

CONSTRUCTION INDUSTRY INSTITUTE®

ENGINEERING PRODUCTIVITY
MEASUREMENTS II

SAN DIEGO STATE UNIVERSITY

KENNETH D. WALSH

ARIZONA STATE UNIVERSITY

JAMES C. HERSHAUER

JOHN G. WACKER

Research Report 192-11

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ENGINEERING PRODUCTIVITY MEASUREMENTS II

by

Kenneth D. Walsh
San Diego State University

James C. Hershauer
John G. Wacker
Arizona State University

A Report to
Construction Industry Institute
The University of Texas at Austin

Under the Guidance of
CII Project Team 192
Engineering Productivity Measurements II

CII Research Report 192-11
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The University of Texas at Austin.

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Cautionary Statement and Appropriate Uses of PT192 Products

CII emphasizes the importance of measuring and assessing engineering productivity. CII also recognizes the extreme complexity of the issues of this research and the many decisions that the project team faced in producing its productivity measurement system.

The “off-the-shelf” (OTS) approach is in a validation stage, and organizations are encouraged to validate the OTS model to confirm applicability to their particular projects. They are also encouraged to share results with CII to facilitate validation of the tool. The OTS tool is not intended for use on individual projects, either for estimating or for productivity. While data are collected for individual projects, analysis of the results should be based on groups of projects.

The “custom-tailored” approach is more suited to individual project applications and to applications in industry settings outside the PT 192 database.

Executive Summary

Although engineering generally accounts for 20 percent of total project costs, the output of the engineering team has direct bearing on the other 80 percent of project costs. For these reasons, it is important to be able to measure engineering productivity effectively. To improve productivity, there must be a good system to measure and track productivity so that the impact of productivity improvement efforts can be judged. This research provides two effective approaches to measure and track engineering productivity.

CII recognized there were no consistent standards being used throughout the industry to measure engineering productivity and commissioned the Engineering Productivity Measurements II Project Team (PT 192). The objective for PT 192 was to develop a standardized productivity measurement methodology and test the methodology in each of seven major disciplines.

PT 192 focused on measuring engineering design hours against quantities of physical design components rather than the traditional “intermediate deliverables” such as drawings or specifications. Measuring productivity against the output of physical design components was considered to be a more consistent and reliable method and not subject to differences in work processes across the industry. Since each engineering discipline designs multiple design components, it is generally not appropriate to define output of the work of a discipline by a single design component. A method for combining quantities across several design components was developed.

An equation was developed for each discipline that uses design component quantities to calculate “basis hours.” The discipline basis hours serve as a surrogate for

actual output represented in the design components. One cannot add measures of physical quantities such as cubic yards, feet, tons and numeric counts. Some method for converting quantities of a wide variety of design components to a common unit is needed. Productivity basis hours provided a common unit of measurement and a conceptual basis for developing coefficients using historical data. This was preferred over use of qualitative expert judgments of weighting factors. A productivity index for each discipline can then be calculated by dividing the actual discipline design hours by the discipline basis hours calculated from quantities of design components.

An organization needs data on a set of projects to establish a baseline. It is expected that over time the productivity index for a given organization or discipline would improve as changes are made to work processes and procedures.

The research from PT 192 offers two different methods to measure engineering productivity using the techniques discussed above:

- The “Off-the-Shelf” approach — uses “basis hours” equations developed from the PT 192 data set to measure productivity and establish baselines. It is available in CII Implementation Resource 192-2. It can be used immediately with minimal start-up costs to monitor current and future projects. The project team collected data for 118 projects with a total installed cost of approximately \$15 billion from 14 different organizations. Discipline workshops, discipline conference calls, and team discussions yielded a strong conceptual basis for which design components to include. Empirical results were used to confirm these design components and to develop models and coefficients.

- The “Custom-Tailored” approach — uses the same methodology as described in step-by-step detail in CII Research Report 192-11 to develop organization- or project-specific equations to measure or benchmark productivity. The “Custom-Tailored” approach may provide a more accurate system linked to organization-specific projects or work processes.

PT 192 TEAM MEMBERS

Owners

Kent Goddard – Solutia (Chair)
Charlie Green – Aramco Services
Bill Harris – GM
Bob Houghtaling – DuPont
Katy Johansson – ExxonMobil
Steve Page – Chevron Phillips
Mike Wick – GM
Paul Woldy – ChevronTexaco

Contractors

Don Bounds – Fru-Con
David Edmondson – Technip USA
Mike Garrett – Washington Group
Alan Helton – Alstom
Burrell Higdon – D&Z
Steve Horton – BE&K
Frank McMahon – Hilti
Gary Minnick – Lockwood Greene
Greg Robertson – Black & Veatch
Karl Seil – Shaw Group

Academia

Jim Hershauer – Arizona State
Ganesh Shenbagaraman – Arizona State (Doctoral Assistant)
Ken Walsh – San Diego State (Lead)
Jack Wacker – Arizona State

Construction Industry Institute

Les Prudhomme

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1 INTRODUCTION

1.1 Overview of Importance of Productivity

Many academics and government officials have pointed to the need for improved productivity. For example, consider a recent statement by the U.S. Commissioner of Labor Statistics: *“Increases in productivity lead to higher real wages, to lower inflation, and generally to better standards of living. A 1 percent increase in productivity cuts the cumulative deficit by \$2 trillion over 10 years. That means \$2 trillion in lower taxes, \$2 trillion in more government service, or \$2 trillion in debt reduction. Also a 1 percent reduction would reduce the shortfall in Social Security by one-half to one-quarter.”* (Utgoff, 2002) Additionally, some have noted the extreme importance to economic improvement, “Productivity is the most important economic statistic. It drives living standards and the profitability of companies.” (Brynjolfsson, 2003, p.6). The significance of productivity points to an increased need for understanding how to measure productivity performance.

Economic welfare depends on the improvement of productivity. On a national level, productivity is an important element of economic growth. Increases in productivity over the last 30 years have led to much of the growth in the U.S. gross domestic product (GDP). On an industry level, many sectors that experienced growth in productivity have also experienced decline in costs and prices. On a company level, firms with higher productivity than the industry average often have higher profit margins.

A common measurement of productivity is the ratio of outputs to inputs, and is concerned with the transformation or flow of goods or services into, through, and out of the organization or a function (Packer 1991). The flows into the organization are called inputs and those things that flow out of the organization are referred to as outputs. The underlying theme in the study of productivity is to measure the magnitudes of these inputs and outputs and to study the

transformation process. Partial or single factor productivity relates an output to a single type of input – labor, capital or material. Total or multi-factor productivity relates the output to all input types. The productivity concept has developed from the manufacturing industry where the manufacturing of physical goods is studied as a production function (Mansfield, 1980). The American Productivity & Quality Center model (APQC) defines productivity as the growth in real output over the growth in real inputs between two periods. It also ties it to the ratio of prices of outputs and inputs between two base periods, which is termed the “price recovery ratio”. The APQC model allows for the breaking down of the effect on profits in dollars into three components: change in productivity, pricing recovery and profitability (Grossman, 1994). The AT&T’s net income model (NIPA) follows an accounting approach. Productivity impact is measured as change in net income between two periods decomposed into income augmenting and income absorbing factors (Grossman, 1994).

While there have been numerous studies assessing inter-industry differences in productivity growth, only a handful of studies have attempted to compare productivity at the firm level (Lieberman, Lau, & Williams, 1990). In the auto manufacturing industry, value added per worker has been used to compare productivity levels across firms. The hours per worker have been further broken down into vehicles per worker, sales revenue per worker, and value added per sales revenue (Lieberman, Lau, & Williams, 1990). The movement towards studying productivity at a firm level can be attributed to Hayes and Clark in their development of a multi-factor productivity index at a plant level (Hayes & Clark, 1985) and to the studies by Schmenner on the factors that influence factory productivity (Schmenner, 1991; Schmenner & Cook, 1985). Research in productivity measurement in the manufacturing industry has benefited from the physical nature of the output, i.e., it is easy to count, it is consistent in its measurement, it has a terminal quality, and it can be used as an input to other processes (Taylor, 1982, 1984). Despite the extensive research in productivity measurement in the manufacturing industry, the conceptual

problems regarding the relationship between input and outputs still exist. The output-input model implies causality and a precise relationship between inputs and outputs. In a dynamic environment where the nature and mix of the different inputs (labor, capital, materials, equipment, and energy) are constantly changing it is difficult to predict a causal relationship. In addition, the input factors interact with one another, making it difficult to identify the input factor that is really responsible for a change in productivity.

1.2 Productivity in Services

During the decade beginning in 1990, the shift from a manufacturing to a service economy in the U.S. became more evident. There has also been an increase in the relative importance of services to manufacturing firms. A service component has been added to most manufactured products. While new industries that represented the service sectors were studied and productivity indices for these industries were reported by the Bureau of Labor Statistics, it was also widely accepted that there existed severe definition and measurement problems in quantifying the outputs in services (Mark 1988).

Research in the field of service productivity has lagged similar work in the manufacturing sector. There are many reasons for the lack of conclusive research in the service sectors, such as non-tangible outputs, variations in quality of output, direct interaction with the customer, outputs for many different clients, and the independent nature of service workers.

Even though considerable data on revenues of services are available, there still exist problems relating to the measurement of real service output. These output related problems can be viewed as either problems associated with defining the unit of output or problems that deal with the issue of quality (Sherwood, 1994). The difficulties in identifying variations in the quality of services include the inability to standardize the unit of output and the bundled nature of services.

Research in productivity measurement has focused primarily on two ways of measuring outputs. The first approach is to measure the transaction and the second approach is to measure the outcome (Sherwood, 1994). Based on Sherwood, the differences in the two approaches can be summarized as follows.

Outcomes Approach: The output can be specified as a final product/service delivered. Thus the measure is simplified. Differences in the quality and changes in the process/service due to innovations are indirectly captured in the outcome measure. The fact that quality changes and process innovation tend to be built into the outcome measure also depends on the type of outcome measure used (Griliches, 1986). Another drawback of the outcome measure is its inability to account for customer involvement. Factors such as customer experience and current technical capability can contribute to changes in the outcomes measured. Allocation of these changes in productivity to the service provider may be unfair.

Transaction approach: The alternate approach to developing productivity measures is to measure the transaction unit itself and make explicit adjustments for quality changes. This is relatively simple in manufacturing where the transaction unit can be clearly specified. The limitations of the transaction approach are primarily due to the difficulty to conceptualize the unit of transactions in services. For example, drawing counts and specification document counts have not been satisfactory in engineering.

Productivity measures vary across service functions. In information systems, common measures have been lines of code per hour and function points per hour of development (Christopher, 1994a; Mahmood, Pettingell, & Shaskevich, 1996). In research and development, it has been number of new products developed per R&D hour (Fitz-enz, 1994). In maintenance, it has been the amount produced per maintenance hour (Lofsten, 2000). In engineering, it has been number of drawings or specifications per engineering hour (Stewart & Calloway, 1982). In

purchasing, it has been orders or line items handled per purchasing staff person or buyer (Thor, 1994b). None of these are very satisfactory in establishing a link to actual value of the service.

This research project conceptualizes a service productivity model and a specific application model for the detailed engineering design function. This study uses construction industry data from the Construction Industry Institute sponsoring firms to empirically test its theories. The proposed empirical model addresses many of the difficulties associated with measuring productivity in the service industry.

1.3 Research Motivation

The delivery of a constructed facility is a multi-phase task that begins with conceptual planning and continues through detailed design and engineering, implementation and maintenance phases. Successful completion of the facility requires numerous inputs from various agencies over the life cycle of the facility. In general terms, the life cycle of the facility can be divided into three main phases: the pre-construction phase, the construction phase, and the use phase. During the pre-construction phase extensive design and engineering activities are conducted to produce working drawings and specifications that are “constructible.” In the construction phase, projects require a multitude of inputs including information and decisions of participating agents, numerous resources such as architectural drawings, specifications, construction crews, heavy equipment and materials. In the use phase, maintenance, renovation, renewal, and enhancement projects vary considerably in size and complexity. Measurement of the output from all phases and determination of resulting productivity is important.

A great deal of attention has been focused on the measurement and improvement of productivity during the construction phase. Although construction is often likened to manufacturing, there are many differences. Primary differences relate to the unique nature of a given capital project and the lack of control of the environment at the workspace. However, many of the processes which take place on a construction site are, taken by themselves, quite

repetitive, and as a result construction productivity and performance measurement builds heavily on manufacturing methodologies. Productivity is generally defined as the output of work put in place for some unit of input (for example, cubic measure of concrete finished per labor hour, or pipe hangars installed per labor hour). When multiple steps are required for a portion of the work, methods for allocating partial completion, usually based on a weighted earned-value analysis, are used. Thomas and Kramer (1988) provide an excellent and frequently used summary of construction productivity measurement.

It is interesting to note that the development of construction productivity measurement systems has supported subsequent detailed evaluations of the factors that might affect productivity on a particular job. For example, Sanders and Thomas (1991) consider a number of factors that influence masonry productivity, using a statistical regression process. Other studies have considered the impact of overtime (Thomas, 1992), changes during construction (Hanna, et al, 1998; Thomas and Napolitan, 1995), wait times between consecutive trade processes (Howell, et al, 1993), and even geographic location (Proverbs, et al, 1998). This is by no means an exhaustive list, but serves to point out how the many complex factors that might affect construction productivity can be evaluated given an accepted measurement. The increase in understanding leads, in turn, to an improved ability to estimate, plan, and control construction projects (Thomas, et al, 1990; Sanders and Thomas, 1993). Certainly this is important from the perspective of the facility delivery process.

Measurement of output and productivity during the design and engineering phase is also important and is required to enhance the facility delivery process. Not much attention has been paid to defining, measuring, and benchmarking productivity during the pre-construction phase. Productivity measurement systems (and their attendant benefits) have not been available for engineering functions in the construction industry. Certainly the most rigorous evaluation of engineering performance to date arises from work sponsored by the Construction Industry

Institute (CII) in the middle 1980's (Chalabi, et al, 1987; Stull and Tucker, 1986). Chalabi, et al (1987) identified seven general parameters which described the quality of the design work, based on an extensive survey of owners, engineers, and designers. The parameters they identified were: final project schedule; final project cost; constructability; quality of design; plant start-up; performance; and safety. They then set about identifying what owner inputs from the planning process most directly influenced which of these parameters, also using a qualitative survey method. In this way, they pointed out the importance of the input of the owner and the work of previous phases in the procurement process to the performance of the engineer. Furthermore, there are quantitative methods for evaluating the scope definition and planning phase which creates the input to the design phase. Dumont, et al (1997) reports the development of a Project Definition Rating Index (PDRI), which built on the work of Chalabi, et al (1987). The PDRI consists of 70 elements which describe the state of the project definition and scoping process, combined into a single index with a standardized weighting scheme. The index has been shown to be correlated to project success (with $R^2=0.4$), and is now frequently used by a number of large industrial owners to guide their pre-project planning process. The correlation to project success was performed by comparing the PDRI to an index function of ratios of planned to actual schedule, budget, plant capacity, and plant utilization.

Stull and Tucker (1986) attempted to make a quantitative evaluation of the effectiveness of the design process itself. In recognition of the complexity of the design effort for an entire project, they considered only the piping design process and the subsequent construction of the piping described by the resulting design documents. They were aware of the ongoing work of Chalabi, et al, (1987) but because they were attempting to develop a quantitative measure they selected slightly different parameters to describe the effectiveness of the design, namely: accuracy of the design documents, usability of the design documents, cost of the design, constructability, performance against design schedule, economy of the design, and ease of start-

up. They then attempted to evaluate these parameters. Some were evaluated quantitatively (e.g. “accuracy” = number of drawings requiring revision/total number of drawings), while others were evaluated using a 1-10 scale (e.g. constructability and usability). All of these factors were then entered into an objectives matrix, in which the value of each parameter was mapped to a standard for that parameter. Then all of the mapped parameter scores were combined into a single score ranging from 0-1000 by weighting the individual scores. Through this process, the performance of the design effort could be evaluated, at least semi-quantitatively. However, this procedure suffers from the subjectivity of the scoring of individual parameters and the weighting of those parameters into a combined score (Glavan and Tucker, 1991; Dumont, et al, 1997). This work does validate the idea of evaluating design effectiveness.

Most engineering companies have some means (usually with an earned-value basis) for tracking progress, but these systems are not formulated or usable as productivity measurements. It is also common to measure productivity using the intermediate deliverable of drawings as an output. But engineering drawings are not very satisfying as a deliverable, because they are not objectively definable to the final project, especially when computer-based engineering tools are used.

To address these shortcomings, CII Research Team 156 studied the engineering productivity measurement problem. The team concluded that the final installed quantity was the appropriate measure of engineering output. The team piloted this concept on the piping function for a number of projects and concluded that field quantities could indeed be used effectively as an engineering output measure. Engineering Productivity Measurement II builds on the success of RT 156 to further develop the measurement system.

1.4 Brief Review of Related Productivity Literature

Extensive work on productivity exists at the individual and firm levels and industry and economy levels. Although productivity of intermediate functions is vital to all of these levels, the literature

is not as extensive. In general, productivity measurement systems for professional knowledge workers are not as well developed and empirical results are not very prevalent. To assist readers with the literature, an extensive bibliography is provided at the end of the report, and the reader is referred to Appendix C in CII publication RR 156-11 for a review of literature by that team. The following overview is provided to assist with understanding the application of productivity measurement literature to the concept of measuring detailed design productivity in capital projects. The overview is presented in two sections focusing on engineering productivity and attributes of metrics for output.

1.4.1 Overview of Engineering Productivity

A study of the archival journals pertinent to the architecture, engineering, and construction (AEC) industry reveals that there is little quantitative work reported on the topic of measurement of engineering productivity and performance. Most of the work reported pertains to productivity during the construction phase of the project. References to productivity and/or performance of engineers in the literature are typically qualitative in nature, and usually made in the context of a recommendation for a given product. In such cases, one frequently finds references to the idea that, by making use of the technique under discussion, one can improve the productivity, quality, and/or performance of engineers. Examples of such claims are many, and can be found in all branches of engineering. Several papers have reported potential performance improvements resulting from the use of particular techniques such as concurrent engineering schemes (Isbell, 1993; Benayoune and McGreavy, 1994) and software for integrated circuit, process, or civil engineering design (Girczyc and Carlson, 1993; Graham, 1990; Sackett and Evans, 1984; Winter, 1992). In these studies there is an abundance of conclusions and a lack of data.

Engineering productivity is defined as the relationship between physical inputs and physical outputs. Productivity is not conceptually synonymous with financial measures that

relate financial inputs to financial outputs. Ideally, productivity relates physical inputs (as flows of labor hours, actual usage of capital equipment pieces, material types, etc.) to physical outputs (units produced).

From classical economic productivity theory, outputs are caused by inputs. The literature is rife with different estimation procedures and models. From the late 1920's and early 1930's, there have been many variations of the production functions statistically relating inputs to the outputs they caused. Typical functions are the Cobb-Douglas, constant elasticity of substitution (CES), transcendental functions, etc. (see Krelle, 1983 for more detail). Although these studies have suffered some difficulty with implementation they are still widely accepted as being the most appropriate methodology for productivity estimation.

In the modern business world, market-oriented firms acquire resources to react to the customer's demand. The resource acquirement is caused by the customer. Customers cause the output specifications that cause individual resource needs. This logic chain means that in modern business marketing strategy, causality is reversed from the classical inputs causing outputs, since required outputs cause specific needed inputs. Productivity is still the relationship between output and inputs; however, the assumed direction of causality is reversed. Figure 1.1 illustrates this relationship between the customers and the resource requirements in capital projects. Typically, the customer (eventual owner of the capital project) specifies the project requirements that cause specific designs. These specific designs require exact specifications that, in turn, cause specific resources to be used in the design and construction firms. Even though the exact facility and equipment specifications are not given by the customer, the customer's required function (benefits) causes the output specification that, in turn, causes the engineering firm's required resources. The ultimate owner of the facility determines the facility mission and function. The owner's (customer's) choice of contractors is based upon the design and construction of the capital facility and the facility's equipment. The owners' output design requirements (quantity

and quality of designed components s needed for the output) are, in fact, causing the contractor inputs. In the context of this study, engineering design components are a function of the designed specifications of facility and equipment given by the owner. These engineering designs are also frequently called design quantities. The design components cause each specific discipline to consume engineering hours. Figure 1.1 illustrates the relationship between the owner's requirements and the design engineering firm. The owner has specified functional needs that in turn specify the design components that in turn cause the engineering design hours (along with other resources). In our estimation procedure, the required design components cause the discipline design hours.

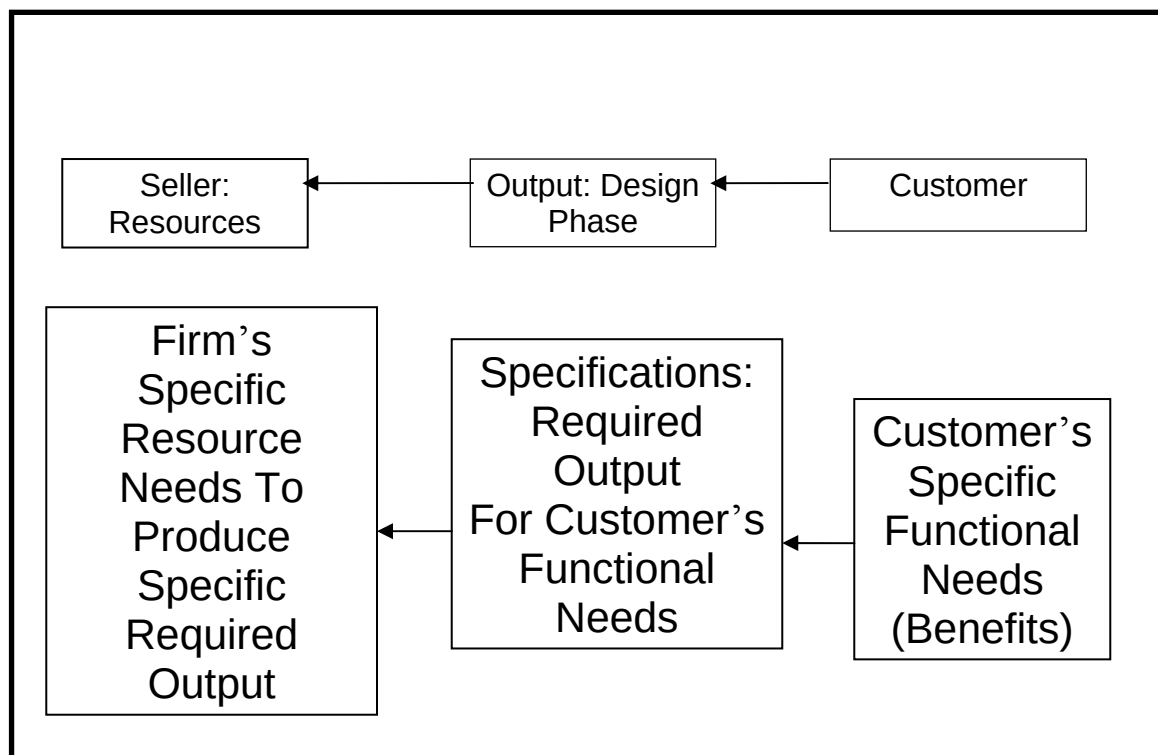


Figure 1.1: A General Productivity Model

In the economic terms, there are many difficulties to overcome to measure outputs of an organization because most organizations produce many different outputs. To make them homogenous, economists measure output as value-added (defined as the amount of value an organization adds to inputs; value-added is measured as sales minus external purchases) divided

by inputs. For the national economy, the sum of all value-added of all organizations is equal to gross national product (GNP). Although there are many other productivity measures, the one most publicly quoted is value-added divided by the number of workers (or labor hours). For each individual firm, it is possible to calculate productivity, but this measure is too aggregated to be used for the strategic planning and evaluation of individual activity.

No analyses of productivity would be complete without discussing traditional work measurement. Work measurement has two major methods: traditional work sampling or time study. It may seem that these methods could be used to determine productivity of each worker. Yet, these methods have four important drawbacks: 1) heterogeneous output; 2) inter-relatedness of design components; 3) small sample sizes; and 4) data are not available. First, the outputs are non-homogenous. Estimates of the actual amount of output are difficult to understand and usually not meaningful. Second, individual construction projects are composed of many inter-related items. Any analysis would reveal that the actual time associated with the time an engineer spends on an individual design component is highly dependent upon the degree of interrelationship with other design components within the engineering organization. Consequently, timing the worker on an individual item would be highly misleading. In any case, neither work sampling nor time study would provide a good estimate of the amount of effort needed for an individual design component. Third, there are numerous design components in each engineering design discipline. In many cases, there are zero quantities of a component for some engineering disciplines causing typical engineering design firms to not have enough observations for meaningful work standard analyses. Fourth, organizations do not systematically gather data on individual design components associated with the engineer's design hours because of the amount of effort needed to do so. In sum, work measurement techniques can not be easily implemented in engineering organizations.

Like all private organizations, the capital project construction industry has struggled with the issue of discipline performance assessment. In general, all business organizations attempt to evaluate personnel to determine their worth to the organization. The need for this evaluation is based upon fairness to each individual in the organization. Unless there is a transparent method of evaluation, organizations can neither be unbiased nor fair to their employees.

Historically, engineering design disciplines have had their productivity evaluated by the number of drawings produced (see CII RR 156-11). With the advent of computerized design programs to generate drawings, both design engineers and their managers have become increasingly dissatisfied with such measures of productivity. Consequently, the construction organizations are seeking alternative measures for design engineers' output. Design components are considered the preferred alternative measure. Project team 192 pursued this research avenue. Early studies by PT 156 by the Construction Industry Institute (CII) demonstrated that this method has merit.

Productivity is defined as the relationship between inputs and outputs. In the conceptual framework, it is the relationship between physical inputs and physical outputs. In classical productivity studies, productivity is measured as outputs divided by the inputs. But in the construction industry the productivity measure is usually the inputs divided by outputs. There is no conceptual reason for believing that either measure is superior to the other. This study will use the construction industry standard: inputs divided by outputs. The measures are numerically calculated as actual hours divided by the sum of quantities of physical design components. Each design component in a capital project has its own unique metric such as cubic yards, tons, count, flow rate, and watts. The design component outputs from a particular discipline are quite varied and common physical metrics for summation across design components are not possible. For this study, physical quantities of design components installed in the capital facility are still the focus. In addition, engineers on the team and engineers that participated in discipline workshops have

strongly indicated that the engineering efforts on the design components are intertwined through first, second, and more complicated interactive relationships. Data on discipline engineering hours devoted to a single design component were not available from the 14 companies that provided data. Companies were able to provide engineering hours by discipline and quantities of design components developed by each discipline. This study estimates total discipline design hours using the physical design components for each discipline. From this statistical estimate, the total expected hours statistically are estimated based on quantities of specific design components from the actual total discipline design hours. Input is measured by actual total discipline design hours charged to a project. Output is measured by total standard discipline design hours represented (expected) by the quantities of the design components. The focus of the data collection and analyses for this study is to develop a method of deriving expected hours of for a given project from quantities of design components specified. The traditional construction industry metric used for productivity is inputs divided by outputs. Inputs are in total hours of actual discipline detailed design. Outputs are in expected hours for a discipline based on quantities of design components. The productivity metric is thus an index not affected by project scale.

The productivity of design engineers is very complex due to the number of different outputs produced by engineers. Traditionally, many firms have used the number of drawings produced by engineers. However, in recent years with the increase in computerization there has been dissatisfaction with the number of drawings. Computerization and other technological advances cause the number of drawings not to match either the amount of engineer effort nor contribution to the project goals.

1.4.2 Attributes of Outputs from the Detailed Design Function

Productivity measurement systems aim at identifying the areas of low performance and the gap between the optimal output and actual performance in a meaningful, understandable and intuitive

way (Sardana & Vrat, 1987). Taylor (Taylor, 1982, 1984) in his study of information processes and productivity identified three attributes of output that should make a metric.

- 1) “It should be an identifiable point in a process
- 2) It should have a terminal quality.
- 3) It should be in a form which can be analyzed in the future as input to other processes.”

(Taylor, 1982, p. 137)

The attributes identified above provide useful guidelines in determining what can and should be counted and, how it should be counted. It is particularly relevant to the service industry where the difficulty in conceptualizing the output has led to slower development of productivity measures (McLaughlin & Coffey, 1990). The three attributes of output identified above allows us to look at the organization or function as a socio-technical system. In a socio-technical system the focus is on the throughput where throughput is defined as “the demand for service to the conversion process, changes in the state of the throughput as some expected serviced output” (Adam, Hershauer, & Ruch, 1981). Taking a socio-technical view of the organization allows one to focus on the transformation process regardless of the combination of technical systems and social systems input required for the state change to occur (Adam et al., 1981). This study addresses the issues dealing with conceptualizing the output measures by identifying the detailed design function as the unit of operation and the physical designed components as the exiting state of the design function. The output attributes along with the unit of operation were the starting points for the workshops. As a process, developing a productivity measurement system follows distinct phases such as identifying the purpose for measuring, using a family of measures concept, incorporating the customer’s perspective in the measures, and understanding adjustments required in the interpretation of measured trends (Hordes, 1988; Thor, 1994a). Taking a process view of productivity measurement help firms’ to better develop, install and manage measurement systems.

The procedure for developing a productivity measurement system should start with an identifiable point in a process. Detailed engineering design usually starts after an initial concept development often referred to as front end loading (FEL) and subsequent approval from the customer. Detailed design often terminates when drawing and specifications are issued for construction (IFC). The detailed design output is drawings, and specifications, for the physical design components. These outputs can be abstracted to represent the formal documentation of the quantity and technical information required to plan and build the parts of a facility. For example, drawings and specifications are representations of data related to physical installed components like boilers, electrical fixtures, pipes and building area. In the construction industry the point at which data is issued for construction (IFC) by the design function account for a majority of the labor hours spent in the design work and at this point the outputs (drawings/specifications/and designed components) can be identified and isolated.

Next, it is important to find a metric that is easy to count and consistent with historical data and existing information systems. The number designed physical components are relatively easy to count and document. Designed components are physical quantities that exist at the end of the design process and thus tangible to the customer. For example the square feet of pavement as an output measure can be determined for almost every project and it exists as a physical component at the end of the construction process. A historical context is relevant so as to enable comparisons to be made over time. If historical data is not available then the data must be defined and collected so that some kind of time series can be established for comparison. To develop a new statistically sound output measure a firm would have to collect data on at least 40 projects, which in the construction industry could take a long time even for the largest firm. The importance of using existing information systems and historical data to determine a baseline for productivity measures is of paramount importance in the continuing study of service productivity.

If a metric is available and easy to count, then it should have a terminal attribute. By “terminal,” Taylor (1982) implied that “the output, though it may be part of a longer process should be identifiable and isolated for measurement”. The word terminal does not mean that the output has to be a final product or service. Though Taylor defined this attribute as a terminal quality, in this study we prefer not to use the term quality so as to avoid issues relating to the measurement of service quality. By terminal we mean the output measure should be an identifiable point representing a value added process and that it should be possible to count in dollars of hours associated with producing a particular type of output (for example the time taken to design a pressure vessel). The terminal attribute of a product or service is similar to the outcome measure (Sherwood, 1994) in that we look at the output rather than the process. The construction process transforms the designed components into actual physical installed components.

A product or service is designed for the purpose of future use or consumption. It has an effect on some future act, decision or value adding process. The section of the output measure should in some way relate to the work performed by the recipient of the output. In the case of a construction project, the contractors are the recipients of the outputs from the detailed design function. It is the design components on which the contractors base their purchase orders and the relationship between different design components provide the necessary information for on-going everyday activities of the contractors and sub contractors. The construction industry is rich in data related to construction hours associated with specific design components, for example hours per quantity of earthwork and construction cost estimations are based on publicly available data on unit work hours. Specifying the outputs of the design discipline in terms of detailed design quantities will enable over time, the industry to develop similar unit design work hours for different design components.

In this research project, the list of design components identified during a set of discipline workshops was scrutinized based on the above-mentioned attributes and only those components that possessed the necessary attributes were considered for data collection and further analysis. These workshops are discussed in Chapter 3.

1.5 Brief Background of CII Related Work

CII has a long history of study and development related to engineering performance and productivity. Table 1.1 presents a sampling of relevant research teams and research products produced by CII, and demonstrates that the productivity, performance, and conduct of the engineering effort has been studied by CII throughout its existence. In spite of this extensive consideration of the general topic, CII also recognized that engineering performance, in general and productivity, in particular, are difficult to measure quantitatively. Furthermore, CII also considered that there were no recognized, standardized methods for measuring engineering productivity, similar to those that exist in, for example, the construction portion of the project delivery process.

Table 1.1: CII Research Projects and Products Relating to Engineering Productivity and/or Performance

Year	Research/Project Team	Products
1986	Task Force 84-8, Design	Evaluation of Design Effectiveness (SD-16) Defining and Evaluating Input Variables Impacting Design Effectiveness: Research Phase I (SD-19)
1989	Task Force 84-8, Design	Cost Effectiveness of Computerization in Design and Construction (SD-50)
1994	Total Quality Management Task Force	Implementing TQM in Engineering and Construction (SP 31-1)
1997-1998	Research Team 112	2% Engineering – Can It Work for You? (RS 112-1) A Framework and Practices for Cost-Effective Engineering in Capital Projects in the A/E/C Industry (RR112-11)
2000	Research Team 152	Three-Dimensional Computer Models and Fully Automated Project Processes for the Management of Construction (RR152-11)
2001	Research Team 156	Engineering Productivity Measurement (RR156-11)

The importance of productivity measurement in every industry has been well established. As the saying goes, “What gets measured gets improved.” Construction productivity measurement based on construction hours and physical quantities installed in the field, long an interest area for CII research (see RS 2-3), allows for measurement and identification of areas for improvement of construction processes, and can be built into estimating and progress reporting processes within companies. The belief that standardized methods for measuring engineering productivity based on a similar viable output measure would lead to these same benefits for the engineering effort led CII to consider developing a system to measure and track engineering productivity.

CII Research Team (RT) 156 advanced the concept of measuring engineering productivity, not by the traditional method of using design hours per direct engineering output of drawings and specifications, but by the physical quantities to be installed in the field. RT 156 conducted a detailed evaluation of the piping design process and sought correlations between the engineering hours for piping design and physical measures of the quantities of designed piping. The team found good correlation between hours and the total length of pipe designed and the number of equipment pieces in the piping systems. Equipment piece count was seen as an indication of project complexity. RT 156 developed a conceptual model in which detailed design engineering productivity would consist of a raw productivity (hours per designed quantity), which could be adjusted to account for the project complexity, the quality of input to detailed design, and the quality of the design output.

The conceptual model developed by RT 156 provides a balanced, project-centered approach to engineering productivity evaluation. The raw productivity addresses the productivity of the actual work itself, by measuring the time required to produce designs for the physical quantities to be installed in the field. However, some projects are more complex than others, and there are economy-of-scale considerations, so an adjustment to account for the scope and complexity of the project was suggested. In the case where the design basis is incomplete, or the

client changes the project in midstream, the design hours may reasonably be expected to increase, so the quality of the input must also be considered. Finally, RT 156 realized that a possible (but undesirable) path to apparent productivity improvement would be to transfer design work from the design phase to the construction phase of the project. Accordingly, the quality of the engineering deliverables must also be considered. Taken together, these four components provide a good understanding of the engineering performance.

In a nutshell, RT 156 completed the following:

1. Reviewed the literature and industry practices on engineering productivity. Normalized definitions with CII, including productivity definition as input/output.
2. Concluded that intermediate deliverables (such as drawings) were the wrong output measure
3. Concluded that the field quantity actually installed was a better output measure because
 - a. More directly tied to the design activity
 - b. Less subject to manipulation
 - c. Already tracked in most design environments
 - d. Puts construction and design on same basis
 - e. Focuses attention on the final product
4. Determined that the best productivity to track for a given project is the productivity for the driver discipline using a facilitated workshop of team members
5. Evaluated driver disciplines for several project types (Light industrial process, Heavy industrial process, light industrial mechanical, heavy industrial mechanical, buildings, and infrastructure)
6. Developed a conceptual model in which the productivity is calculated using raw productivity (discipline design hours per units of design components) adjusted by an input factor, a complexity factor, and an output factor.

7. Developed a proposed model for the piping function. This model was:
 - a. Raw productivity = piping engineering hours/linear feet of pipe
 - b. Complexity factor is a function of the number of equipment pieces
 - c. Input and output factors were not determined although the PDRI (CII's Project Definition Rating Index) was suggested for input and rework was suggested for output.
8. Tested this model on some actual data and concluded that it could work.

1.6 Approach of Engineering Productivity Measurement II Team

Using RT 156 results as proof of concept, Project Team (PT) 192 was formed in 2002 to build on the work of RT 156 by extending its concept for the piping discipline to other engineering disciplines and by quantifying the input/output adjustments. Based on the results of RT 156, the work of PT 192 has been to develop productivity models for detailed engineering design in the seven disciplines of architecture, civil/structural, mechanical, piping, electrical, process, instruments and controls.

As the key to exploring these seven disciplines, the PT 192 team conducted a series of discipline workshops to establish the factors and variables for models similar to those developed in RT 156. These workshops were held from March through June 2002. The workshops provided the information necessary to determine the variables to incorporate in a data collection instrument. The workshops focused on outputs, inputs, complexity factors, and data collection issues. Experts from all disciplines helped establish the ability to get output and input data by discipline, the difficulty in getting design effectiveness data by discipline, and the lack of available data for engineering hours for any single design component.

The team invested considerable time in reviewing a designed-quantity-based engineering productivity system in use at Dow Chemical Company. The material provided by Dow helped the team develop lists of possible design components for inclusion in the project. The Dow

system led the team to seek a model that would be amenable to determining a combined engineering productivity across disciplines in future research by CII. The team also reviewed the results of efforts by the Benchmarking and Metrics Committee to establish engineering productivity metrics from the RT 156 concept.

The PT 192 team used all of these sources to develop a data collection instrument to document engineering design components by discipline, actual discipline hours expended to complete the design, and project-specific input/output factors that could potentially impact productivity for a sample of projects. The instrument provided extensive detail on the engineering process for each project in the sample database (Table 1.2).

Table 1.2: Summary of Data Collection Questions

	Project Descr.	Input/ Output Quality	Design Components						
			Arch.	Civil/ Struc.	Mech	Piping	Instr. & Cont.	Elec.	Process
Number of Questions	80	49	6	24	63	16	13	29	15

The data for this study was collected during the months of June-December 2002 from a group of engineering design firms and owner-operators that are members of CII. The large number and different types of companies in the CII membership provides a good target population for empirical studies. The active participation and the structure of PT 192 membership provided sufficient motivation and large sample sizes for obtaining statistically meaningful data input and productivity output. Data quality is indicated by the experience level of the person completing the questionnaire, which averaged 22.7 years.

Our primary sources of project data were the companies who were active members of this research study. All the companies were involved throughout the research from concept development to research design and later data collection and analysis of the findings. The entire process was iterative and cyclical in nature involving understanding the concept, exploring the data, explaining the results and redefining or confirming the concept.

In total, historical data on 118 projects was collected from 14 different companies. The different projects can be categorized on a number of different dimensions. The following three tables provide descriptive data for several different ways to categorize the projects. Table 1.3 lists the type of companies providing the data. Table 1.4 describes the projects in terms of the type/category of industry and the type of project. Table 1.5 looks at the projects in terms of size as defined by the area, dollar value and the amount of total detailed design hours.

Table 1.3: Type of Companies Providing the Data for Study Sample) (n= 118)

Type of Company	Number in Sample	Percentage of Sample
Owner w/ in house capabilities	26	22%
Owner w/o in house capabilities	8	7%
Constructor	20	17%
Designer/Constructor	28	24%
Full-service firm	36	30%

Table 1.4: Industry Breakdown of Projects in the Study Sample (n=118)

Description	Number in Sample	Percentage of Sample
Type of Industry		
Heavy	114	97%
Light	4	3%
Category of Industry		
Chemical	44	37%
Power	46	39%
Environmental	19	16%
Oil refining	3	2%
Metals refining	2	2%
Pharmaceutical	1	1%
Optical Fiber	3	3%
Type of Project		
Greenfield	38	32%
Retrofit	14	12%
New Plant in existing facility	40	34%
Expansion of existing facility	14	12%
Modernization	8	7%
Other	4	3%

Table 1.5: Descriptors of Size of Projects in the Study Sample (n= 118)

Description	Units	Mean	Median	Min	Max
Size of plant in terms of area	Sq. Feet	750,901	259,770	3,500	7,500,000
Number of raw materials	#	4	3	1	19
Number of finished goods	#	2	1	1	12
Number of design sites	#	1	1	1	4
Number of startup systems	#	58	30	1	337
Detailed design Cost	\$	7,462,970	3,735,000	10,132	65,751,000
Total Installed Cost	\$	115,210,431	62,858,366	249,931	549,900,000
Total Detailed Design Hours	Hours	70,164	39,982	219	935,215

Based on this database, statistical methods were used to develop equations for the empirical relationships between design hours for a discipline and the design components for that discipline. The empirically calculated number of hours for each discipline is then used as the basis for the productivity index. The actual discipline hours for a given project divided by the productivity basis hours (from the empirical calculation) is defined as the productivity index for that project. A company that is improving its detailed engineering process would see this ratio decrease over time. The productivity basis hours are a function of the design components and other complicating factors for each discipline, and provide a baseline for calculating relative productivity over time. *NOTE: The resulting hour coefficients on the statistically significant explanatory design components are used to compute an expected number of discipline design hours to be used in a productivity index ratio with actual discipline hours, and are not intended as a way to estimate the discipline hours that will be needed to complete a specific project.*

$$\text{Productivity Index} = \frac{\text{Actual Design Hours}}{\text{Productivity Basis Hours (calculated from designed quantities)}}$$

PT 192 included only direct hours in our data gathering (from discipline engineers, designers and technicians) not indirect hours (for document control, reproduction graphics, project management, project controls, project engineer, secretary, clerk, procurement, construction

support, quality assurance, accounting, and legal). Users of the productivity model should use the same basis. A family-of-measures concept (see Thor, 1994c and Adam, et al., 1986) is introduced to deal with the input and output quality issues and other major variables.

2 PROJECT METHODOLOGY

As indicated in Chapter 1, this project was designed from its inception to build on the work of RT 156. RT 156 developed a conceptual model for engineering productivity in which the basic measurement of the detailed engineering effort was based on the design components, rather than the design deliverables. The concept was pilot tested in the piping discipline. RT 156 expanded their model to include the concept of modifying “raw productivity” – which would be measured by dividing engineering hours by a single, fundamental design component for each discipline – by incorporating the scope and complexity of the project, the quality of the design basis, and the quality of the design deliverables.

PT 192’s charge was to carry this model forward to develop a useful system for engineering productivity measurement. PT 192 was not convened to repeat the conceptual model development, and in fact repetition of this fundamental underpinning was specifically excluded from the scope of the project team. Rather, the goal of PT 192 was to expand upon the work of RT 156 and attempt to develop its conceptual model into a workable measurement system.

The conceptual model developed by RT 156 represents a new way of looking at the detailed design effort. In this chapter, the fundamental assumptions of this approach will be reviewed. This will be followed by a brief summary of the methods used in accomplishing the objectives of this project team. Further detail will be provided on the specific details of these methods in subsequent chapters.

2.1 Basic Assumptions

Assumption 1: There exists a quantifiable relationship between outputs and inputs.

In the case of the detailed design function we assume that there exists a set(s) of design quantities that can be associated with the amount of labor hours expended by the design function. Such an assumption would have been erroneous especially in the case where an external firm

was performing 100% of the design work and the only work hours associated with the internal design function was that of coordination. In order to avoid such cases the total hours spent by all parties involved including those outsourced should be considered as input hours, and should be sought by definitions of hours.

Assumption 2: The labor inputs in a design process are heterogeneous but additive.

The design function involves creative and innovative work, which may be approached very differently by different professionals, even within a single discipline. There exists inherent heterogeneity in the inputs at the professional level, which may be the result of many factors such as the intelligence, education, and/or experience of individual design engineers and managers. Despite this heterogeneity, the individual inputs measured in work hours per employee are additive in nature. At the functional level changes in productivity levels may be due to changes in the creative process of knowledge creation. As a consequence of this assumption, it should be noted that heterogeneity implies that cumulative hours across several different professionals, as for example all engineers in a given discipline, may be more effectively modeled than individual performance.

Assumption 3: All design tasks are associated with physical design components, components which will ultimately be installed in the designed facility.

The primary function of a design discipline is the designing of physical components and in some cases software that form a part of a facility that generates a user defined output (s). For example the design of a power generating facility would involve the design of turbines, generators, and automation software which, once installed, will operate in combination with input resources to generate a particular level of electrical power. The design tasks may include RFI and RFQ from vendors, team meetings, coordination with customers and other disciplines,

the creation of specification documents and drawings, and the creation of quality control documentation. Though many of these design tasks may be simultaneously associated with a number of design quantities, we nonetheless assume that all these tasks can be associated, directly or statistically, to a particular set(s) of design components. In the extreme case a project with no design quantities should not require any design hours. Only direct labor hours are considered.

Assumption 4: The design tasks associated with different design components may be heterogeneous in nature.

The second assumption is related to the heterogeneity of the tasks involved in the detailed design process. Different design quantities may involve varying tasks associated with them, for example, the design of a mechanical pump may be as simple as selecting a vendor-supplied specification whereas the design of a cooling tower may involve coordination with other disciplines such as civil and piping, in addition to selecting a vendor-supplied specification. The variations in the tasks may be due to a number of environmental factors including but not limited to the nature of the project (greenfield vs. retrofit for example), the type of industry (power vs. chemical), the geographical properties of the plant (seismic code, applicable regulations), or the capacity of the facility being designed. Even though there may be project-to-project variations in the tasks associated with the design of a particular design component, in a large sample of projects we assume that there exists a set(s) of design components that are homogenous across projects and that there exists a set(s) of design components that explain the heterogeneity in the projects. For example, in the civil and architectural disciplines design quantities like building area and volume of structural steel involve similar design tasks across different projects. Design quantities such as (for example) hangers and supports in the piping discipline may account for

the variations in the design tasks for the piping discipline. Though the hangers on their own do not consume a large amount of design hours, they indirectly account for the complexity associated with the piping design tasks (for example a large number of hangers may indicate a greater number of pipe bends or the use of stress treated or double contained pipes).

Assumption 5: The design tasks associated with different design components are (or may be) related.

The design function is highly team-oriented and cross-functional. The designs for many of the design components are inputs to the design process of other components, in the same discipline and in other disciplines. For example, the design of intakes and outflows of pumps serve as inputs to the design of pipe connections. The type of pump serves as an input to the design of electrical terminations. Thus, the design hours associated with a particular design component would not only indicate the task associated with the design of that particular component, but would also be indicative of the coordination between engineers and the subsequent design hours spent on other components.

Assumption 6: The design can and may be reused.

Similar to the concept of code reuse in the software industry, it is assumed that a design that successfully documents an aspect of a finished structure may be duplicable in similar aspects of another project or even within the same project. The duplication would require only a marginal increase in the design hours associated with creating additional documentation and customization. A project with 100 similar pumps would require only a marginal increase in design hours related to pumps, when compared to a project with say 50 similar pumps. The higher number of pumps, though, represents the increased size of the project and the increase in the design tasks associated with other design components within the piping discipline and

perhaps across disciplines, such as the design of terminations by the electrical discipline and the design of foundations for the pumps by the civil-structural discipline. More importantly, a design from one project may be used in another project. This leads to variability in hours devoted to a design component from project to project. This variability makes it more difficult to establish baseline coefficients; however, it is one of the reasons to have productivity measures. Organizations need to know if the set of design decisions, including degree of reuse, leads to improvement in total discipline design productivity. It is not appropriate to adjust productivity measures for differences in approach; the intent is to discern when differences in approach actually improve productivity.

Assumption 7: It is possible to create uniformity in the measurement of design hours and design components among projects and among companies.

Considerable variance in the accounting of design hours and design components can significantly complicate a productivity study. Such variations can arise because of different interpretations within the industry of what constitutes design hours and/or how to count a particular design component, the boundaries that define the start and end of detailed design function, the use of different accounting systems, the coupling of different design discipline hours, the amount of design work outsourced, the use of vendor designed packages or simply due to the unavailability of appropriate data. This study assumes that such variations have been minimized by the detailed definition of the design hours and the standardization of the design components to be used. In fact, the research methods are structured to seek design components that are counted in a standard manner and that are readily available from all current information systems.

Assumption 8: Quality measures are to be stated explicitly.

A productivity measure in the manufacturing industry often assumes a constant quality of the output. In services, intangibility and co production of output introduces considerable variation in the customer-perceived quality. A productivity measure that utilizes designed components may include the influence of both the quality of the design basis as well as the quality of the design completed, but the outputs need not directly represent the quality of the output or the quality of inputs. In order to consider the quality aspect of the detailed design output, measures of input quality and customer perceived quality need to be explicitly considered, either functionally or via a “family of measures” approach.

2.2 Fundamental Approach to Project

The fundamental approach of this project team was to address the engineering productivity problem while being mindful of the project charter. This means that the project was directed toward the development of an engineering productivity system that could be put into service by most CII member companies, and that would provide results which would be relevant and useful to the improvement of productivity of the detailed engineering process for the seven disciplines identified. The seven disciplines are architecture, civil/structural, mechanical, piping, process, electrical, and instrumentation and controls. Given this fundamental approach, the project was designed to identify data which could be relevant *and* could be obtained by member companies, to collect such data, to use it to develop productivity equations and/or relationships which could be readily understood by practitioners, and to develop an implementation resource to facilitate rapid deployment of the system. The balance of this chapter will be dedicated to general description of these aspects of the project activities.

2.3 Data Collection Methods

Data for subsequent statistical analysis and identification of productivity equations and relationships was obtained from project team members and CII member companies. Data was required to convey measurements of all aspects of the conceptual model, in particular the number of design components, indicators of project complexity, indicators of the quality of the design basis, and indicators of the quality of the deliverables from the detailed design effort. A near-infinite number of variables could be imagined that would be relevant to these concepts, and of course it would not be practical to collect all such variables. Accordingly, the first task of the project team was to identify a manageable number of candidate variables to describe these concepts, and to design an instrument to collect them. The candidate variables were identified via a number of processes, including: variables suggested by RT 156 (see Chang, et al. 2001), variables suggested in workshops conducted for this project, variables identified in a productivity measurement system provided to the project team by the Dow Chemical Company, and variables identified in workshops conducted by the Benchmarking and Metrics Committee in their efforts to develop an engineering productivity metric.

2.3.1 Sources of Design Components and Other Variables

A series of discipline workshops were conducted by the academic team of PT 192 in the spring of 2002. to solicit suggestions from industry experts for ways to quantify the raw productivity (basic design quantities that fundamentally reflect the output of the discipline engineers), scope and complexity (design quantities or measures that might indicate above- or below-average scope and complexity), the quality of the input to the discipline engineering process, and the quality of the output from the detailed engineering process. Seven discipline workshops were held (one each for the Architectural, Civil-Structural, Mechanical, Piping, Instruments and

Controls, Process, and Electrical discipline areas) with small groups of practitioners in the appropriate discipline. Each workshop followed a structured group process for developing lists of candidate productivity metric variables (see Delbecq, et al. 1975 and Adam, et al. 1981). Small groups provided for active participation by all of the experts and for detailed discussion and exploration of variables suggested. In keeping with the fundamental approach of this project team, significant time was devoted in each workshop to the discussion of the feasibility, practicality, accuracy and availability of data for suggested variables. Detailed discussion of the workshop process and the results of the individual workshops can be found in Chapter 3.

In addition to this avenue for obtaining candidate variable suggestions, the project team was fortunate to obtain productivity instruments from two other sources. First, very early in the project, the academic team was approached by the Dow Chemical Company. They had developed a productivity measurement system based primarily on design components a few years prior to the effort of RT 156. Their system used a combination of many design components to achieve a point count for the size of the design, which could then be adjusted for project execution factors which described the input and output requirements for the detailed design. This system covered the civil, piping, electrical, mechanical, instrument, and process containment engineering disciplines, with a number of design components to capture the discipline effort ranging from 2 to 280 per discipline. Additional detail on this model, including the equations used, will be kept confidential at the request of the Dow Chemical Company. However, the project team was able to use the variables identified by Dow as candidate variables for possible inclusion in the data collected for this project. The project team is very grateful to the Dow Chemical Company for its dedication to industry improvement as demonstrated by their willingness to share this instrument.

In addition, the Benchmarking and Metrics Committee has been pursuing the development of productivity measures for use in benchmarking by CII members for some years. Following their successful efforts to develop construction productivity measures, the Committee went on to conduct workshops to consider potential engineering productivity models for possible benchmarking of engineering productivity. These workshops were used to develop a pilot benchmarking instrument in engineering productivity, indexing as much as possible the engineering effort to components previously used for the construction productivity benchmarking effort. The Committee provided this instrument to PT 192 in the spring of 2002, and the project team was able to use the variables identified by the Committee as candidate variables for possible inclusion in the data collected for this project. The project team is very grateful to the Benchmarking and Metrics Committee for sharing this effort.

2.3.2 Creating a Data Collection Instrument

The candidate variables obtained from RT 156, the PT 192 workshops, the Dow Chemical Company's instrument, and the Benchmarking and Metrics pilot instrument, were used to develop a data collection instrument specific to the needs of this project. Chapter 4 provides a detailed description of the instrument, the process for its development, and the source of the specific data items requested on the instrument. Briefly stated, the procedure consisted of comparing and contrasting the various lists, comparing them with feedback on data availability provided by the workshops and the industry members of the project team, and developing a single consensus list. The instrument was piloted at a PT 192 member company, modified based on that experience, and then rolled out to the rest of the project team. The Dow Chemical Company provided data for a number of projects directly in the format of their own instrument, and then augmented this data with additional data identified on the PT 192 instrument.

2.4 Summary of Data Analysis Process

Data were collected using the instrument previously described for a total of 118 projects. The data were provided to the academic team for PT 192 confidentially, in many cases requiring non-disclosure agreements. As such, the data themselves are not included in this research report. However, the projects are summarized and characterized in Chapter 4. Detailed discussion of the analysis methods employed to identify productivity equations and relationships is also provided in Chapter 4, and the results of these analyses are presented in detail in Chapter 5. A brief summary of the process is provided here.

Productivity is a relatively straightforward concept that consists of a relationship between inputs and outputs of a process. As has been stated previously, RT 156 developed a conceptual model of engineering productivity in which inputs would be indicated by engineering hours and outputs would be indicated by counting some design components, and this result could be modified or contextualized by measures of the design basis (quality of the input to the engineering effort) and the design deliverables (quality of the output of the design deliverables). This model can be idealized as a relatively simple relationship model, as shown in Figure 2.1.

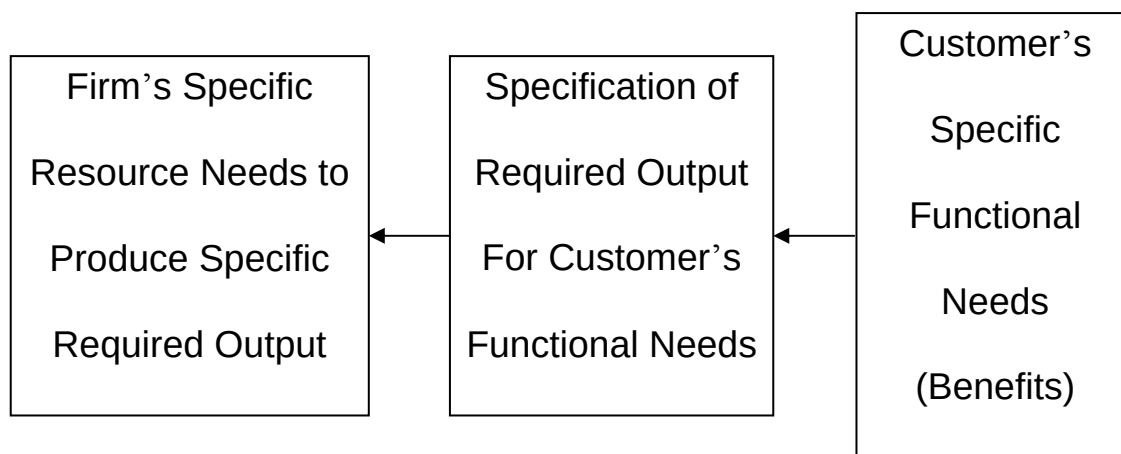


Figure 2.1: Conceptual Relationships among Project Inputs and Outputs

The simplicity of the relationship shown in Figure 2.1 hides the complexity in application to practice, however. Specifically, a great deal of “noise” is introduced in this model by the presence of interactions between disciplines, by heterogeneities between the capabilities of individual engineers and the characteristics of projects, and by the need to complete activities which may not be directly related to the design effort, among other things. Accepting for the moment that a simple relationship exists between inputs (engineering hours) and outputs (design components), then this relationship should be identifiable in project data by the correlation between the discipline hours and the appropriate design component. This would be stated in statistical language as a regression function of the designed components (the independent variables in this case) which serves as an estimator of the discipline hours (the dependent variable in this case). Note that the term estimator in this case does not carry its traditional meaning in a construction setting, but rather implies only that the hours and the design components are related. If this relationship does not exist, there is little point in measuring productivity. This statement was made under the simplifying assumption that the relationship was simple; we know based on our assumptions that this is not the case (Figure 2.2). These influences will vary from project to project, and from company to company, so that the relationship between the basic variables will be obscured to some degree. The objective of the statistical analysis, at its simplest level, is to illuminate these relationships in spite of the noise, and to quantify the amount of noise superimposed over them.

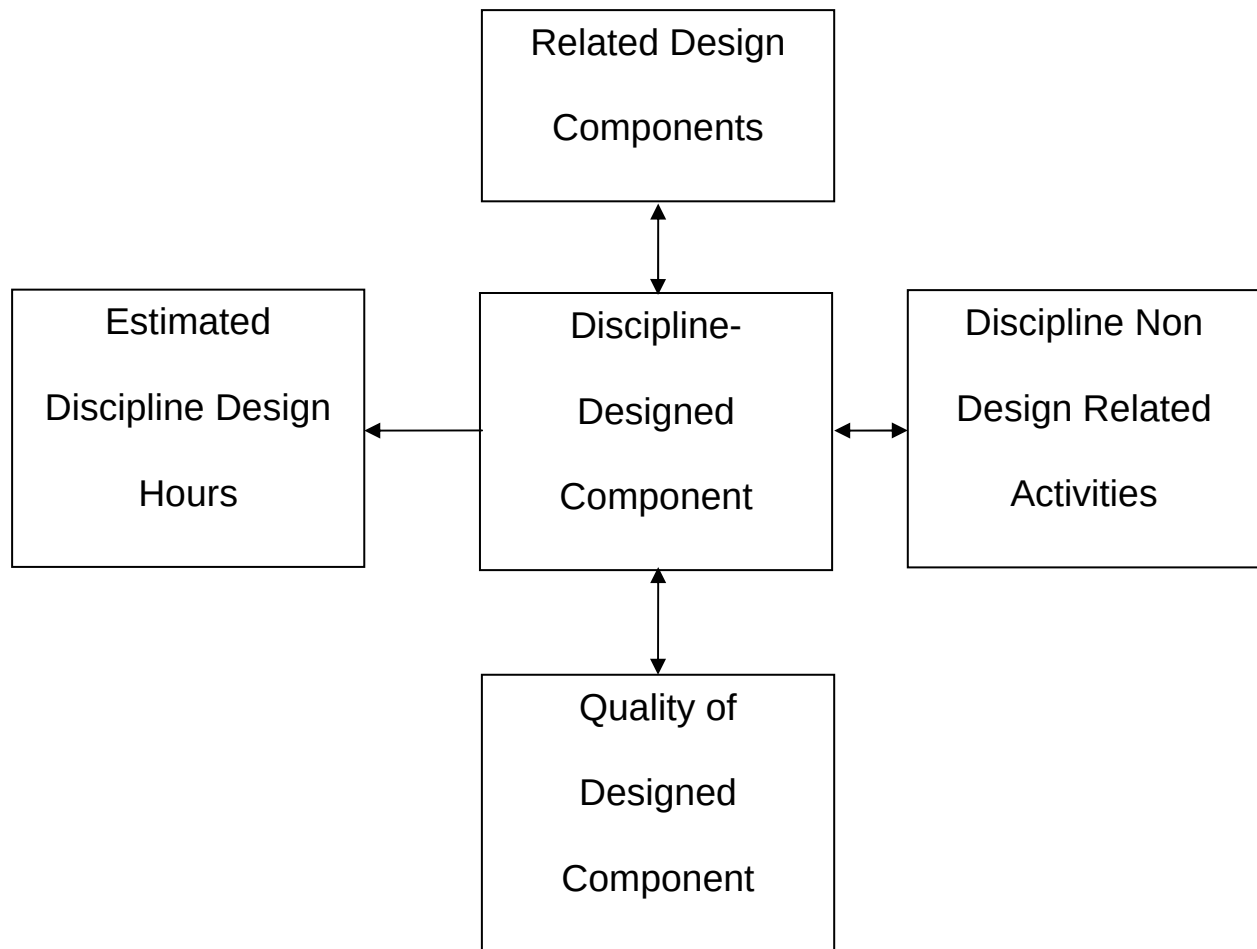


Figure 2.2: Sources of Noise in the Productivity Estimators for Engineering Productivity

In order to accomplish this task, the project team used a few simplifying assumptions as a starting point in the search for meaningful relationships, based on the feedback from the project team and the workshop participants. These assumptions include:

- As a first approximation, scope and complexity for a discipline can be conveyed by combining design components.
- Maintain a preference for practicality and usability of the models. As a consequence of this preference:

- o In the absence of any firm conceptual grounds to believe otherwise, the relationships can be taken as linear combinations of design components. Other functional forms may give better fits from a purely statistical perspective, but would make the model more difficult to understand and apply.
- o Seek relationships in which larger quantities of design components are associated with more engineering hours.
- o Seek relationships in which a discipline which will produce no design components will require no hours.
- As a starting point for the indication of the quality of the design basis, RT 156 suggested that the Project Definition Rating Index (PDRI, CII 1996) might be an effective tool. This variable should be tested at workshops and in statistical analyses.
- As a starting point for the indication of the quality of the output of the engineering effort, RT 156 suggested that engineering rework could be an effective variable. This variable should be tested in workshops and in statistical analyses.

The statistical analysis followed the following general procedure for each discipline (see Chapter 4 for detailed discussion)

1. Conduct simple correlations between each of the design components and design hours of a given discipline. The purpose of these estimations is to determine which design components are correlated to the design hours.