Quantifying Engineering Project Scope for Productivity Modeling

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Abstract: A poor scope definition in an engineering design project disrupts project rhythm, causes rework, increases project time and cost, and lowers the productivity and morale of the workforce. A quantitative measurement of the project scope is the basis for productivity modeling that involves the measurement, estimation, control, and evaluation of productivity. This paper proposes a conceptual model, the quantitative engineering project scope definition (QEPSD), to standardize the measurement of engineering project scope in construction projects, within a computer aided design environment. The QEPSD quantitatively measures engineering project scope, in terms of the complexity of design items by defining design categories and complexity functions appropriate to the particular discipline. The proposed method was originally verified and implemented specifically for steel drafting projects. Actual data was analyzed and used to demonstrate the benefits of historical data prepared using QEPSD for project scope definition. It was found that the new method led to increased utilization of previously untapped values in historical data, improving the accuracy of project scope definition, and productivity modeling. The paper concludes with a discussion of the potential benefits of adopting the QEPSD method, and its implications upon various project management functions.

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Introduction

Project scope management is critical to the success of an engineering design project. The scope management defines the specific design items or services required to meet the project objectives. The Project Management Institute (PMI) defines the project scope management process as involving initiation, scope planning, scope definition, scope verification, and scope change control (PMI 1996). Design engineering firms define project scope as encompassing different engineering design phases. According to American Institute of Architects (AIA) *Document B141*, these phases include schematic design, design development, construction document, bidding or negotiation, and construction or contract administration (AIA 1987). Each scope management process usually occurs at least once in each design phase. Scope definition involves subdividing the overall project deliverables into smaller and more manageable components, resulting in better project planning and control. Scope definition plays an important role in the management of design processes. After some degree of pre-project planning and project authorization, the project scope can be defined in a more detailed manner using work breakdown structures. A survey conducted by the Construction Industry Institute (CII) shows that the current practice followed by design firms is to determine engineering scope and progress by relating them to the number of design documents for each design discipline (CII 2001; Diekmann and Thrush 1986). Essentially, this method treats the output of the design process as any paper design document such as a drawing or specification. The scope for a new project is defined subjectively based on the output produced in the previous design phase and data taken from historical projects. The project scope is measured by an estimate of the quantity of documents to be produced, and the progress is measured by the actual quantity of documents produced to date.

However, due to the current proliferation of computer aided design (CAD) tools, a particular representation of the physical design deliverables as documents is no longer relevant. In the CAD environment, a product model is created and verified on a computer and then the model and any of its components can be selected and printed to the desired drawing size on a plotter. This renders the measurement of the quantity of drawings or paper size irrelevant. There is no standard definition for the contents and complexities of design documents. Armentrout (1986) argues that these units of measure, such as drawings, procurements, and specifications, do not truly reflect the total service rendered by an engineering organization. As projects become much larger, they are almost impossible to compare in any orderly or consistent way. Nonetheless, engineering firms still must use this system of measurement to quantify the project scope for the sake of project planning and control, despite the obvious drawbacks associated with it. Engineers normally evaluate the content and complexity of design documents subjectively and account for this bias through a simple document count. Knowledge utilized during the evaluation process is generated from personal judgment based on

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historical data, and its validity resides with an experienced individual. An implicit measurement, which does not use consistent quantitative methods, makes a full understanding of the project scope difficult, and causes misunderstandings regarding project scope during project planning and control. The current practice of project scope definition in the design industry is much less effective as a medium for carrying project scope information regarding project planning and control.

Poor scope definition is recognized by industry practitioners as one of the leading causes of project failure, adversely affecting projects in the areas of cost, schedule, and operation (Cho and Gibson 2001). This is due to the fact that the project scope definition is the reference point for developing estimates and schedules, coordinating teamwork, applying control strategies, and evaluating engineering performance. An interesting observation is that the fundamental information underlying all these project management functions is regarding engineering productivity. The lack of a quantitative and reliable method for defining the project scope has been a major obstacle for modeling engineering productivity, and therefore causes collateral ineffectiveness in the management of the design process. Thus, a measurement of the project scope for the productivity modeling process, which involves productivity measurement, estimating, control, and performance evaluation, is of great importance and interest to engineering firms.

This paper proposes a conceptual model for measuring the project scope of construction engineering projects for the purpose of productivity modeling. This scope definition method, the quantitative engineering project scope definition (QEPSD), measures project scope in terms of complexity of each design item at a design discipline level, within a CAD environment. The potential benefits and implications of applying this technique in engineering productivity modeling are explained. The scope of this paper is limited to steel drafting as a pilot to verify the applicability of this new approach. Steel drafting is an engineering function within the detailed design level of steel structural design. Based on the architectural and structural design, the drafting process produces detail drawings for fabrication and erection in compliance with the project requirements, fabricator standards, and erector standards and specifications. The benefits of applying the QEPSD method to steel drafting are demonstrated with a focus on project scope definition and estimating respects using historical data. The method is illustrated using actual data collected from the drafting department of our collaborating company.

Literature Review

In spite of some awareness of problems in the definition of engineering project scope, there have been only limited studies in response to the industry's growing need. This need continues to increase with further changes in design methods, tools and project planning requirements.

Traditional cost modeling methods, such as the unit method, cube method, superficial area method, and approximate quantities method, measure the project scope by function unit, square meter of area, or cubic meter of volume (Jaggar et al. 2002). These units measure project scope at the project level for the purpose of cost estimating only. However, according to a survey conducted by the CII, 91% of the surveyed companies focus on the discipline level for project control, due to the fact that most design firms drive accountability to the department or discipline level on projects (CII 2001). These measurement units based on cost modeling methods are limited by the level of detail at which they can be applied and the amount of project information which they can represent. Therefore, they have limited use for project scope management, such as progress measurement, schedule control, and cost control at the discipline level.

Studies focusing on performance evaluation and improvement at the postproject stage normally do not explicitly and quantitatively measure the project scope. The Construction Industry Institute (CII 1986) proposed a system for evaluating design effectiveness. The method is based on combining the weights and ratings of seven evaluation criteria into a single performance index which describes the design effectiveness. Armentrout (1986) discussed a method of measuring performance by tracking several indices affecting specific aspects of the engineering organization, in order to evaluate design effectiveness.

The lack of quantitative information in those methods is a serious deficiency for engineering project planning and control. The project scope definition component in several reported engineering project control systems was based on the delineation of work hours according to a cost accounts code, instead of the products of the design process (Thomas et al. 1999). Thomas et al. (1999) created a conceptual model for measuring engineering productivity during the construction document phase. The measurement of the design output accounts for the differences among all design documents, such as detail drawings, specifications, and other documents, by using conversion factors. However, the accuracy of any measurement is compromised due to the use of CAD tools and because of the lack of a standard definition of content and design document complexity, as previously mentioned. The CII Engineering Productivity Measures Research Team (CII 2001) identified that there was no standard measurement of productivity in the engineering phase for internal improvement and external benchmarking. The research team proposed a model focused on measurable, installed quantities, for the measurement of the design output, such as the length of a pipe or the weight of steel as per the design. This method was applied to the discipline level during the detailed design phase of a project. Raw productivity, which is measured based on installed quantities, is subjectively adjusted by three influencing factors: input quality, scope and complexity, and design effectiveness. However, our experience with steel drafting projects showed that the installed quantity could be misleading due to the unaccounted design complexity and weight values. The evaluation of the scope and complexity factor on a project level lacks too much accuracy to be used for productivity modeling.

The review of available literature resulted in additional observations. First, a project scope definition method must be developed before many problems in productivity modeling, project planning, and control can be addressed. Second, the scope definition, quantitatively, is required to measure the design outputs consistently, rather than the design inputs. Finally, historical project data contain a large amount of untapped values and should be used to extract predictive information for project scope definition.

Quantitative Engineering Project Definition Method

It is necessary to clarify the concept of project scope definition due to confusion arising out of design input and output measurement methods. A decision can subsequently be made regarding the measurement of project scope and the level of detail that should be measured.

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Design Input, Output, and Project Scope

Engineering design creates and transforms ideas and concepts into a product definition that will satisfy customer needs. A civil engineering design is accomplished through the collaborative efforts of a number of different design disciplines, such as architectural, civil/structural, mechanical, electrical, piping, and project management. Engineering work hours represent a major resource for design inputs in the design process. Many other resources are consumed, such as computer time and other equipment use. Also, certain materials are correlated to engineering work hours, so their cost can be accounted for by assigning an appropriate engineering hourly rate. Work hours are, thus, an appropriate measure of design input and are traceable. Most engineering companies have a cost accounting system or time-sheet system that keeps track of work hours. However, the input measured by work hours should not be interpreted as the project scope. This confusion results in a project scope measured by hours or monetary value. The disadvantage of such an approach is that it tends to use inefficiencies to build future projects.

The design output can be viewed as information, or as design documents. For example, the output of steel drafting is a complete set of fabrication drawings and erection drawings. From the owner's point of view, the output is complete technical information, allowing steel fabricators and erectors to accomplish their assignments. When a project has been completed, the project scope can be precisely defined using the design output. For new projects, scope definition is normally obtained from an expert who relies on his or her own judgment and similar past projects. Therefore, analyzing historical projects and their outputs is extremely important to project scope definition for future projects. It is easy to describe the design output, but quantifying the design output is difficult in practice. This difficulty has driven our research in this paper.

Scope Definition Based on Complexity of Design Items

In a construction project, the project scope is defined by the quantities of construction items within each labor discipline that can be easily measured, such as the volume of earth hauled or concrete poured or the length of pipe installed. Design information from different design disciplines is carried through to the construction work itself, and finally synthesized and materialized by the constructed facility. The engineering output can be measured naturally based on the quantity of design items, such as a beam or a window, within a discipline. For example, rather than using the total quantity of concrete drawings as a measure, the project scope for structural concrete design can be measured based on the quantity of concrete needs that will be designed. However, a consideration should be given to the configuration and complexity of the design items in terms of design efforts required. A simple count of the physical quantities would be misleading. For example, the design of a concrete wall, slab, or column represents different degrees of complexity to engineers. The project scope can be measured by the sum of design items in terms of their relative complexity when compared to a particular design item as a standard unit. Applying this method to various design items, the design output can be measured uniformly into an abstract unit of measure. This is analogous to a "unitization" scheme used in quantifying industrial fabrication shop work (Alfeld 1988).

It is necessary to differentiate between the complexity of design items and the environment where these items are produced. This proposed method does not measure environment variables,

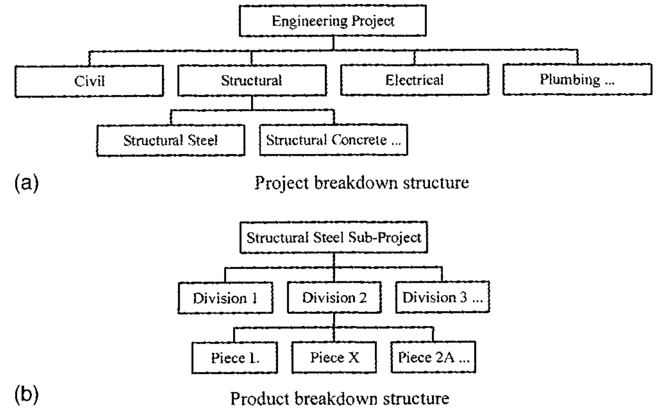

Fig. 1. Work breakdown structure for project scope definition

such as crew qualification and the quality of preproject planning. Additionally, overall project complexities (e.g., structure type, type of construction, and climatologic design considerations) are not included in this detailed item-level measurement method. Instead, the environment variables and overall project complexity are considered as factors affecting engineering productivity and were studied separately from this study (Song et al. 2003).

A work breakdown structure (WBS) is a frequently used technique in project scope definition to decompose the project into measurable elements. The WBSs used specifically for the proposed method decompose a project to the design item level using the project and the product breakdown structure, as shown in Fig. 1. The WBS in Fig. 1(a) divides the project at the design discipline level first. This is the level most design companies focus upon for project control. In order to uniquely quantify a discipline's work scope, more levels of decomposition may be required. Within the structural discipline, for example, further division of structural concrete design and structural steel design is possible. The product breakdown structure was designed to represent the final product model in order to facilitate the quantitative measurement of design items. Product models are designed for each discipline to represent its final product. Fig. 1(b) is an example of structural steel design. The structural steel design subproject can be further divided into divisions representing different physical locations, each of these divisions containing more steel pieces with certain material requirements.

This WBS model is a structured approach to manage the project scope, but does not necessarily result in a quantitative measure of work scope that can be easily communicated to all project participants. As mentioned above, design items vary considerably in terms of complexities. Complexities are evaluated based on two functions in the QEPSD method: design category and category complexity.

Design Category

The first step toward a measurement of design item complexities is to group similar design items within a design discipline. This grouping process defines a list of design categories. A design category is a variable that describes distinct groups of design complexities. Design items in one category will share the same attributes with regards to complexity. Design item descriptions used by an engineer to describe item functions within an overall product, provide a good starting point for the definition of design categories. For example, design categories with the HVAC design discipline may include ducts, air devices, access doors, dampers,

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Table 1. Design Categories for Steel Drafting

ID number	Description	Complexity variable	a	b
1	Column	Number of fittings	1.00	0.67
2	Beam	Number of fittings	1.13	0.53
3	Girder	Number of fittings	2.20	1.33
4	Bracing	Number of fittings	1.40	0.53
5	Girt	Number of fittings	1.13	0.67
6	Purlin	Number of fittings	1.13	0.53
7	Hanger	Number of fittings	1.53	0.53
8	Support	Number of fittings	2.93	0.53
9	Monorail–straight	Number of fittings	1.53	0.53
10	Monorail–curved	Number of fittings	3.47	0.53
11	Crane rail	Single piece	2.80	0.00
12	Stiffener	Single piece	0.67	0.00
13	Gusset	Single piece	4.00	0.00
14	Sag Rod	Single piece	1.53	0.00
15	Truss	Number of fittings	0.67	1.40
16	Frame	Number of fittings	0.67	1.40
17	Conveyor gallery	Number of fittings	0.67	1.40
18	Utility bridge	Number of fittings	0.67	1.40
19	Platform	Number of fittings	0.67	1.40
20	Walkway	Number of fittings	0.67	1.40
21	Stair	Number of fittings	0.67	2.67
22	Stair tread	Number of fittings	0.00	0.67
23	Handrail–straight	Number of fittings	0.67	0.53
24	Handrail–sloping	Number of fittings	0.67	1.00
25	Handrail–circular	Number of fittings	0.67	1.67
26	Ladder no cage	Number of fittings	0.67	0.40
27	Ladder with cage	Number of fittings	0.67	0.33
28	Checker plate	Number of fittings	6.00	1.33
29	Toe plate	Single piece	2.00	0.00
30	Safety gate	Single piece	4.13	0.00

fan units, and architectural features. A design item should be classifiable into one of the defined categories. The design item categories and classifications may be expressed mathematically as follows.

$C_1, C_2, C_3, \ldots, C_m$ is a set of mutually exclusive and exhaustive categories so that $C_i \cap C_j = \Phi$ and $C_1 \cup C_2 \cup C_3 \cup \cdots \cup C_m$ is the entire design item space. The design item classification is to assign a design item, $p_j\ \{p_j\colon\ j=1,\ldots,n\}$, to one of M categories $\{C_i\colon\ i=1,\ldots,m\}$, so that $p_j \in C_i$.

In our study, the steel drafting design categories grouped similar steel pieces together based on their function within a steel structure. The developed drafting category consisted of 30 categories, as shown in Column 2 of Table 1. An effort in attempting to standardize the naming convention used by draftspersons is currently underway in the collaborating company.

Category Complexity Functions

Considerable variability with regards to design complexity may still exist within each category. This requires a more in-depth evaluation of design complexity, resulting in a definition of category complexity variables and complexity functions. Category complexity variables are factors describing the complexity of design items within a design category. Complexity functions evaluate a design item's complexity based on category complexity variables. For each category, complexity variables can be identified and the relationship between the variables and the complexity can be formulated:

Let x_{jk}, $k=1,2,\ldots,s$, be all complexity variables for the design category C_j. The complexity q_i of a piece p_i in this category is given by

$$q_i = f_j(x_{j1}, x_{j2}, \ldots, x_{js}) \tag{1}$$

For example, the number of fittings is a complexity variable within the column category in steel drafting. A complexity function f must be defined for each design category. Experienced engineers may help in defining these functions based on their experience.

In practice, more than one variable may affect a design category's complexity. However, for each design category, if it is properly defined, one dominant variable may adequately describe the complexity associated with all items in that category. For example, within the handrail category in steel drafting, the type of handrail and number of fittings affect the design complexity. To reduce the dimension of the relationship, the type of handrail is considered as one of the definitions of the design categories. Handrails are classified as three categories, as shown in the first column of Table 1: "Handrail–straight," "Handrail–sloping," and "Handrail–circular." A dominant complexity variable is identified

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Table 2. Complexity Factor Table

			Complexity variable value (number of fittings)			
Category	a	b	0	1	2	3
Column	1.00	0.67	1.00	1.67	2.34	3.01
Beam	1.13	0.53	1.13	1.66	2.19	2.72
Gird	2.20	1.33	2.20	3.53	4.86	6.19
Bracing	1.40	0.53	1.40	1.93	2.46	2.99

Table 3. Results of Correlation Analysis

Measure unit	Drawing	Piece	Weight	Drafting unit	Hours
Drawing	1	—	—	—	—
Piece	0.48	1	—	—	—
Weight	0.50	0.45	1	—	—
Drafting unit	0.81	0.51	0.79	1	—
Hours	0.75	0.53	0.67	0.88	1

for each category. Column 3 of Table 1 shows the complexity variable defined for each drafting category. "Number of fittings" refers to the quantity of detail materials, or steel fittings, on a steel piece. "Single piece" indicates that the complexity of the piece is measured by a single design item.

Based on the draftsperson's experiences and the accumulative nature of drafting design, the relationship between a dominant complexity variable and the complexity of a single piece was assumed to be a linear function, which is

$$f_j(x_j) = a_j + b_j x_j \tag{2}$$

where a_j=base complexity value for category C_j and b_j=coefficient for the complexity variable x_j. A standard design item can be defined as an abstract unit of measurement. The quantification is a conversion based on weighting other design items for their degree of complexity compared to the standard unit. For steel drafting, a simple steel column with no fitting is defined as a standard unit, called a "drafting unit." To assist the weighting, the degree of complexity can be compared at the design process level. The design process involves multiple stages of development, review, and revision. To facilitate the definition of a_j and b_j in Eq. (2), the steel drafting process is broken down into wire frame modeling, bill of material, two-dimensional drawing, electronic drawing, check and administration (Allouche and Song 2003). a_j and b_j are defined by the sum of the complexity evaluated at the process level. The systematic decomposition of a project into clearly defined design items and the use of process modeling makes the definition of complexity functions easier and more accurate. Additionally, the user can gain confidence in using this method by securing the quantification procedure.

To illustrate the result from the unit measure, a sample complexity factor table is shown in Table 2. A bracing in the bracing category with two fittings is 2.46 units of work, according to the table. The total adjusted quantity of a project output, or project scope, in drafting unit is given by:

$$Q_{\text{total}} = \sum_{i=1}^{n} q_i \tag{3}$$

where Q_{total}=project scope measured by drafting unit; q_i=complexity of a piece p_i measured by drafting unit, which is defined in Eqs. (1) and (2); and n=total number of pieces in a steel drafting project.

Automation of Quantification Process

The quantification procedure is defined by the design categories, category complexity variables, complexity functions, and a standard design unit. Precisely quantifying historical projects using the standard unit of measurement can help accumulate knowledge in project scope definition for future projects. However, the quantification process can be extremely tedious and time consuming due to the large quantity of design items and the difficulty of evaluating complexity. A manual count is inefficient, if not impossible. Currently, a variety of *CAD* software is used in almost every engineering design discipline. The proposed QEPSD method is designed to work in a CAD environment. The CAD system captures vast amounts of data in an electronic format. This creates a unique opportunity in automating the measurement of design outputs from past projects. Data required for measuring design output is normally recorded in a project CAD model. Most commercial CAD systems have the capability of interfacing with other software systems; exporting design data in a text format is a minimum requirement. Data exchange interface can be implemented to transfer the design data from a CAD model to a database system. The complexity evaluation algorithm can be encapsulated within a software module to automate the quantification process.

Our collaborating company uses specialized *CAD* drafting software, *StruCAD* (StuCAD user manual 2003), for its steel drafting work. File exporting, data exchange interfaces, and database systems have already been used by the company for material listing, and they were used in this study. The complexity evaluation algorithm was built using structured query language, and was integrated into the database system and an interface for users. Over 1 million steel pieces from projects in the last 5 years were quantified in drafting units over the course of our study.

Quantitative Engineering Project Scope Definition Validation

The proposed conceptual model aims at quantitatively measuring the engineering project scope for construction projects. Experienced engineers define the design category and complexity functions. To verify its capability and accuracy, the model must be tested on actual projects for each discipline in the engineering design. However, this method has not been used previously. Therefore, in this pilot study, only steel drafting was studied for the QEPSD validation. Historically, the weight of steel, the quantity of drawings, and the quantity of steel pieces were used to measure steel drafting project scope. These records will be compared to the newly developed drafting unit. The criterion of the comparison is that a good measurement of project scope has a high correlation to the input, which is in work hours. An analysis correlating the different measurements with the inputted work hours is performed to compare the relative effectiveness.

Data from a total of 69 steel drafting projects has been collected for the correlation analysis. Scatter diagrams were constructed for each measured unit and correlation coefficients were calculated and compared, as shown in Table 3. The correlation analysis shows that the drafting unit outperforms other commonly used measures. The correlation value for the drafting unit R is 0.88, which is the highest value. The value rankings following this are the quantity of drawings, the weight of steel, and the

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quantity of steel pieces. The major reasons behind this ranking are the use of CAD tools, and the irrelevancy of draftspersons' work regarding the physical weight. A t test at the 95% level shows that the correlation between the drafting unit and work hours is statistically significant. Thus, the drafting unit is considered to be the best measure of project scope, and the most accurate predictor of drafting work hours based on other units of measure.

By definition, the coefficient of determination (R^2) represents the proportion of variation in the dependent variable that has been explained or accounted for by an independent variable. The quantity of drafting unit accounts for about 77.4% of the drafting man hours required. An explanation of the residual is expected by other environment variables and overall project complexity factors as previously defined (e.g., degree of cloning, draftsperson experience, and engineering standard) (Song et al. 2003).

Project Scope Definition with Quantitative Engineering Project Scope Definition

Engineers must determine a project scope using only the information available at the time for project scope definition. The proper approach for quantifying project scope of a new project is a function of the availability of usable information. In the light of this fact, both project scope definition possessing complete project information and scope definition possessing incomplete project information were studied.

Project Scope Definition with Complete Project Information

This situation may be encountered by some drafting disciplines during the construction document phase. For example, in most lump sum contracts, the steel drafting begins after the architectural and structural design, and uses structural arrangements and layout drawings as a design basis. Project scope can be measured directly, using the described QEPSD method, based on information from a manual or an automated quantity takeoff from engineering drawings or a CAD model, coupled with some estimations on the quantity specified by category complexity variables (e.g., number of fittings). Therefore, this will not be further investigated.

Project Scope Definition with Incomplete Project Information

To relate scope definition to quantities of design items, the scope of the project must be completely defined. Such is not the case for most design disciplines in engineering projects. During schematic design and design development, the scope is described in a vague manner that prevents any direct measure of the final product. In this case, historical data and past experiences are the best information to use to estimate the project scope quantitatively, as far as these are available and relevant. Obviously, the confidence in any estimate will be higher if it is based on relevant past experience, particularly if the new project can be defined in some assured details. QEPSD can help to quantify historical projects for this purpose.

In the preproject planning phase, if a facility's capacity information is all that is available, for example, the capacity of a concrete tank or the area of an office building, then simple statistics, equations, or other advanced models derived from historical data prepared using QEPSD, such as the six-tenths rule (Steward et al. 1995), and neural network models (Creese and Li 1995), may be used to measure a new project's scope. A comprehensive discussion of these estimating techniques falls outside the scope of this paper. Estimating based on historical data is an alternative to the existing method that is based on personal judgment. One of the applications of QEPSD in project scope definition and estimating for steel drafting project using historical data is illustrated with a case study.

Case Study

The selected project is a unit price contract, involving the drafting of structural and miscellaneous steel of an industrial facility. Under a unit price contract, the contractor must prepare a detailed cost for each category defined by the owner, based on the estimated quantities given in the contractual documents. An estimate of the total number of hours for internal scheduling use is desirable. It is not uncommon that during the bidding stage, architectural and structural design has not yet been completed. Due to the absence of detailed engineering drawings for quantity takeoff for this project, quantities assumed based on a survey given by the owner, are used for defining the project scope and category unit cost. The quantity, in terms of weight, is the only information available for preparing the estimate. The total weight of the project is 120.50 t, in which 41.11 t were drawn by the collaborating company, and 79.39 t were subcontracted to two other drafting companies. Our case study is limited to analyze only the part of the project drawn by the collaborating company. For confidentiality reasons, productivity data used in this case study were scaled.

In this project, 15 unit-price categories were listed in the contract document, as shown in Column 2 of Table 4. For the selected project, the quantities measured by weight in tons are available for each unit-price category. The weight is assumed to be accurate in this case study, so the actual weight of each unit-price category is used, as shown in Column 3. An estimator subjectively predicted a category-specific drafting productivity level in work hours per ton (Column 4), in which the complexity of each unit-price category and profits were accounted for by his or her experiences. Thus, the unit cost for a unit-price category is the sum of the productivity and a predefined hourly rate.

This estimating problem can be approached alternatively using historical data to evaluate the complexity and unit cost for each unit-price category. A total of 216 similar types of projects were quantified and stored in a database system using the QEPSD method developed for steel drafting. Queries were performed to find out the ratios of the drafting unit quantity to the weight of each unit-price category from the database system. For a specific category, this ratio will vary from project to project. The uncertainties of this ratio can be modeled by fitting a standard statistical distribution to historical data. BestFit (BestFit users manual 1999) was used for the data-fitting analysis. Either normal or uniform distribution was found to reasonably represent the distributions underlying the sample data for a category. The distribution type and parameters are listed in Column 6. In order to get a point estimate of the work scope, the mean value of each category's drafting unit–weight ratio was used. The quantity of work measured in drafting units (Column 7) is the product of the mean value in Column 6 and the weight of each category in Column 3.

A drafting productivity prediction model based on an evaluation of various productivity-influencing factors was used to predict the productivity value for this project (Song et al. 2003). The

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Table 4. Case Study: Unit Price Contract Steel Drafting Project

ID number	Category description	Weight (t)	Productivity (h/ton)	Estimated hours (h)	Unit per ton (unit/t)	Quantity (unit)	Estimated hours (h)	Productivity (h/t)
1	Rolled shapes 15–31 kg/m<2,744 mm	2.44	26.07	63.61	Normal(73.38,35.55)	178.68	82.19	33.69
2	Rolled shapes 32–61 kg/m<2,744 mm	3.46	16.53	57.19	Normal(32.82,12.38)	113.39	52.16	15.07
3	Rolled shapes 62–100 kg/m<2,744 mm	0.29	14.46	4.19	Normal(12.34,4)	3.62	1.67	5.74
4	Rolled shapes 32–61 kg/m>2,744 mm	14.37	14.39	206.78	Normal(11.25,2.71)	161.69	74.38	5.18
5	Rolled shapes 62–100 kg/m>2,744 mm	3.32	12.48	41.43	Normal(5.49,1.8)	18.22	8.38	2.52
6	Rolled shapes 101–150 kg/m>2,744 mm	5.90	9.83	58.00	Normal(5.46,2.31)	32.21	14.82	2.51
7	Bracing–WT section <2,744 mm	1.16	27.20	31.55	Normal(86.07,43.03)	99.50	45.77	39.46
8	Bracing–WT section >2,744 mm	2.43	24.13	58.64	Normal(25.39,13.96)	61.65	28.36	11.67
9	Girt<30 kg/m>2,744 mm	0.17	22.54	3.83	Uniform(19.2,27.2)	4.04	1.86	10.93
10	Girt>30 kg/m>2,744 mm	0.42	16.14	6.78	Uniform(3.2,7.75)	2.31	1.06	2.53
11	Web stiffeners W14–W18 section	0.02	58.99	1.18	Normal(120,50.08)	2.28	1.05	52.44
12	Web stiffeners>W18 section	0.05	58.99	2.95	Normal(92.5,25.2)	5.00	2.30	46.00
13	Ladder	0.92	40.49	37.25	Normal(90.26,19.39)	82.68	38.03	41.34
14	Handrail–straight	4.40	44.66	196.50	Normal(104,20.2)	457.39	210.40	47.82
15	Handrail–sloped	1.76	44.66	78.60	Normal(192,59.9)	337.34	155.18	88.17
	Total	41.11	—	848.50	—	1,560.00	717.62	—

estimated productivity is 0.46 h per drafting unit. The estimated hours (Column 8) for each category based on the mean value of the drafting unit–weight ratio is the product of the quantity in Column 7 and the estimated productivity value. For bidding purposes, the productivity measured in work hours per drafting unit is converted to work hours per ton in Column 9.

The Monte Carlo simulation technique was used to evaluate the risk and uncertainty of the estimate (Ahujia et al. 1994). The work hours of each category were calculated as the product of the productivity in work hours per drafting unit, the weight, and the unit–weight ratio. The experiment was implemented in *Microsoft Excel*. Fig. 2 shows the histogram of the project's total hours and the probability density function of a fitted normal distribution for the total hours showing a mean value of 722.00 h, and a 90% confidence level that the total hours are between 614.67 and 829.30 h. The 80th percentile of the project completion time is 792.56 h.

After the completion of this project, QEPSD measured the project scope as 1,537.01 drafting units. That is a total of 341 drawings. The actual drafting hours collected through the company's office time sheet system was 676.50 h. This is inside the 90% confidence interval. The 80th percentile indicates an overestimate of 17.16% of the total actual hours when using the new approach that is based on the drafting unit. The model output is considered to be accurate. The results obtained from historical data are different than those obtained from the estimator's estimate. Unlike the existing estimating method, the new approach obtains the results by separating the estimate of a project scope using the QEPSD method and the estimate of productivity using appropriate influencing factors. More accurate estimates can be

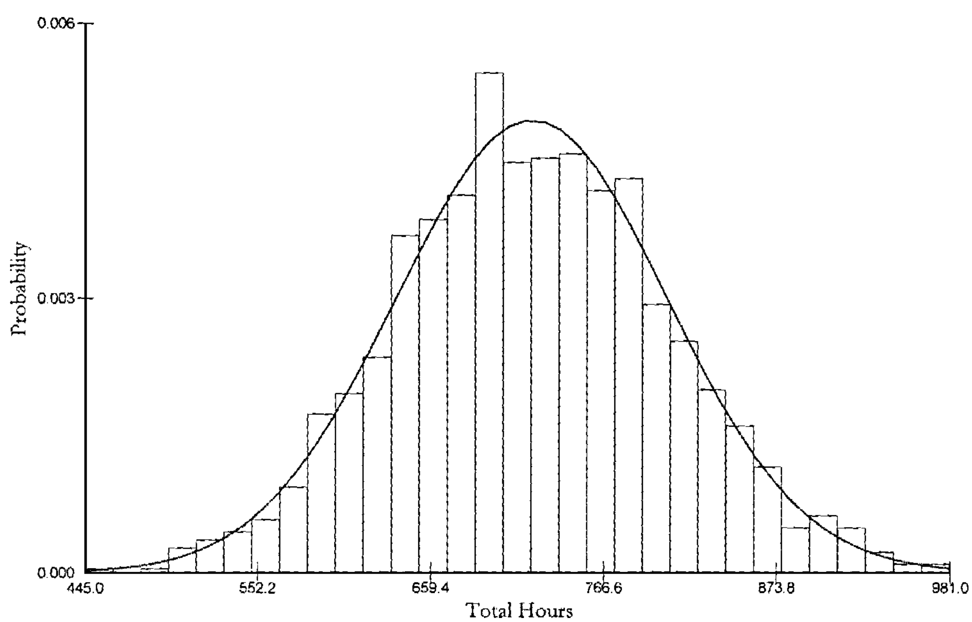

Fig. 2. Probability density function for project total hours

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achieved using this structured estimating approach than using the estimator's subjective judgment. Moreover, the result of this approach is an estimate of actual productivity and hours to be consumed, in which the profit is considered separately. It establishes a baseline for scheduling and project control.

Conclusion

The measurement at the design item level suggested by QEPSD allows a quantitative indication of project scope in terms of the design items' complexities from a bottom up approach. The approach presents a number of good characteristics:

- the complexity of design items has a high correlation to the work hours;
- the complexity can be counted with properly defined design units;
- the measure is quantitative and consistent; and
- the method is practical to use in a CAD environment.

Many problems associated with measuring project scope and engineering productivity can be alleviated and resolved with the quantitative measurement of project scope using QEPSD. Engineering productivity can be conveniently measured by work hours per unit of design. Both scope measurement and productivity measurement address the need for estimating, scheduling, project control, and performance evaluation. These project management functions need to be revisited and updated accordingly with the new measurements. The following discussion presents some of the implications and benefits of adopting the proposed method.

Estimating and Scheduling

Estimating and scheduling the engineering design process is highly subjective, as it is affected not only by the quantity of work, but also the productivity that can be achieved. The project scope can be measured using the QEPSD method; productivity influencing factors can be evaluated using historical productivity data prepared by the QEPSD method (Song et al. 2003).

Project Control

During detailed design phase, subjectivities in progress reporting can be removed using the QEPSD method to automate progress measurement in a CAD environment. Quantities can be rolled up to any level in the WBS for project planning and control. This allows for the monitoring and control of an engineering project, at a greater detail than only at the project level.

Performance Evaluation

The proposed approach measures productivity quantitatively in terms of work hours per unit of work. However, it does not measure the design effectiveness, which may be measured by constructability, rework rate, and other field complications arising from the engineering design. At the completion of a project, the quantitative productivity measurement can be combined with evaluation factors, measuring time, cost, quality, and safety performance, to give a more comprehensive evaluation of the engineering performance.

The QEPSD method has been implemented and verified on steel drafting projects. It leads to increased utilization of untapped values in historical data for project scope definition and productivity modeling. It improves the common understanding of the work scope and the accuracy of estimating through project participants. It holds significant potential as a force in improving the project management process. This pilot study offers insights into the implementation of this method for measuring project scope in other engineering disciplines. The QEPSD method will be applied to different design disciplines, and its applicability will be further verified.

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