measurement

Reliable labor productivity measurement is a crucial element of measured mile/baseline method to prove productivity loss in construction, and then reliable engineering productivity measurement is also crucial to the method's application to proving engineering productivity loss. In spite of the awareness of the essentiality of engineering productivity, there have been only limited studies in engineering productivity measurement.

Thomas and his co-authors proposed a conceptual model for measuring productivity on design and engineering, in which conversion factors and rule of credit were used to account for the differences of various work products in different stage of design engineering [14]. The application of this conceptual model is discouraged by the involvement of conversion factors and rule of credit, which are heavily affected by personal preference. The accuracy of the model is also compromised due to lack of an industry consensus on design document complexity.

The Engineering Productivity Measurement Research Team of Construction Industry Institute (CII), or Research Team 156 (RT 156), acknowledged that there was no standard measurement of productivity in the engineering phase for internal and external benchmarking [4]. CII RT 156 proposed to use measurable installed quantities for the measurement of design output. RT 156 conducted a detailed evaluation of the piping design process and found a good correlation between the engineering productivity measured as worker-hours spent per linear foot of piping and the number of equipment pieces in the piping systems. On the basis that engineering productivity is affected by project complexity, quality of input, quality of design output, RT 156 proposed a conceptual model for engineering productivity, in which engineering productivity is measured as engineering hours per installed quantity adjusted by three factors, input quality factor, scope and complexity factors, and design effectiveness factor.

Song and others focused on the activities of steel drafting to characterize complexity factors for engineering productivity through literature review, interview and survey [10]. They proposed a neural network model of engineering productivity quantification to facilitate project management using 17 project-level influence factors, including project type, contract type, piece cloning, etc. In contrast to project level factors, Song and AbouRizk proposed a conceptual scope definition method, quantitative engineering project scope definition (QEPSD), to measure engineering project scope quantitatively and quantify engineering complexity at the element level, such as number of fittings and drafted quantity for steel drafting [11]. In QEPSD, different design components are converted into the same design units using complexity functions, which may only exist conceptually.

For the purpose of establishing a precise and reliable engineering productivity benchmarking in the construction industry, the CII Benchmarking and Metrics (BM&M) program developed the Engineering Productivity Metric System (EPMS), which included quantity-based metrics. BM&M proposed using direct work-hours as the input and issued for construction (IFC) quantities as the output to measure engineering productivity [7]. The EPMS includes a set of metrics hierarchically at multiple levels, including Level I (project), Level II (major category), Level III (sub-category), and Level IV (element). EPMS consists of six major categories, including concrete, steel, electrical, piping, instrumentation, and equipment. Engineering productivity was proposed to be measured at various levels and categories. BM&M collected engineering productivity data from 87 projects provided by 21 different owner and contractor companies and examined the engineering productivity in different categories and levels. BM&M also performed a correlation analysis between direct engineering work-hours and IFC design quantities on structural steel and piping, and found statistically significant bivariate relationships in those two categories. CII's research effort also included the method to calculate a comprehensive index for productivity assessment at the project level based on the interdependencies among various disciplines and at different levels [8].

Other researches on engineering productivity include Chang and Ibbs and Ebrahimi and Rokni [2, 5]. Chang and Ibbs used a deliverable-based engineering productivity measure. They examined various engineering productivity factors, and highlighted two significant ones: phase involvement and project size. Ebrahimi and Rokni illustrated the expected values for existing metrics in the industry are dependent on the size of the projects.

In summary, although various attempts have been made to establish a standard measurement of engineering productivity and develop engineering productivity benchmarking for construction industry, the models and methods proposed by various researchers remain in a conceptual stage. Moreover, researchers still differ significantly in how to quantify the measurement of engineering output, but most researchers agree that engineering productivity is influenced by multiple factors, including project size and complexity, which could explain why a linear or close to linear relationship was not observed between engineering work-hours and output quantities based on the historical data from various projects.

Measured Mile/Baseline Method to Calculate Lost Engineering Productivity

Although a consensus on reliable engineering productivity measurement for construction industry has not been widely reached, it does not prevent the measured mile/baseline method from being an effective method to calculate engineering productivity loss. First, measured mile/baseline method has been a widely accepted method in the construction industry. Second, measured mile/baseline method is project specific, which is not influenced by the factors that differ from project to project.

In the measured mile/baseline method for labor productivity, the measured mile/baseline is defined as the period of time during which the labor productivity was unimpacted or lightly impacted. This definition is not appropriate for engineering work. According to AIA Document B141 [1], design professionals provide services in five phases, schematic design, design development, construction document, bidding or negotiation, and construction or contract administration. For a design build project, the design and engineering work usually cover from design development, construction documents through the end of construction. The output for design professionals during the period from design development through the end of construction includes drawings, specifications, calculations, data sheets and others. The engineering efforts are also spent in both design and construction phases. The engineering output for a particular item in a project may go through multiple design revisions as the construction proceeds. Therefore, it is more appropriate to define the engineering measured mile/baseline as the area (segment, system, component, unit ...) where engineering productivity was not impacted or lightly impacted.

Loulakis and Santiago presented the following basic guidelines that should be followed in determining a measured mile for labor productivity [9].

- The work performed in the measured mile and the impacted period should be substantially similar in type, nature and complexity;
- The composition and level of skill of crews should be comparable; and,
- The above principles should also apply to the measured mile/baseline for engineering productivity.

The output used for engineering productivity calculation needs to represent the scope of construction work that is designed and engineered. There are three different ways to quantify engineering output in literature:

Quantities of Engineering Documents [2][14]

In order to account for the differences among various documents, conversion is needed to normalize the quantities, which compromises the reliability of this measurement because of the lack of a standard definition of complexity and content, and the use of CAD technology [3, 4, 11]. Although this approach is not preferred, the authors would not rule out the possibility that under some special circumstances, it may be appropriate to quantify engineering output with the mutual agreements between the parties in the project.

Installed Quantities or the IFC Quantities

CII used the installed quantities and the IFC quantities to measure engineering output. CII's research indicates that significant correlation exists between expended engineering work-hours and engineering output measured with Installed quantities or the IFC quantities [4, 7].

Other Quantifiable Elements for the Scope of Work

Song and others proposed to use the quantity of design items within a discipline, such as a beam or a window to measure engineering output [11].

Since this paper is focused on a general measured mile/baseline method for engineering productivity, engineering output quantification is not specified here, and it should be chosen depending on the data and the characteristics of the work to be designed and engineered. The measured mile/baseline calculation for engineering productivity can be performed using the following procedure:

- Segregate the scope of engineering work into areas (segments, systems, components, units ...).
- Quantify work hours for each area (segment, system, component, unit ...).
- Quantify engineering output for each area (segment, system, component, unit ...).
- Calculate engineering productivity for each area (segment, system, component, unit ...).
- Identify unimpacted or lightly impacted areas (segments, systems, components, units ...) as the measured mile/baseline subset. (This is generally determined by the magnitude of changes, modifications, or review oversight initiated by the owner or third parties, and the engineering effort required to address them)
- The measured mile/baseline productivity is the productivity of the measured mile/baseline subset using total work-hours divided by the total quantities representing design output in the same subset.

It is known that disruptions reduce productivity; therefore, it is natural to rule out disrupted areas (segments, systems, components, units ...). The proposed method is only dependent on the causation study to determine the baseline, which is different from Zink's measured mile procedure, Thomas's baseline method, and Ibbs and Liu's *K*-means clustering technique based approach. In order to test the quality of the baseline, a correlation analysis on the measured mile/baseline set may be performed. Furthermore, the above baseline selection and calculation should be corroborated by a cause-and-effect analysis to ascertain the causes for the productivity losses, and allocate the losses to the responsible parties.

Case Study

The proposed measured mile/baseline method to calculate engineering productivity loss has been applied to a multi-hundred million dollar international project to design and build a process plant. The project experienced multiple owner responsible impacts, which caused tremendous cost overrun. The owner issued extensive change orders and the EPC contractor was paid for part of the direct cost of the changes estimated for the normal conditions, adding up to several hundred million dollars.

There was, however, still millions of dollars in engineering that remained uncompensated, which could not be discretely captured in those change orders. During the course of the design and construction of the project, the owner and its representatives issued tens of thousands of design comments, the majority of which were owner changes. The measured mile/baseline method was used to quantify the engineering productivity loss, which was impossible to be captured discretely in the change orders, because of the cumulative impacts of numerous changes that the owner was responsible for. This case study is limited to the piping discipline to demonstrate the application of the proposed method. For confidentiality reason, productivity data used here was scaled and altered from the actual.

The engineering work on piping is divided by various systems in the case study and the number of pipe lines is used to measure engineering output. Detailed project cost reports were evaluated to segregate and summarize direct work-hours on each system. Then the as built P&ID and isometrics were studied to identify the number of pipe lines in each system. The engineering productivity in this case study was defined as the work-hours spent on a pipe line. The direct work-hours, number of pipe lines, and calculated productivities are summarized in table 1.

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System Name	ID	Direct Hours	Number of Lines	Hours Per Line
Boiler Blowdown		140	5	28.0
Boiler Feedwater		340	7	48.6
Chemical A		20	1	20.0
Chemical B		730	24	30.4
Chemical C		190	2	95.0
Chemical D		10	1	10.0
Fire Protection Foam		190	4	47.5
Fire Water		26,870	144	186.6
Instrument Air		1,370	95	14.4
Liquid State Chemical B		19,690	90	218.8
Low Pressure Steam		7,550	350	21.6
Lube Oil		50	2	25.0
Process Water		1,000	44	22.7
Service Air		960	55	17.5
Service Water		7,005	275	25.5
Steam Condensate		7,600	330	23.0
Tempered Water		365	17	21.5
Waste Water		1,650	29	56.9

Table 1— Piping Productivity Data

According to the contract, the design builder was required to prepare a 90% design, and then complete the IFC design upon the receipt of the owner’s comments on 90% design. In this case study, systems were segregated into those where the owner made fewer or no changes, and those where the owner made significant changes. The systems summarized in table 2 are those with little or no owner changes, so they were selected as the measured mile/baseline. The baseline productivity was calculated to be 22.2 hours per line.

System Name	Direct Hours	Number of Lines	Hours Per Line
Boiler Blowdown	140	5	24.0
Chemical A	20	1	16.0
Chemical D	10	1	12.0
Instrument Air	1,370	95	14.4
Low Pressure Steam	7,550	350	22.3
Lube Oil	50	2	25.5
Process Water	1,000	44	23.0
Service Air	960	55	17.4
Service Water	7,005	275	25.1
Steam Condensate	7,600	330	23.0
Tempered Water	365	17	20.6
Total	26,070	1,175	22.2

Table 2— Piping Design Productivity Baseline

The remaining systems were determined to be the impacted, as either 90% design had to be redone due to modification by the owner or the IFC documents were revised multiple times because of the owner's changes. The productivity loss calculation is summarized in table 3.

In order to assess the quality of the measured mile/baseline subset, a correlation analysis between number of lines and work-hours expended is conducted for the subset, as shown in figure 1. The calculated correlation coefficient was 0.9869, which shows a significant linear relationship between the number of lines and work-hours expended in the case study. This indicates that in the case study, not only the number of lines is a good metric to quantify piping design and engineering, but also the selected measured mile/baseline has been proven to be consistently unimpacted or lightly impacted systems.

System Name	Direct Hours	Number of Lines	Hours Per Line	Per Baseline	Productivity Loss
Boiler Feedwater	340	7	48.0	22.2	181
Chemical B	730	24	30.3	22.2	195
Chemical C	190	2	92.5	22.2	141
Fire Protection Foam	190	4	47.5	22.2	101
Fire Water	26,870	144	186.6	22.2	23,670
Liquid Chemical B	19,690	90	218.8	22.2	17,692
Waste Water	1,650	29	56.9	22.2	1,007

Table 3— Piping Design Productivity Loss

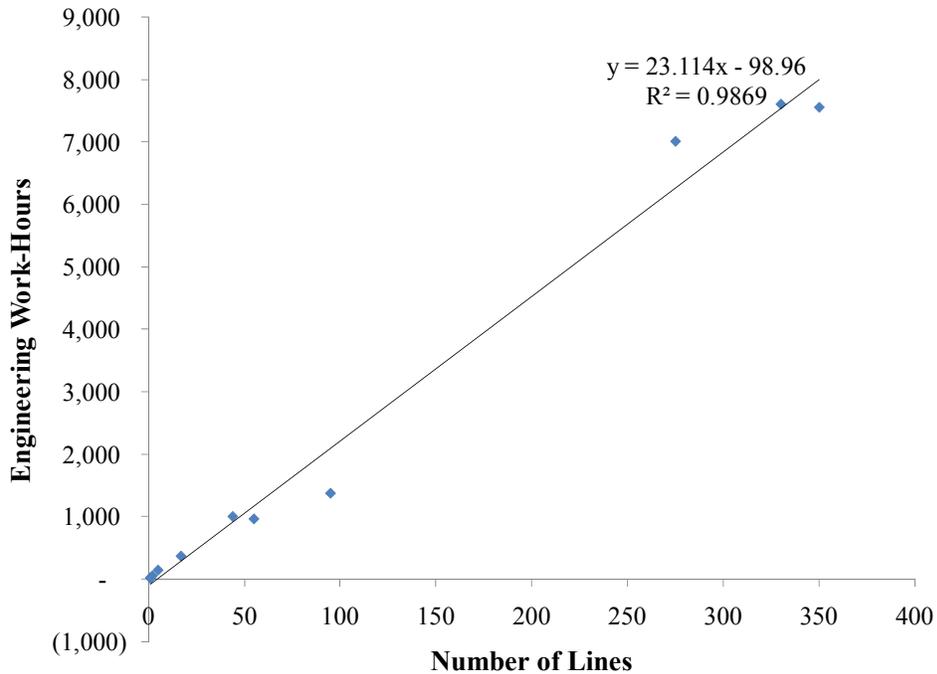


Figure 1 — Correlation Between Work Hours and Number of Lines in the Baseline

Two Mile Method to Quantify Engineering Productivity Loss with Complexity Difference

The underlying premise for the measured mile/baseline method is comparison of identical or similar work with the same complexity. Unlike labor productivity, which can be isolated and sampled daily, weekly or monthly, sampling engineering productivity requires the whole life cycle of design and construction. The engineering effort on a particular area (segment, system, component, unit ...) of the facility to be built does not end when the IFC documents are issued; instead the effort may continue until the construction is completed. Furthermore, it is impractical to record engineering work-hours for each installed unit of work.

Engineering productivity sampling relies on the work break down in the project cost accounting system, and the time keeping efforts by every designer/engineer on the project. Even though it may be possible to measure engineering productivity for each dividable area (segment, system, component, or unit ...) under a well designed project cost accounting system and with the diligent efforts for each engineering time keeper, the number of comparable areas (segments, systems, components, or units ...) are often limited, and finding quantifiable engineering work with the same complexity is still very difficult. Therefore, although the concept of measured mile/baseline method is straightforward, the implementation in practice may be challenging because of the difficulties in finding the measured mile/baseline with the same complexity as the impacted.

RT 156 of CII researched the relationship between piping engineering work hours and physical measurement of quantities, and concluded that equipment piece count represents the complexity of piping engineering [4]. RT 156 then formulated a linear relationship between the piping

engineering productivity measured as work-hours per installed quantity and number of pieces of equipment in the piping discipline based on a regression analysis on the data from 40 projects.

$$\text{Hours/Feet of Piping} = 0.44985 + 0.00134 \cdot (\text{Number of Pieces of Equipment})$$

equation 1

The above finding by RT 156 of CII indicates that piping engineering productivity when measured as work hours per feet of piping is driven by the number of pieces of equipment, and the more pieces of equipment that are in the piping system, the more engineering hours are expended. This finding proved that it is a practical and reasonable assumption to model engineering productivity (P) as a linear function of a variable (C) that represents engineering complexity (complexity variable), or

$$P = a \cdot C + b$$

equation 2

P = engineering productivity.

C = the variable representing engineering complexity.

a , b = parameters.

If productivity and complexity information are available for two not impacted (or lightly impacted) areas (segments, systems, components, or units ...), or

$$P_1 = a \cdot C_1 + b$$

equation 3

$$P_2 = a \cdot C_2 + b$$

equation 4

then parameters a and b can be solved as

$$a = \frac{P_1 - P_2}{C_1 - C_2}$$

equation 5

$$b = \frac{C_1 P_2 - C_2 P_1}{C_1 - C_2}$$

equation 6

Given the actual productivity $P_{3,a}$ per linear foot of piping and complexity C_3 for an impacted area (segment, system, component, or unit ...), the productivity that would have been without impacts (or lightly impacted) P_3 is

$$P_3 = a \cdot C_3 + b$$

equation 7

or

$$P_3 = \frac{P_1 - P_2}{C_1 - C_2} \cdot C_3 + \frac{C_1 P_2 - C_2 P_1}{C_1 - C_2}$$

equation 8

Then the productivity loss on a linear foot of piping for the impact area is

$$\Delta P = P_{3,a} - P_3$$

equation 9

Since data from two unaffected (or lightly impacted) areas (segments, systems, components, or units ...) is needed to solve equations (3) and (4) for parameters *a* and *b*, this method is named the two mile method. If there are more than two unaffected areas (segments, systems, components, or units ...) available in the unaffected set, or the measured mile/baseline set, least square regression is recommended to approximate the parameters *a* and *b* that would be representative. In fact, the size of the measured mile/baseline set should not be limited to 2, and it should include all the areas (segments, systems, components, or units ...) that can be identified as unaffected or lightly impacted. The advantage of this method is that it makes it possible to calculate engineering productivity at different complexity with as few as two measured mile/baseline needed. The procedures to implement the two mile method, summarized below, are similar to the measured mile/baseline method, and are also very straightforward:

- Segregate the scope of engineering work into areas (segments, systems, components, units ...).
- Quantify work hours for each area (segment, system, component, unit ...).
- Quantify engineering output for each area (segment, system, component, unit ...).
- Calculate engineering productivity for each area (segment, system, component, unit ...).
- Identify the complexity factor, and determine the complexity value for area (segment, system, component, unit ...).
- Determine all the unaffected or lightly impacted areas (segments, systems, components, units ...) as the benchmark.
- If there are only two areas (segments, systems, components, units ...) in the benchmark subset, go to 8; if there are more than two areas (segments, systems, components, units ...), go to 9.
- Use Equations (5) and (6) to calculate parameters *a* and *b*, go to 10.
- Use least square regression to determine parameters *a* and *b*.
- Use Equations (8) and (9) to calculate productivity loss for a linear foot of piping in the impacted area (segment, system, component, unit ...). And,
- The total productivity loss for a given area (segment, system, component, unit ...) is calculated as the product of the productivity loss per linear foot and the total pipe length in the area (segment, system, component, unit ...).

Conclusion

This paper has reviewed and summarized the measurement technique of engineering productivity, and applied the measured mile/baseline method to quantify engineering productivity loss for cumulative impacts of multiple disruptions, which are difficult to quantify discretely. The implementation has been demonstrated by a case study, which illustrates that project specific information can be successfully used to prove engineering productivity loss. In addition, in order to alleviate the difficulty of identify measured miles or baseline from areas (segments, systems, components, units ...) with same complexity, a two mile method is proposed. The two mile method is designed to calculate engineering productivity loss for similar work with different complexity under the condition that engineering productivity is a linear function of engineering complexity. The proposed method is straightforward and easy to understand and use.

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