University of Alberta

Productivity Modeling for Steel Fabrication Projects

by

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PREFACE

This thesis is prepared in a paper-based format, consisting of seven chapters and one appendix. Every chapter is an independent paper and can be read separately. However, all the chapters are logically coherent and pertinent to the theme of the thesis. The thesis starts with an introductory chapter that presents an overview of the entire thesis, including the background, problem statement, research objectives, methodologies used and contributions made. Chapter 2 describes the data acquisition system developed based on the prior efforts in collecting historical data for productivity modeling. Chapter 3 addresses the problem of measuring and estimating engineering productivity and describes the proposed engineering productivity measurement system and its application to the steel drafting discipline. Steel fabrication productivity modeling is discussed in Chapter 4, Chapter 5, and Chapter 6. Chapter 4 describes the steel fabrication process and presents the virtual shop modeling system. Chapter 5 discusses the uncertainty in the shop environment, and presents an approach to classify, model, and reduce uncertainty. The use of the virtual shop modeling system to develop an integrated virtual shop system for the proposed project planning technique, experimental planning, is presented in Chapter 6. Chapter 7 summarizes what has been achieved in this thesis research, and outlines a proposal for future research. Appendix A is the system documentation for the virtual shop modeling system.

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CHAPTER 1: INTRODUCTION

BACKGROUND

Productivity is a fundamental piece of information involved in many project management functions, such as estimating, scheduling, and project control. Appropriately measuring and analyzing productivity is of great importance to the success of any construction project. The scope of the research presented herein is productivity modeling for steel fabrication projects.

Steel Fabrication Projects

Steel has been the most important component of essential utilities and basic industry facilities for more than a century. The use of steel has allowed designers and contractors to construct both simple and complex structures in efficient, timesaving, orderly, and economical ways (AISC 1999). While structural steel procurement and construction management have many similarities to the procurement of other building materials, steel construction has some unique characteristics. Structural steel is largely fabricated off-site. On-site erection and assembly are conducted rapidly. This research studies the production process from a steel fabricator's point of view. Steel fabricators are responsible for the fabrication of primary steel components to the point that they are ready to erect by a steel erector. A steel fabrication project consists of two major processes: steel drafting and shop fabrication. Steel Drafting is one of the engineering functions at the detail design level. Based on the 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. Shop fabrication refers to the production of steel components through a series of operations, which normally include detailing, fitting, welding, and surface processing in a fabrication shop, according to the engineer's design.

Productivity Modeling

By definition, productivity is the relationship between quantities of input and output. Productivity modeling is a systematic study of productivity measurement, productivity-influencing factors, and the relationship between these factors and productivity using historical data for the benefits of project planning, control, and productivity improvement. In the context of this research, historical data are defined as data collected from past projects regarding project scope, expenditures, and factors that affect project performance.

Productivity is normally measured by the cost per unit of work or the man-hour per unit of work. The first measurement combines all inputs into monetary value. Like other construction projects, steel fabrication projects are labour intensive. Man-hours represent the major input to the steel drafting and the steel fabrication processes. Other inputs, such as equipment and overhead costs, are highly correlated to man-hours. Therefore, in the context of this research, productivity is measured by man-hour per unit of work. Another basic decision to be made related to measuring productivity is the level at which productivity is measured. There are a variety of possible levels for engineering and construction projects, including individual level, discipline level, and project level, from the highest level of detail to the lowest. Engineering and construction projects require a significant degree of individual collaboration to deliver the final product. The measurement of individual productivity is inappropriate and does not provide a system-wide view of project performance for planning and control. Some companies measure productivity at the project level for cost estimating and benchmarking. However, construction is a process-based industry (Halpin 1992). Productivity measurements at the project level normally serve only as a benchmark for measuring general project performance and offer no insight into the efficiency of the production process. This greatly limits their capability for detailed project planning, control, and performance improvement. The research presented herein measures the productivity of each discipline for the process with which it is associated, such as that of draftspersons, fitters, welders, and painters.

Identifying productivity-influencing factors and subsequently analyzing their effect on productivity are the most important stages in understanding productivity performance under various conditions. Influencing factors can be normally identified through literature reviews, interviews, and surveys among domain experts. Historical productivity data, which are specific to a particular company and a particular production process, contain valuable information for defining analytically the relationship between productivity and its influencing factors. Productivity data can be collected through a variety of means, such as project management information systems and time studies. Productivity models in the form of simple equations or non-linear equations can be defined and calibrated by analyzing the collected data. These productivity models make productivity not only measurable but also predictable. Once established, they will play a critical role in estimating, scheduling, and project control. Influencing factors and their expected effects on productivity also reveal important information about how productivity can be improved.

By nature, steel drafting is a discipline of design engineering, while steel fabrication is a discipline of construction. This difference makes it necessary to study them separately for productivity modeling. Productivity studies for integrated design-construction process are left for future research in this area. Background information regarding state-of-the-art practices in modeling engineering productivity and construction productivity are provided in the following subsections.

Engineering Productivity Studies

In the context of this research, engineering refers to the design of public works, such as bridges or plants, and other large facilities (Merriam-Webster 2003). Engineering productivity has received limited attention in design organizations (CII 2001). There has been little research into how engineering productivity can be quantitatively measured and analyzed. Design engineers are knowledge workers whose responsibility are predominantly concerned with generating or interpreting information, as contrasted with manual labor. The term "productivity" becomes difficult to understand in relation to design engineers.

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 project total cost estimating only. However, according to a survey conducted by CII (CII 2001), 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. 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 it can represent. Therefore, they have limited use for project scope management, such as progress measurement, schedule control, and cost control at the discipline level.

The majority of research in engineering productivity has been focused on performance evaluation and improvement studies. CII (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. These studies that focus on performance evaluation and improvement at the post-project stage do not explicitly and quantitatively measure engineering project scope and productivity.

CII developed a project scope definition tool, called the Project Definition Rating Index (PDRI), for industrial building projects (Gibson and Dumont 1996; Cho and Gibson 2001). PDRI is presented in a score format with a weighted checklist of scope definition elements. PDRI provides an individual or project team with a means to evaluate the completeness of a project scope definition using a single index for risk assessment during the pre-project planning stage. The index indicates the quality of project definition, but it is not suitable for productivity modeling. The lack of quantitative information is often cited as a serious deficiency (Thomas et al. 1999).

Many engineering companies base their productivity measurement systems on cost accounting systems that are similar in structure to those used by construction companies. Engineers report the time spent on a specific project according to a breakdown of predefined project activities or cost codes. These systems focus only on measuring the input or the work hours required to produce the contract documents. They do not measure another important dimension of productivity: the output. A survey conducted by 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 (Diekmann and Thrush 1986). Thomas et al. (1999) created a conceptual model for measuring the productivity of architecture design firms at the project level during the contract document phase. Differences among all design outputs, such as detail drawings, specifications, and other documents, are accounted for using conversion factors. However, the measurement accuracy is compromised due to the use of CAD tools and the lack of a standard definition of the content and the complexity of design documents.

White and Austin (1989) developed a productivity measurement model that uses weighted values to apply to work tasks. It is a workload-forecasting model developed for larger organizations. The factors that drive the workload are identified and weighted according to their relative importance. These factors are then combined into a productivity model. Project data are then collected to establish and validate the overall model. Unfortunately, the model is only applicable to large projects for predicting work hours and does not identify problems with various design disciplines.

The CII Engineering Productivity Measures Research Team (CII 2001) concluded that there was no standard measurement for productivity in the engineering phase for internal improvement and external benchmarking. The research team proposed a model focused on measurable, installed quantities to measure the design output, such as length of pipe and weight of steel designed. This method was applied to the discipline level in the detailed design phase of a project. The raw productivity, which is measured by installed quantities, is subjectively adjusted by three influencing factors: input quality, scope and complexity, and design effectiveness. The team also identified data collection as a major problem in implementing the measurement system. Unfortunately, the installed quantity can also be misleading due to the lack of correlation between the design complexity and the physical quantity. Thus, the evaluation of limited scope and complexity factors at the project level is less accurate for productivity modeling.

Construction Productivity Modeling

By comparison, construction productivity modeling has been better addressed and a number of quantitative modeling methods have been established. Most of them have their origins in such modeling techniques as statistical and regression modeling, expert systems, Artificial Neural Networks (ANN), and simulation.

Various statistical models, such as the delay model, the activity model, and the task model, have been borrowed from industrial engineering to model construction productivity. These models are limited by the number of influencing factors that can be included. Regression-based models, such as the additive linear regression model for masonry construction (Sander and Thomas 1993) and the factor model (Thomas and Sakarcan 1994), study the effects of factors on productivity using historical data. A key component in those models is the coefficient of each influencing factor. These coefficients are constants based upon the average values of historical data. Such coefficients were derived independently of other influencing factors without considering any combined effect. Moreover, they do not reflect the fact that these coefficients may vary with specific job conditions (Lu 2001).

An exemplary use of expert systems for productivity modeling is the system developed by Hendrickson et al. (1987) for masonry construction. The system first estimates a maximum productivity and then adjusts this baseline value using rules collected from domain experts. Due to the quantity of factors and complex nature of the relationship involved, rules obtained from domain experts are subjective and affected by personal prejudices and attitudes.

ANN and simulation are two other major techniques that have been used for the purpose of analyzing productivity. The following sections give an overview of these modeling techniques.

Artificial Neural Networks

An ANN model is a data processing system consisting of a large number of simple, highly interconnected processing elements in an architecture inspired by the structure of a biological nervous system (Swingler 1996). The processing elements and connection weights in a neural network demonstrate a distributed knowledge representation. Learning is achieved through a process of adjusting connection weights. In comparison to conventional computation techniques that employ complicated sets of equations to solve a complex problem, ANN uses very simple computational operations, such as addition, multiplication, and fundamental logic elements, to solve complex, mathematically ill-structured problems. Theoretically, an ANN model with a proper network structure is able to learn from examples and approximate any complicated functional relationship between dependent and independent variables (Bishop 1995). The task of finding a mapping function from the influencing factors to the productivity is similar to that performed by some of the ANN models and regression models (Sonmez and Rowings 1998). However, unlike regression models, ANN models require no predefined function form. ANN models also have good capability in tolerating moderate amounts of noise in the historical data, and generalizing knowledge from incomplete or noisy data (Swingler 1996).

Moselhi et al. (1991) argued that ANN models are more suitable for modeling construction industry problems requiring analogy-based solutions than either traditional decision analysis techniques or conventional expert systems. ANN has been used to model construction productivity, such as earth-moving equipment productivity (Karshenas and Feng 1992), excavation productivity (Chao and Skibniewski 1994), concrete construction productivity (Sonmez and Rowings 1998), the effect of environmental conditions on productivity (Wales and AbouRizk 1996), formwork production rates (Portas and AbouRizk 1997; AbouRizk et al. 2001), and pipe spool fabrication and installation productivity (Lu et al. 2000). The Probability Inference Neural Network (PINN) developed by Lu, AbouRizk, and Hermann (2000) was created and applied to predict labour production rates for industrial construction. PINN modeling uses a classification-prediction combined neural network model based on Kohonen's LVQ concept (Kohonen 1995), but integrated with a probabilistic approach. The PINN model predicts output as a probability density distribution instead of a point-prediction value. This gives the estimator a sense of uncertainty in the predicted result. The PINN model was proved to be effective in dealing with high dimensional input-output mapping with multiple influential factors.

Construction productivity is influenced by a variety of factors. The relationship between these factors and productivity cannot be given in a precise and explicit fashion. The effectiveness of ANN in modeling construction productivity was demonstrated by these applications and the comparison made to other productivity models. Therefore, ANN was studied and applied in this research for modeling steel drafting productivity and productivity of certain labour disciplines in steel fabrication.

Simulation

Computer simulation is the process of designing a mathematical-logical model of a real world system and experimenting with the model on a computer (Pristker et al. 1997). One type of simulation, discrete-event simulation (referred to as "simulation" hereafter) concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time (Law and Kelton 2000). Production systems in manufacturing and construction can be arbitrarily complex and difficult to understand due to the number of possible combinations of influencing factors and their effects on production performance. Other methods of analysis, such as scheduling network-based methods and analytic optimization-based methods, may not capture all of the intricacies of process interactions, interruptions, uncertainties, and other phenomena observed in the actual production system. A simulation model, which can be used to represent almost any level of system detail, provides a powerful tool in assisting multi-level decision-making. Simulation is proposed herein as the underlying technique to model the shop fabrication process and its productivity. There has been a wealth of simulation applications in both the manufacturing and construction industries. Due to the similarities between steel fabrication and manufacturing and construction, the literature on simulation applications for productivity modeling from both fields were reviewed.

Simulation has been widely applied to manufacturing systems for production planning and performance evaluation, as indicated in the annual proceedings of the Winter Simulation Conference. In the construction industry, simulation is a mature research area with many applications, such as those in productivity measurement, risk analysis, resource planning, design and analysis of construction methods, and site planning (Halpin and Riggs 1992).

A variety of modeling concepts and software tools have been developed to facilitate the application of simulation to model production systems. Modeling concepts, such as object-oriented modeling, hierarchical modeling, graphic modeling, modular modeling, library-based modeling, and their combinations have helped to simplify simulation modeling and extend its capability to model complex and large systems. Overviews of software for simulation are available in several publications (Law and Kelton 2000; Banks 1998; and AbouRizk et al. 1992). Hajjar and AbouRizk (2002) presented a comprehensive new approach, Unified Modeling Methodology, for construction simulation. The methodology combines several of the above state-of-the-art concepts as well as newly developed ones, such as integrated simulation and Special-Purpose Simulation (SPS). This methodology was used in the development of a complete simulation tool development and utilization environment called *Simphony*. *Simphony* allows users to develop highly flexible simulation tools with relatively less time and a lower cost.

The integration of simulation with other modeling techniques and engineering applications enable the modeling of a product's life cycle, from conceptual design, through predefining the production process, to the final production, in a computer without any physical application required. Examples of these technologies are CAD, 3D modeling, Computer-Aided Process Planning (CAPP), visualization, Artificial Intelligence (AI), and other external applications (Fishwick and Modjeski 1991; Banks 1998). In short, simulation has reached a technological level that provides companies with the flexibility and integration capability necessary to develop towards a fully digital simulation environment for productivity analysis.

PROBLEM STATEMENTS

This research was driven by the industry need to measure and analyze productivity for project planning, control, and performance improvement. In this regard, the current practice of productivity measurement and estimating in steel fabrication projects was reviewed by searching available literatures, interviewing with two steel fabricators including the collaborating company, and inquiring a number of users in an online steel drafting and fabrication community. This ensures that the review reflects the problems and challenges confronting the industry instead of a particular company. It also ensures that the methodology developed subsequently through this research is generic and may be applied to other fabrication companies. Both the problems and the challenges in measuring and analyzing productivity for steel fabrication projects are outlined below.

Data Collection

The fundamental theme underlying this thesis research is taking advantage of historical project data for the purpose of productivity modeling. The availability of accurate historical data of both the productivity-influencing factors as well as the corresponding productivity values are critical to the proposed approach for productivity modeling. Many advanced productivity modeling techniques, such as simulation and ANN, proposed in this research have not been effectively utilized by companies due to the lack of accurate, consistent, and comprehensive data from past projects. In many cases, data may simply be unavailable, or not consistent and not in an electronic format for meaningful analysis, due to the lack of an effective data collection solution to record productivity data. Some companies use a cost accounting system, or more sophisticated cost control system to produce productivity data. However, for financial control purposes, data are gathered at an aggregated level; for productivity measurement and control, data must also be tracked at a more detailed level. Most companies are reluctant to pay added overhead expenses for additional data collection efforts. Therefore, the data to be collected must be minimal and require no special support staff. There is also a great need for improved sharing and management of the large quantity of collected data and flexible information processing tools to assist with data analysis. In short, the industry needs a data acquisition solution that is cost effective, reliable, and flexible in meeting the needs of productivity analysis.

Steel Drafting Productivity

There is no standard measurement of work scope and productivity for steel drafting projects. Historically, the measurement of steel drafting work scope is defined as weight in tonnes or quantities of steel pieces or drawings. Draftspersons work on the conceptual model of the final product, which has little relevance to the physical weight of steel. Furthermore, steel pieces vary so much in configuration that a simple quantity count, when applied to measure drafting work scope, would be misleading as well. With the proliferated use of CAD tools, the measure of the physical design deliverables, such as design drawings and specifications, are also no longer appropriate. In the CAD environment, a product model is created and verified on a computer, and the model and any of its components can be selected and printed to any desired size of drawings on a plotter. This makes the measurement of the quantity of drawings or paper size irrelevant.

A good measure of the work scope or design output should have a high correlation to the input, which can be represented by man-hours. Historical data from 69 steel drafting projects were collected from the collaborating company. A correlation analysis of the engineering hours to measurement units, including weight, quantity of drawings, and quantity of pieces, was conducted. The results showed that the largest correlation coefficient is lower than 75%, which means that the measurement units are not adequately correlated to the engineering effort. Additionally, as projects get larger, they become more and more difficult, if not impossible, to compare in any orderly or consistent way (Armentrout 1986). As a consequence of the lack of appropriate work scope measurement, drafting productivity becomes difficult to measure and analyze.

Nonetheless, engineering firms must still use these measures to quantify the work scope and productivity for the purposes of project planning and control, despite the obvious drawbacks associated with them. The content and complexity of a design project is subjectively evaluated by project managers so that any bias caused by these measurement units can be accounted for. Various factors that affect engineering productivity make estimating work very challenging. Generally, the most accurate estimate for engineering hours is obtained by requesting an estimate quoted in range from an experienced engineer. Once a project commences, project managers use their experience to evaluate the project progress and performance. The knowledge source utilized in this project management process is personal judgment, which resides with an individual and is subject to prejudices. This implicit measurement of work scope and productivity without using a consistent quantitative measure adversely affects project planning, control, and performance evaluation.

The review of the current practice and available literatures has thus resulted in the following observations. First of all, engineering productivity has not drawn appropriate attention at a time when design tools and work processes are continuously changing. Second, there is no standard and effective measurement of the work scope or productivity for engineering projects for project planning, control, and productivity improvement. Finally, no research has quantitatively analyzed the relationship between engineering productivity and its influencing factors and, as a result, few contributions have been made to improve the accuracy of productivity estimating.

Steel Fabrication Productivity

The steel fabrication process is characterized by an extremely high product mix and is subject to a multitude of random external processes. This distinguishes the steel fabrication process from most manufacturing processes where identical products are produced *en masse*. The productivity of a steel fabrication operation, such as detailing, fitting, welding, or painting, is greatly affected by the physical complexity of the steel pieces and the characteristics of the working environment. Fabricated pieces are unique within a project and vary considerably from one project to another in terms of piece geometry, material properties, and specifications. The performance of an operation is also subject to significant fluctuations due to system dynamics, the existence of uncertainties, interruptions, and other external influencing factors in an industrial shop environment, such as queuing, labour skill, quality of supervision, shift arrangement, shop layout, equipment breakdown, and design changes. Due to its great variability, productivity manuals found in many companies serve only as guidelines for estimating. Extensive experience and knowledge about the fabrication process are required to produce an accurate estimate and production schedule. On the shop floor, shop superintendents measure productivity by visual inspection. The effectiveness of the current planning and control practices greatly depends on personal experience.

Work measurement and time study methods are widely used at the process level to determine productivity (Herzog 1985). Productivity is determined by relating the number of man-hours that should have been spent to the number of productive man-hours actually expended to produce the number of units. Although it provides a general guideline in measuring and improving production operations and individual tasks, it offers little to quantify productivity for project planning and control. First, due to the uniqueness of steel pieces, both standard processing time and unit of work are difficult to define without bias. Second, it does not quantify the productivity-influencing factors and their combined effects on the processing time. Third, time studies analyze individual production components (such as a machine or a crew) and provide only a local view of the productivity on the targeted operation. Productivity improvement in one operation does not guarantee an overall improvement of the production process. A coherent, systematic methodology for productivity measurement and analysis at the system level is required.

Simulation has many advantages over scheduling network-based techniques and analytic optimization-based techniques in modeling the complex steel fabrication process. Although generic simulation applications that have their origins in manufacturing are available, they do not address the unique requirements of the steel fabrication industry. When compared to manufacturing in general, steel fabrication has higher product mix, higher level of manual operations, and a higher degree of dependency on other processes in the supply chain (e.g., engineering and site erection). Moreover, though production engineers possess analytical skills, they are often lacking in either the knowledge or the time required to develop simulation models.

Due to the industry's growth and advances in fabrication technologies, production systems are becoming more complex and are increasingly characterized by high levels of integration and greater demands on performance. Measuring and analyzing productivity requires both a local view and a system-wide view of the production performance. Hence, the productivity modeling and analysis for complex production systems has always been a challenge for engineers and academic researchers.

RESEARCH OBJECTIVES

The primary goal of this thesis research is to develop a methodology to measure and analyze the productivity of steel fabrication projects. Productivity was studied at the process level for each labour discipline involved. To achieve this goal, three objectives are defined below.

Data Acquisition for Productivity Modeling

Identify the characteristics of productivity data in steel fabrication projects; develop a data acquisition system to facilitate the collection of comprehensive data for productivity modeling.

Modeling Steel Drafting Productivity

Develop an engineering productivity measurement system to measure quantitatively steel drafting project scope and productivity; identify productivity-influencing factors and define the relationship of these influencing factors to the steel drafting productivity.

Modeling Steel Fabrication Productivity

Develop a virtual shop modeling system to model steel products and the steel fabrication process; classify uncertainty in the industrial shop environment and model its effects on productivity; identify strategies to reduce uncertainty; develop an integrated virtual shop model that integrates with CAD systems, existing business information systems, and external planning applications for productivity analysis and production planning.

At a more practical and industrial level, the objectives are to standardize the measurement of project scope and productivity in steel fabrication projects, improve the collection and utilization of productivity data by standardizing its structure and enhancing its interpretation and analysis, and improve the accuracy of project planning.

METHODOLOGIES

To achieve the abovementioned objectives, an overall framework was proposed for collecting productivity data, measuring and modeling productivity for steel drafting and shop fabrication projects. Figure 1-1 shows the structure of the conceptual framework tilted "Virtual Production System for Productivity Modeling". It contains three main modules, which are component-based productivity measurement, virtual project repository, and productivity models.

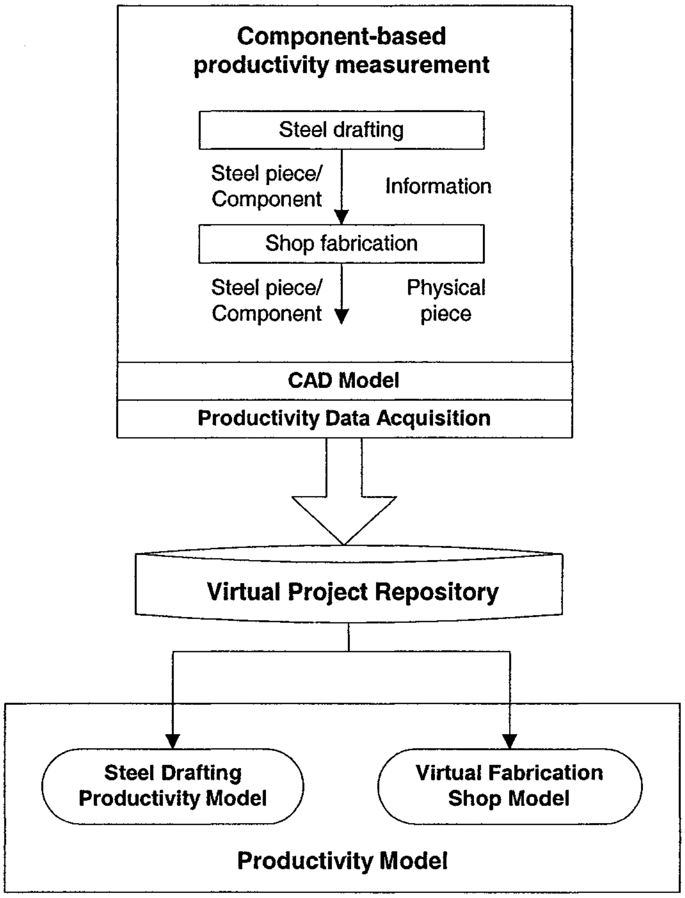

Figure 1-1. Virtual Production System for Productivity Modeling

The component-based productivity measurement module establishes an innovative way to measure the output and productivity of steel drafting and fabrication on the same basis. Traditionally, the outputs of the drafting process are viewed as drawings and specifications, while the outputs of the fabrication process are steel pieces. The different views of the output from these two processes make the productivity measurement and control completely different practices. From a production point of view, steel drafting and fabrication are close related production processes, although they are different production functions, which are engineering and construction respectively. It would be beneficial if the output were measured on the same basis, which will result in a more integrated project management practice in planning, control, and quality assurance (CII 2001). Draftspersons work on a piece-by-piece basis to detail a steel structure. They provide information required for steel fabricators to produce physical steel pieces. A steel piece has its physical existence, and it also carries design information. Naturally, the output of steel drafting and fabrication projects can be measured in terms of steel pieces. This method establishes a component-based approach in measuring the drafting and fabrication productivity. A component is defined herein as a basic unit of composition with a contractually specified context. In the steel fabrication domain, a component represents a physical steel piece of a steel structure, such as column, beam, bracing, and handrail. Computer-Aided Design (CAD) software tools have been widely used for steel drafting in many steel fabrication projects. CAD systems capture vast amounts of information about steel pieces, such as material type, dimension, and specification. This creates a unique opportunity to extract automatically steel pieces information for productivity measurement. Other productivity data, such as labor expenditure and work environment variables, can be recorded by applying various data collection techniques.

Data collected from CAD models along with the data acquisition system represents a digitized version of historical project performance. A collection of these past project records creates a Virtual Project Repository ready for further analysis.

To study the productivity performance, a model system is required to accurately reflect the performance characteristics of a production process. Although the outputs from drafting and fabrication can be measured in terms of steel pieces, their working procedures are quite different. This has resulted in applying different techniques in modeling drafting and fabrication productivity. The drafting process involves multiple stages of development, review, and revision. A productivity study at the detailed design activity level will not be accurate. Therefore, the drafting productivity is studied at the project level instead. A drafting productivity model was developed based on the virtual project repository. The fabrication process is a typical flow shop process with well-defined activities. This makes it ideal to study the shop productivity at the activity level using process modeling tools, such as the proposed simulation-based virtual shop model. Detailed methodologies used for developing the data acquisition system, drafting productivity measurement system, and virtual shop model are summarized below.

Data Acquisition System

During the data planning stage, the current and emerging data needs for productivity modeling and the current practices and techniques in data collection were reviewed. Identified data items were classified into categories according to their source, format, and structure. Various data collection technologies were evaluated for their opportunities and benefits in collecting a specific category of data. Based on the results of data planning, a number of data collection solutions were designed and implemented. A data warehouse system was implemented to store and organize collected data for further analysis.

Drafting Productivity Measurement System

Productivity can be modeled only when it is measurable. The thesis research presented herein first focused on developing a measurement unit to quantify drafting project scope in a CAD design environment. A new measurement unit of project scope, a "drafting unit", was introduced and validated using historical data for steel drafting projects. A computer program was developed to automate the quantification of project scope in drafting units, and drafting productivity in man-hours per drafting unit.

ANN was proposed to model the drafting productivity. Influencing factors that affect the drafting productivity were collected through a literature review and interviews with draftspersons and estimators. A survey was also conducted in an online steel fabrication community. A list of seventeen factors was identified from this study. The data collected from the data acquisition system was used to train and validate the ANN model.

Virtual Shop Modeling System

A simulation-based virtual shop model for productivity analysis of steel fabrication projects was developed. As a first step, a virtual shop modeling system was designed and implemented as a platform for building virtual shop models. A product model was designed to represent steel products in the virtual shop model. In order to build a generic simulation tool to model the steel fabrication process, various resources and activities involved in the production process were studied to extract their common behaviours. A special-purpose simulation modeling system for steel fabrication was then developed.

The second step involved a systematic study of uncertainty in an industrial shop environment through a process of classifying, modeling, and reducing uncertainty. Uncertainties involved in a production system were classified according to their origins and characteristics. This classification guided the endeavour in modeling and reducing uncertainty. ANN models were developed to model the cause-effect relationship between uncertainties and activity duration. Strategies for reducing uncertainty were identified by the sensitivity analysis of ANN models.

To create a virtual shop model for productivity analysis and production planning, a three-tier system architecture was designed. This involves the development of a framework that integrates the developed data acquisition system and other existing business information systems to automate the collection of simulation input data. It also involves the integration of the virtual shop model with external applications, which can present simulation experiment results in a manner that is of immediate relevance to the target users.

ACADEMIC CONTRIBUTIONS

The proposed research project will contribute to the following research areas:

- Quantifying engineering project scope in a CAD design environment and using historical data for project scope definition. This has been documented in a paper titled, "Quantifying engineering project scope for productivity modeling", and has been accepted for publication in the *Journal of Construction Engineering and Management*, ASCE;
- Estimating steel drafting productivity using ANN. This has been documented in a paper titled, "Measuring and estimating steel drafting productivity", and published in the proceedings of the ASCE Construction Research Congress in March, 2003;
- Developing an integrated simulation tool for modeling the steel fabrication process. This has been documented in a paper titled, "Building a virtual shop model for steel fabrication", which is published in the proceedings of the Winter Simulation Conference in December, 2003. An extended version of the simulation tool for modeling industrial fabrication projects has been documented in a paper titled, "A

virtual shop modeling system for industrial fabrication shops", which has been submitted for publication in the *Journal of Simulation Modeling and Practice*;

- Modeling uncertainty in construction projects. This has been documented in a paper titled, "Modeling uncertainty with an integrated simulation system", and has been submitted for publication in the *Canadian Journal of Civil Engineering*, CSCE;
- Establishing a virtual shop model system and applying the experimental method for productivity analysis and production planning. This has been documented in a paper titled, "Virtual shop model for experimental planning of steel fabrication shops", and has been submitted for publication in the *Journal of Computing in Civil Engineering*, ASCE.

INDUSTRIAL CONTRIBUTIONS

The data acquisition system implemented in the collaborating company has helped to reduce the cost of data collection and improve the quality of data for productivity modeling. The drafting productivity measurement system formalizes the measurement of steel drafting project scope and productivity. The virtual shop model system provides a powerful tool for analyzing production performance and assisting production planning. It also creates a great potential to improve the accuracy of project planning, control, and productivity improvement.

CONCLUSIONS

The thesis research addressed the fundamental problem regarding how productivity can be measured and analyzed in steel fabrication projects. The research on process-level productivity also has potential benefits to improve the current project planning and control practices. It has laid a solid foundation for future endeavours in building a production-oriented project planning and control system for the steel fabrication industry. The problems addressed in this research regarding productivity modeling are common to the fabrication industry. The productivity modeling methodology presented herein has been successfully applied to steel fabrication projects for the collaborating company. Its fundamental approach will be applied to other fabrication companies to further verify its applicability.

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CHAPTER 2: DATA ACQUISITION SYSTEM FOR PRODUCTIVITY MODELING

INTRODUCTION

Information plays a key role in construction project management. One of the primary roles of a company is to process and communicate information. In order to successfully plan and subsequently control the construction process, the company must collect, process, and interpret vast amounts of information. A contractor's financial failure can be traced to data collection or data processing functions more often than marketing or production causes (Adrian 1985). Productivity-related data, among other types of project data, are the most essential resources for project management. Project control relies on accurate and timely information to measure progress and expenditures and determine appropriate actions to ensure the project is on schedule and within budget. Historical data collected from past projects also contain valuable productivity information for estimating and scheduling future projects.

The fundamental theme underlying this thesis research is taking advantage of historical project data for the purpose of productivity modeling. Productivity models in the form of simple equations, non-linear equations, or advanced forms such as ANN can be defined and calibrated by analyzing a company's historical project data. Once established, they can be used for a variety of purposes, such as forecasting and sensitivity analysis. To achieve these objectives, sufficient and comprehensive historical data from past projects regarding the work quantities, expenditures, and various factors affecting productivity must be available. This chapter describes the development of a data acquisition system for steel fabrication projects. The system was used to collect historical data for modeling steel drafting productivity, which is described in Chapter 3, and modeling the steel fabrication process, which is described in Chapters 4, 5, and 6.

BACKGROUND

Data collection practices vary among companies with different organization structure and project management practices. Data are collected using various techniques and for different purposes (Dozzi and AbouRizk 1993). Some companies do not have a formal process for tracking and collecting actual project progress and expenditures, which means historical data are simply not available for productivity analysis. In other cases, the data collection process may be archaic and varies across projects. This means that the data are not available in a form that is suitable or feasible for meaningful analysis.

Many companies keep project data in their accounting systems. For some large contractors, productivity measurement and project control may have been accomplished as part of large and sophisticated cost control systems (CII 1989). These financial systems account for all project costs. Historical data from these systems can partially fill the data needs for productivity modeling, but this is not sufficient. First, data from these systems are typically collected at a certain aggregated work-package level, such as a project or division, and do not support productivity analysis lower than that level. However, construction is a process-based industry (Halpin 1992). Although productivity can be studied at an aggregated level, it normally serves as a benchmark for measuring general project performance and offers no insight into the productivity of the production process. This can be observed in the current practice of detailed estimating for steel fabrication projects. Although statistics on steel fabrication productivity in terms of man-hours per tonne of steel are available, estimators seldom use these numbers to estimate future projects. Instead, estimators perform detailed quantity takeoff and work on a piece-by-piece basis to estimate labour hours for each fabrication process, with considerations for the piece complexity and working conditions. These labour hours calculated at the process level are then summated to get a base amount of project hours. The base project hours may be adjusted to account for special project conditions. Therefore, data collected from a financial control system at the work-package level must be combined with detailed productivity data at the process level for meaningful productivity analysis to occur. Second, these systems record only the project inputs and outputs, but not influencing factors that affect the project's performance. This means that the data are not sufficient to obtain the relationship between influencing factors and the resultant productivity. In short, many advanced productivity modeling techniques, such as ANN and simulation, have not been effectively utilized by companies due to the lack of accurate, consistent, and comprehensive productivity data from past projects.

A couple of facts contribute to the problem of data collection for productivity modeling. First, is the amount of information. Productivity modeling is an information intensive process, which requires adequate and complete information from historical projects. The large amount of data produced during construction projects eventually turns out to be difficult to collect and process, and in some cases, can be unmanageable. Second is the cost of data collection. A survey revealed that the two field functions that require the most paperwork time are employee timekeeping and material management functions (McCullouch and Gunn 1993). Timekeeping functions require anywhere from 10–15% of a field supervisor's time and material management functions require 26–37%. Most companies are not tolerant to the added expense incurred by data collection activities for productivity modeling.

The objective of this research is to study the nature of productivity data and develop a data acquisition system for steel fabrication projects to collect comprehensive productivity data. Although certain data collection solutions in this research were developed for both project control and productivity modeling, the primary purpose of this system is for productivity modeling. In this research, productivity is measured by man-hours per unit of work. Therefore, the data acquisition system focuses on the collection of project expenditures measured by labour hours instead of cost. This system has been implemented at the collaborating company.

DATA ACQUISITION STRATEGY

The development of a data acquisition system requires an examination of the data needs and the evaluation and selection of feasible data collection techniques. It should be noted that the development of a data acquisition system is an ongoing process. It is driven by new data needs and innovations in data collection technologies.

Data Planning

The first step in developing the data acquisition system involves identifying the current and emerging data items that are required as well as their characteristics. The data required for productivity modeling can be classified into three groups, which are input, output, and productivity-influencing factors. As previously mentioned, in this research, productivity is measured by man-hours per unit of work. Therefore, data items to be collected for the input group are labour hours. The output is measured by the quantity of work. The data required to populate the productivity-influencing factor group are specific to a particular production process. Different production processes have different sets of influencing factors. Productivity-influencing factors for each production process can be identified by domain experts, such as supervisors and senior operators. These data groups will be collected at two levels of detail: the work-package level and the detailed individual component level. Figure 2-1 shows a typical project Work Breakdown Structure (WBS) used to decompose a steel fabrication project into divisions and individual pieces. Productivity can be measured at a work-package level, such as the project level or the division level, or it can be measured at the piece level. According to these data classifications, Table 2-1 shows the six categories of productivity data within the scope of the data collection for steel fabrication projects.

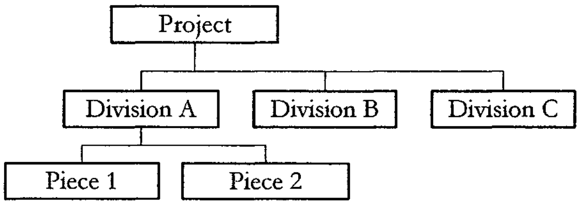


Figure 2-1. Typical Work Breakdown Structure

Table 2-1. Data Classification and Collection Methods

	Input	Output	Influencing factors
	Labour hours	**Quantity**	**Process-specific factors**
Work package level	Computerized timesheet	CAD-based quantity surveying	Online questionnaires
Piece level	Time studies	CAD-based quantity surveying	Time studies

Evaluation of Techniques

The second stage involves an assessment of the opportunities and benefits of using various data collection techniques to collect data in each of the six identified categories. Cost effectiveness, reliability, and user friendliness are the top criteria for evaluating a data collection solution. They ensure that a data acquisition system is practical to use and will experience the lowest possible resistance from users.

Data collection techniques identified for each data category are shown in Table 2-1, including computerized timesheet systems, online questionnaires, CAD-based quantity surveying, and time studies. Computerized data collection methods are very efficient for collecting data at the work package level on a continuous basis, while time studies can be conducted occasionally to collect detail level data. Questionnaires are useful for collecting undocumented data and data that need subjective evaluation. The design and implementation of those data collection techniques are described in the following sections.

SYSTEM STRUCTURE

One of the major issues in data collection is the data management. Data collected for the six identified categories must be integrated in order to represent the whole picture of the productivity issue. An ideal data management solution must also enforce data collection policies company-wide and ensure that all data are validated and maintained consistently. This suggests the use of Relational Database Management System (RDBMS) for data management. A database system was developed using Microsoft SQL Server to manage the collected productivity data and controls its access and integrity (Hajjar et al. 1999). The database consists of tables, queries, and procedures for the manipulation of the six identified data categories. Once the database system was designed and developed, the data acquisition system was implemented.

The data acquisition system for the collaborating company was developed within the overall framework of its information infrastructure. A project information system containing project information and product data was already developed using Microsoft Access and is currently in use at the collaborating company. This has resulted in productivity data spanning across two different database systems: SQL Server and Microsoft Access. This causes many difficulties in querying the data for productivity analysis. A solution to this problem is data warehousing. Data warehousing is an approach to storing data in which heterogeneous data sources are migrated to a separate homogenous data store for data analysis (Chen 2000). For this research, a data warehouse was developed as a central repository for productivity data. Raw data from both database systems were validated, consolidated, and re-organized into useful information to facilitate further analysis.

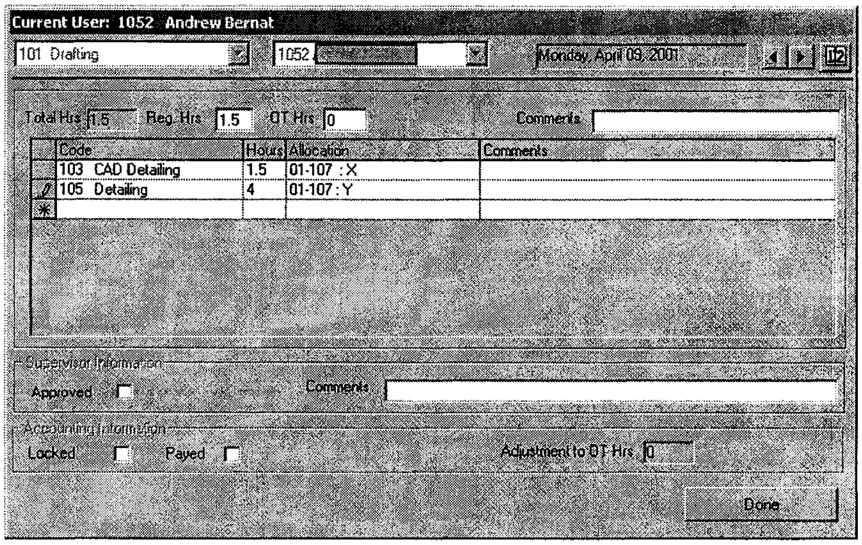
SYSTEM IMPLEMENTATION

The developed data acquisition system is made up of several components, including computerized timesheet systems, a CAD-based quantity survey system, online questionnaires, and time studies.

Computerized Timesheet Systems

The computerized timesheet system focuses on collecting labour hours at the work package level. Employees in a steel fabrication company are classified into two categories: office employees and shop employees. The previous timekeeping system involved manual timesheet recording and processing. Project managers requiring labour expenditure reports typically requested a job report from accounting. This caused a number of problems, which were mainly due to the manual process involved, such as errors in calculation, problems reading the handwriting, etc. Further, the delay between when the work was performed and when the data were entered into accounting systems rendered any short-term monitoring unfeasible. Two timesheet systems, an Office Timesheet System (OTS) and a Shop Labour Tracking System (SLTS) were designed and developed for office employees and shop employees accordingly (Hajjar et al. 1999; Song and AbouRizk 2001).

Most office employees have their own personal computers. OTS is a computerized timesheet system for office employees to enter daily timesheet information and allocate hours to a specific cost code and work package, as shown in Figure 2-2. Supervisors use this program to validate and approve the timesheets for employees in their department. Accountants use this program to perform certain adjustments, spread overtime hours across projects, and generate the appropriate reports for payroll or job costing purposes. Currently, all office employees of the collaborating company are using this system for time reporting.



Current User: 1052 Andrew Bernat

101 Drafting

1052

Monday, April 09, 2001

Total Hrs 1.5

Reg. Hrs 1.5

OT Hrs 0

Comments

Code	Hours	Allocation	Comments
103 CAD Detailing	1.5	01-107 : X	
105 Detailing	4	01-107 : Y	

Supervisor Information

Approved ☐

Comments

Accounting Information

Locked ☐

Payed ☐

Adjustment to OT Hrs 0

Figure 2-2. Office Timesheet System

The previous process for shop labour tracking was based on an electronic time clock and timecard process where information was entered and processed manually by the accounting department. Various techniques in timekeeping were reviewed for potential use, including electronic time clock systems, computerized time recorder systems, and PC-Based time recorder systems. It was concluded that no single system could support all of the needs for collecting labour hours in the fabrication shop, such as allocation of hours to a variety of detail levels, enforcing shift policies, and efficient attendance record processing. As a result, a computer-based time management solution, as shown in Figure 2-3, was developed to record shop labour hours. Shop employees check in and out through time terminals, which identify employees by their identification barcode and record the time. In addition to checking in and out at time terminals, employees also allocate their hours to jobs or divisions on a specially formatted timesheet on a daily basis. The completed timesheets are then electronically scanned and interpreted using optical mark recognition and optical barcode recognition techniques. This automated timesheet processing module extracts employee information and their hourly allocations. This module requires minimal operator involvement, generally only needing assistance in cases of incorrectly completed timesheets. The extracted data are then imported into the central database where it is combined with the check in and out records. These attendance records are validated using the validation program. Timesheets are also electronically archived on CD-ROMs for future reference. SLTS has been completed and implemented at the collaborating company. Approximately 250 shop employees of the collaborating company are using this computer-based time management system.

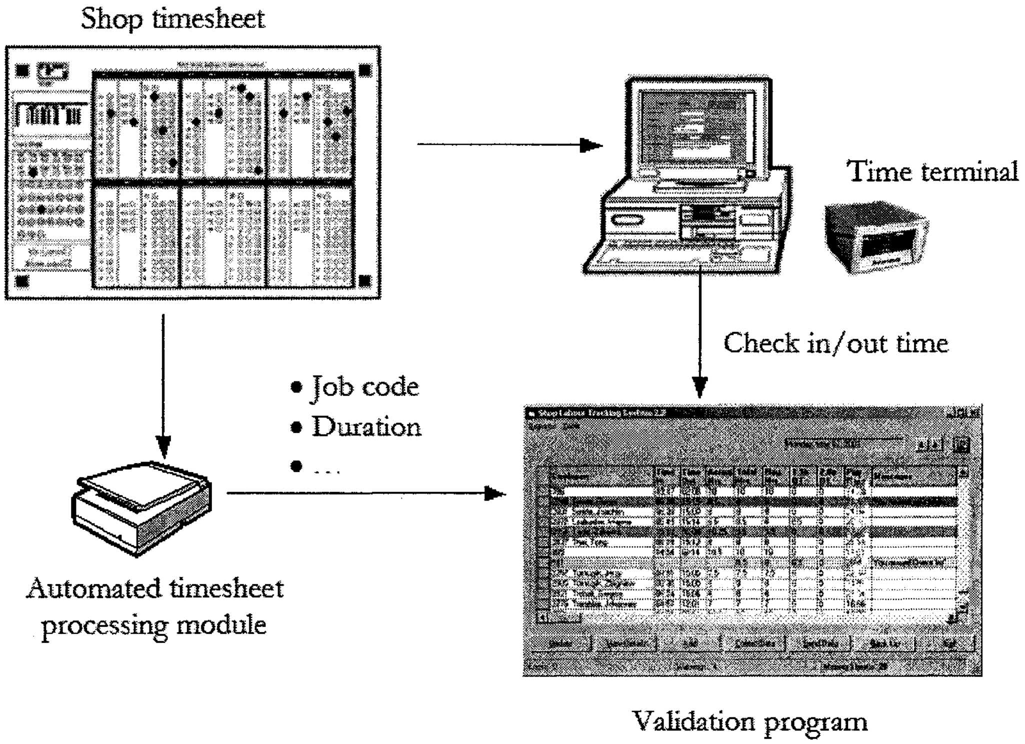


Figure 2-3. Shop Labour Tracking System

CAD-based Quantity Surveying

Measuring output, or work scope, is analogous to quantity survey. A unit must be defined to measure the quantity of work performed. The measurement unit should be directly related to the time and effort spent on an operation and easily quantifiable. In a construction project, the output from an activity is normally defined by the quantities of construction items that can be easily measured, such as the volume of earth hauled, concrete poured, or the length of pipe installed. In steel fabrication, units that may be used to measure the output are the weight, quantity of steel pieces, or quantity of drawings. However, none of these reflect the complexity of steel pieces, which directly affects the amount of labour hours required for a specific operation, such as detailing, fitting, welding, and painting. Although productivity measured by man hours per unit weight of steel has been used to measure shop productivity in the past, it serves only as a benchmark. Steel pieces are unique within a project and vary considerably from one project to the next. Each piece represents a different degree of complexity for each fabrication operation and will generally require a different amount of labour resources. This amount depends on many factors, including the physical attributes of the piece, the number of steel components making up the overall piece, and processing specifications. Therefore, these factors should be recorded for further analysis. However, it is inefficient, if not impossible, to collect this information manually. Currently, a variety of CAD software tools are used for engineering design in almost all steel fabrication projects. CAD systems capture vast amounts of product definition data in an electronic format. This creates a unique opportunity to automate the quantity survey process. Most commercial CAD systems have the capability to interface with other software systems; exporting design data in a plain text format is a minimum requirement. A data exchange interface can then be implemented to extract the design data from a CAD model and transfer the data to the central database. This quantity survey method has been used for measuring steel drafting project scope and modeling steel products, which are described in Chapters 3 and 4 respectively.

A major issue with this data exchange is the data structure. Ideally, any developed product model, which defines the structure of product data, should be based on an industry standard (Froese 2003). This would allow the data exchange to be developed independently and applied in a variety of data acquisition environments. AP230 (ISO 2003), which is currently under development, is an application protocol for the representation and exchange of information relating to structural steel frames. The product model underlying AP230 is based closely on the product model underlying another standard, CIMsteel Integration

Standards (CIS) (CIMsteel 2003). However, these standards have not yet been adopted at a large scale and their proliferation in the industry is hindered by many organizational, cultural, and technological barriers. At the time this research was conducted, the CIS data exchange protocol for shop fabrication was not yet released. Therefore, a product model was designed for this specific research to capture steel component properties, processing specifications, and WBS information. Figure 2-4 demonstrates the structure of this product model. Material attributes include material type, component weight, surface area, and length. Processing specifications for a steel comment include parameters for holes, copes, blocks, marks and welding and painting specifications. WBS information includes a steel component's identifier, its division identifier, and its project identifier.

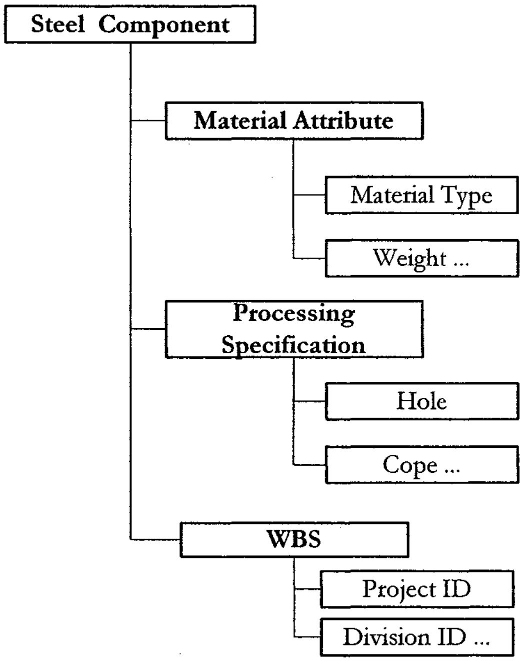
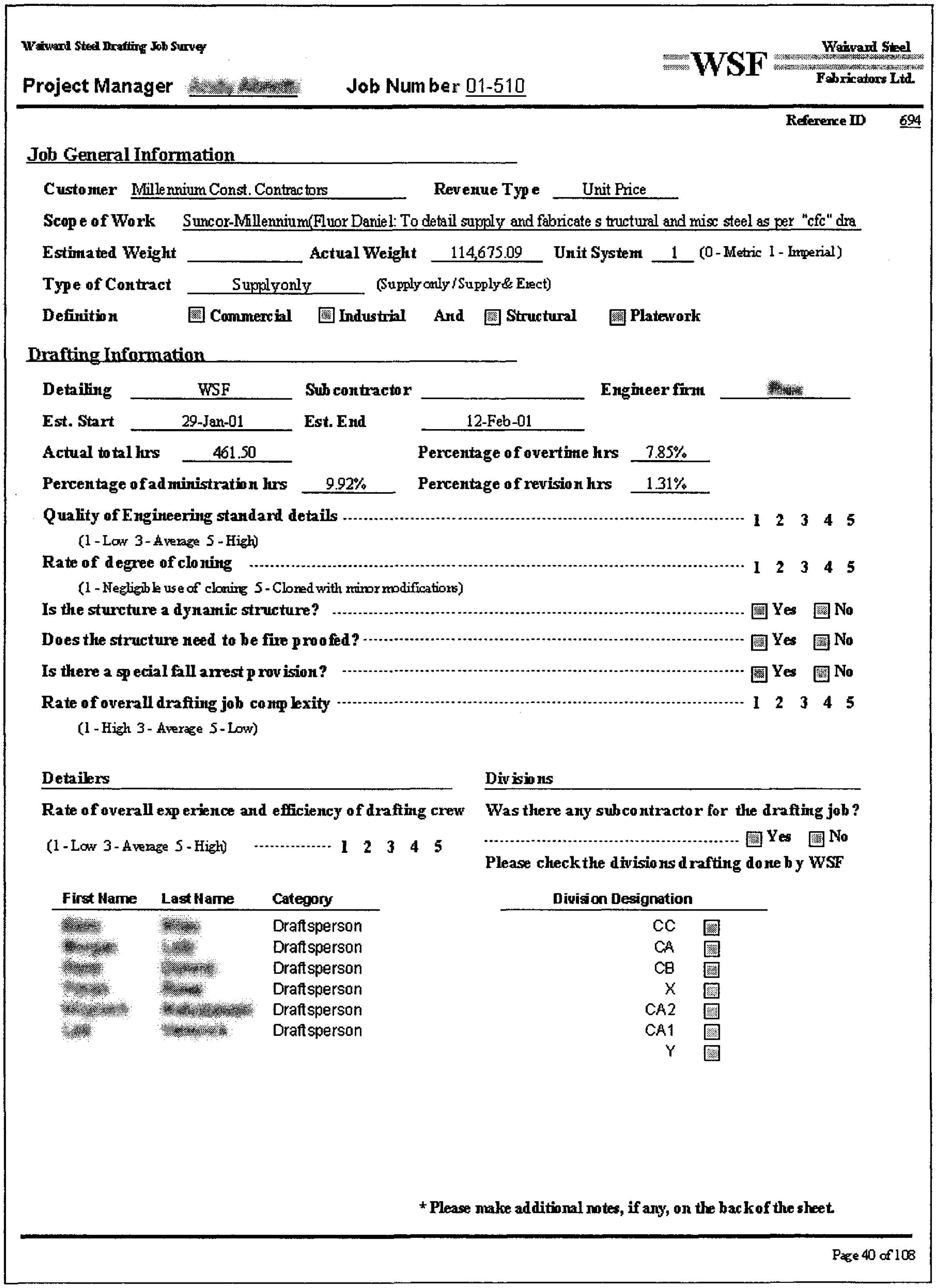


Figure 2-4. Product Model Structure

The collaborating company uses specialized CAD drafting software, StruCAD, for its steel drafting work. StruCAD is capable of generating two types of files. A material report contains material properties of steel pieces. A Computer Numeric Control (CNC) data file contains processing specifications for a steel component. WBS information is recorded by draftspersons in CAD. A computer program was developed to interpret these files and transfer data to the central database. This product data describe the outputs of steel fabrication projects in terms of both physical quantity and complexity.

Online Questionnaires

Incomplete historical data is a common problem for productivity modeling. Some quantitative data and most qualitative data about project conditions may not be recorded for historical projects. Questionnaires are a useful and relatively formal and organized strategy to collect this undocumented data. For example, in this research, questionnaires were designed and used to collect information about past projects for modeling steel drafting productivity. Questionnaires were generated from the company's data warehouse system. The questionnaires inquire information on productivity-influencing factors of past projects from project managers. The identification of these influencing factors is described in the section titled "Modeling drafting productivity using ANN" in Chapter 3. Figure 2-5 shows the questionnaire designed to gain additional information on a steel drafting project regarding productivity influencing factors, such as the complexity of the project and draftsperson qualification. To assist project managers in recalling a past project, project information that is available in the company's existing project information system was also compiled and presented in the questionnaires. Six project managers from the collaborating company were involved in the survey. This survey resulted in a total of 113 projects within the previous three years being studied. A problem with factors that are subjectively evaluated, such as the project overall complexity and draftsperson qualification, is any bias that may be caused by personal opinion. Therefore, the completed questionnaires by the project estimators were cross-validated by a senior project manager to ensure the consistency of evaluation. Adjustments to a specific project were made with the agreement of its project manager. Based on the success of the paper-based questionnaires, an online questionnaire program was developed. Post-project performance evaluations in terms of cost, schedule, and quality were also incorporated in this program. At the end of a project, the project manager fills out this online questionnaire while project information can be accurately recalled. The collected data are then stored in the database system and can be used for productivity modeling and project performance evaluation. By implementing this program, the procedure for the collection of project information was formally incorporated into the company's standard data collection procedure.



Waiward Steel Drafting Job Survey

WSF Waiward Steel Fabricators Ltd.

Project Manager [redacted] **Job Number** 01-510

Reference ID 694

Job General Information

Customer Millennium Const. Contractors **Revenue Type** Unit Price

Scope of Work Suncor-Millennium(Fluor Daniel: To detail supply and fabricate structural and misc steel as per "cfc" dra

Estimated Weight ____ **Actual Weight** 114,675.09 **Unit System** 1 (0 - Metric 1 - Imperial)

Type of Contract Supply only (Supply only / Supply & Erect)

Definition ☐ Commercial ☐ Industrial And ☐ Structural ☐ Platework

Drafting Information

Detailing WSF **Subcontractor** ____ **Engineer firm** [redacted]

Est. Start 29-Jan-01 **Est. End** 12-Feb-01

Actual total hrs 461.50 **Percentage of overtime hrs** 7.85%

Percentage of administration hrs 9.92% **Percentage of revision hrs** 1.31%

Quality of Engineering standard details 1 2 3 4 5
(1 - Low 3 - Average 5 - High)

Rate of degree of cloning 1 2 3 4 5
(1 - Negligible use of cloning 5 - Cloned with minor modifications)

Is the sturcture a dynamic structure? .... ☐ Yes ☐ No

Does the structure need to be fire proofed? .... ☐ Yes ☐ No

Is there a special fall arrest provision? .... ☐ Yes ☐ No

Rate of overall drafting job complexity 1 2 3 4 5
(1 - High 3 - Average 5 - Low)

Detailers

Rate of overall experience and efficiency of drafting crew
(1 - Low 3 - Average 5 - High) 1 2 3 4 5

First Name	Last Name	Category
[redacted]	[redacted]	Draftsperson
[redacted]	[redacted]	Draftsperson
[redacted]	[redacted]	Draftsperson
[redacted]	[redacted]	Draftsperson
[redacted]	[redacted]	Draftsperson
[redacted]	[redacted]	Draftsperson

Divisions

Was there any subcontractor for the drafting job? .... ☐ Yes ☐ No

Please check the divisions drafting done by WSF

Division Designation	
CC	☐
CA	☐
CB	☐
X	☐
CA2	☐
CA1	☐
Y	☐

*** Please make additional notes, if any, on the back of the sheet.**

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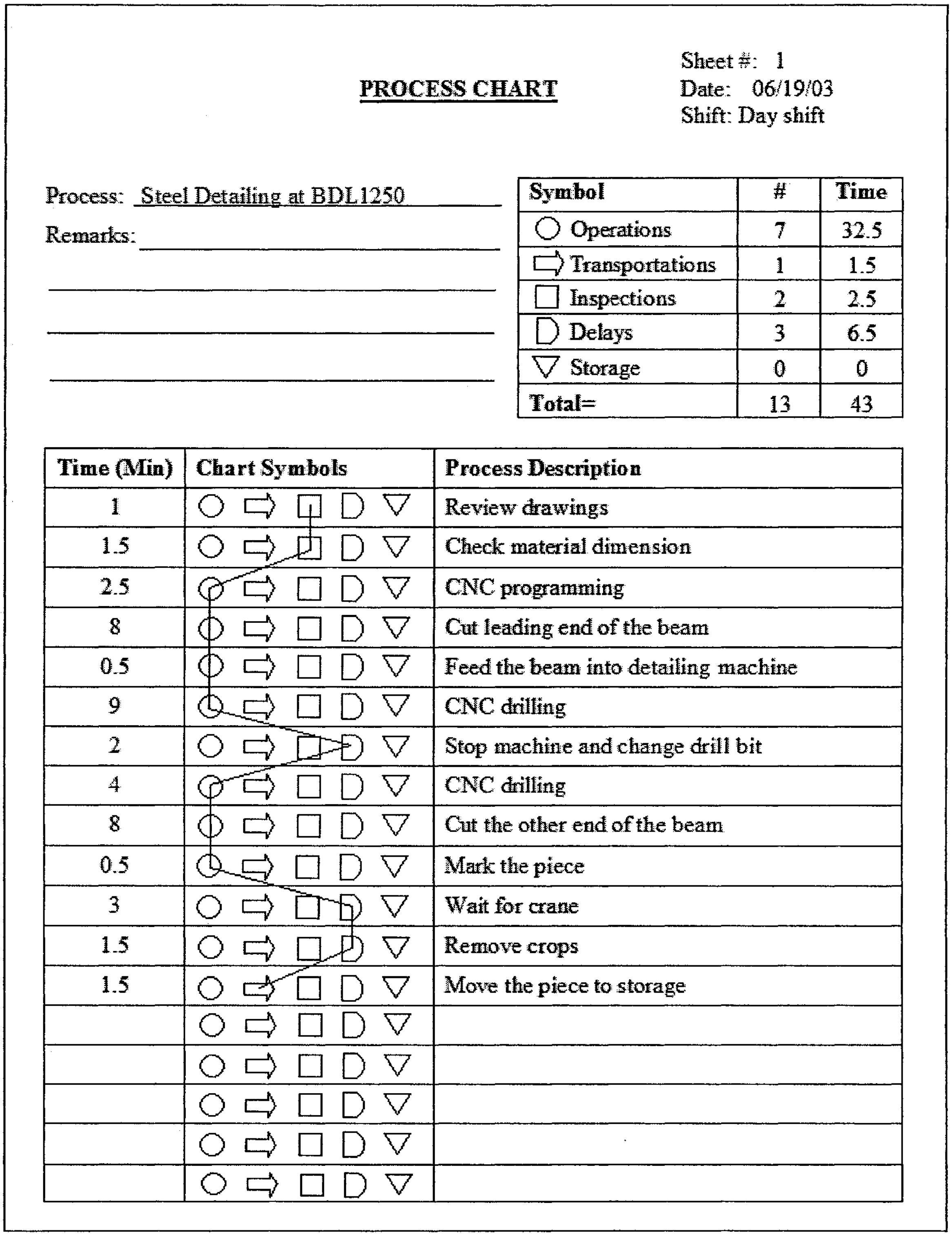
Figure 2-5. A Sample Questionnaire for Steel Drafting Projects

Time Studies

The developed shop labour tracking system proved to be effective in meeting the requirements for project control and accounting. However, the system was designed to collect data at a certain work-package level in the WBS, such as the project level or the division level. It is not feasible to collect labour hours and its influencing factors at the individual piece level using this system. The summary level data is not sufficient for accurate productivity analysis at the component level.

Time studies are indispensable methods of collecting production activity data. Essentially, they record the incremental times of the various steps or tasks that make up an operation (Oglesby et al. 1989). An initial time study was conducted with the objective of defining detailed activities within each fabrication operation and establishing gross elements to be timed. Figure 2-6 shows a sample of the process chart used and data collected from this study. It shows the detailed activities and their durations recorded at a working station. It was found that the majority of activities involved in steel fabrication are repetitive and have medium to long cycle times. Time studies for these activities are prohibitively expensive due to the significantly long activity processing time. Therefore, the initial study only recorded activities that are highly repetitive and have short cycle times, such as equipment setup, grinding, and material handling. To increase the efficiency in recording activities that have medium or long cycle times, shop operators were involved in the time study. Data requirements were stamped on each fabrication drawing to help operators record the information. Figure 2-7 shows the stamp designed for the steel fitting operation to collect data such as fitter's skill rank, processing time for the drawings, and lost time due to interruptions or rework. Operators were trained before the time study to ensure they understood the scope and purpose of the study, and recorded data consistently. The collected data were verified by the foremen. When data were manually recorded in the central database, they were related to the product data records where physical attributes of steel pieces are stored. This time study was conducted for three months and the collected data were used to analyze steel fitting productivity and develop the productivity model, which is described in detail in the section titled "ANN modeling for the steel fitting operation" in Chapter 5.

Unlike the ongoing data collection required by project control, time studies are normally conducted for a period of time to meet the need of productivity analysis. Over time, data can be collected using the same procedure to reflect the most recent level of performance.



PROCESS CHART

Sheet #: 1
Date: 06/19/03
Shift: Day shift

Process: Steel Detailing at BDL1250

Remarks:

Symbol	#	Time
○ Operations	7	32.5
⇨ Transportations	1	1.5
□ Inspections	2	2.5
D Delays	3	6.5
▽ Storage	0	0
Total=	13	43

Time (Min)	Chart Symbols	Process Description
1	○ ⇨ [✓ □] D ▽	Review drawings
1.5	○ ⇨ [✓ □] D ▽	Check material dimension
2.5	[✓ ○] ⇨ □ D ▽	CNC programming
8	[✓ ○] ⇨ □ D ▽	Cut leading end of the beam
0.5	[✓ ○] ⇨ □ D ▽	Feed the beam into detailing machine
9	[✓ ○] ⇨ □ D ▽	CNC drilling
2	○ ⇨ □ [✓ D] ▽	Stop machine and change drill bit
4	[✓ ○] ⇨ □ D ▽	CNC drilling
8	[✓ ○] ⇨ □ D ▽	Cut the other end of the beam
0.5	[✓ ○] ⇨ □ D ▽	Mark the piece
3	○ ⇨ □ [✓ D] ▽	Wait for crane
1.5	○ ⇨ □ [✓ D] ▽	Remove crops
1.5	○ [✓ ⇨] □ D ▽	Move the piece to storage
	○ ⇨ □ D ▽	
	○ ⇨ □ D ▽	
	○ ⇨ □ D ▽	
	○ ⇨ □ D ▽	
	○ ⇨ □ D ▽	

Figure 2-6. Process Chart

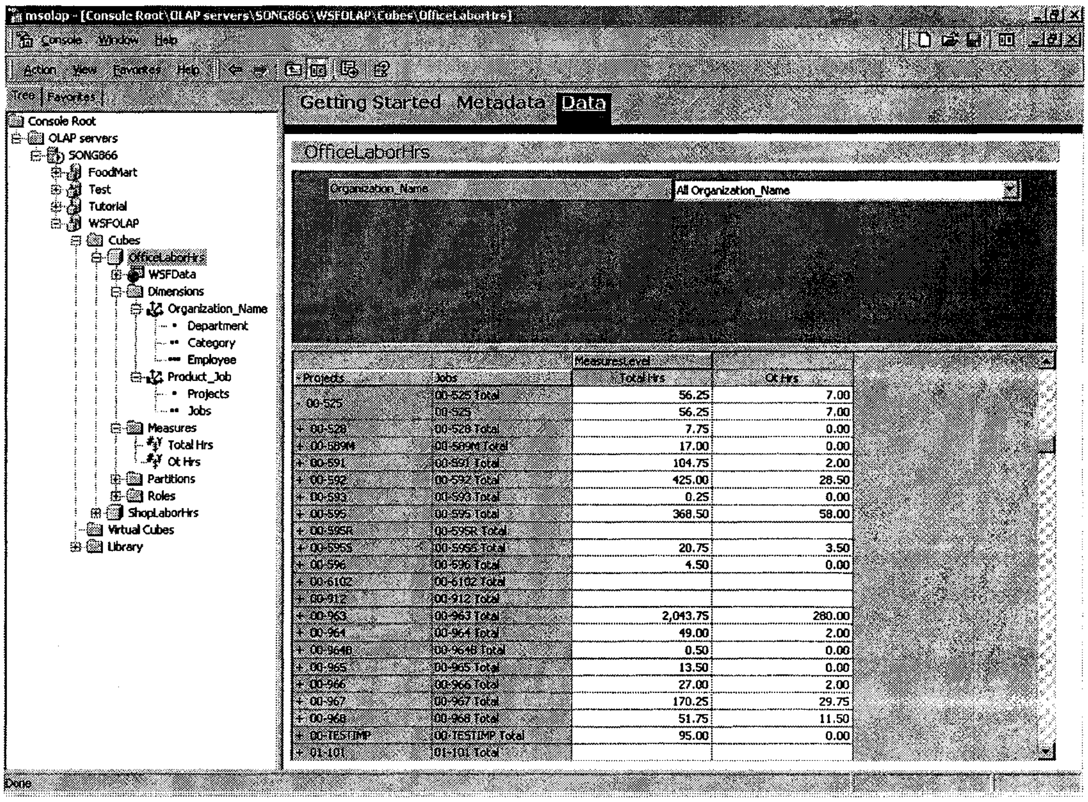
Fitter Rank	1	2	3
Lost Duration			
Mistake Correction Duration			
	Date	Time	
Start	/ / 2003	:	am pm
End	/ / 2003	:	am pm

Figure 2-7. Data Collection Stamp

DATA ANALYSIS WITH ON-LINE ANALYTICAL PROCESSING

The implemented data acquisition system collects a huge amount of data that are measured at a magnitude of gigabytes. Although predefined query reports in a data warehouse system can be used for analysis, they are slow and rigid in presenting information from only a specific perspective. Productivity data analysis requires a wide variety of views of the data set, such as company organization levels, work breakdown structure levels, productivity-influencing factors, and their combinations. This explorative data analysis involves complex ad-hoc user queries. This causes difficulties and inefficiencies in interpreting historical data for productivity analysis.

On-Line Analytical Processing (OLAP) uses a multidimensional view of aggregate data to provide quick access to strategic information for further analysis of data stored in a data warehouse (Chen 2000). In this research, productivity data in the data warehouse were reorganized and stored in a Microsoft SQL OLAP server. It allows a project manager to analyze interactively labour hours by selecting different views and rolling-up or drilling down into the data set from a variety of perspectives without any support from database specialists. Figure 2-8 shows an example of multidimensional views of labour hours for office employees. A project manager can access the "OfficeLaborHrs" item from the tree view at the left panel. Office employees' time allocation can be summarized by department, employee category, individual employee, WBS, or standard/overtime hours.



Organization_Name: All Organization_Name

		MeasuresLevel	
- Projects	Jobs	Total Hrs	Ot Hrs
- 00-525	00-525 Total	56.25	7.00
	00-525	56.25	7.00
+ 00-528	00-528 Total	7.75	0.00
+ 00-589M	00-589M Total	17.00	0.00
+ 00-591	00-591 Total	104.75	2.00
+ 00-592	00-592 Total	425.00	28.50
+ 00-593	00-593 Total	0.25	0.00
+ 00-595	00-595 Total	368.50	58.00
+ 00-595R	00-595R Total		
+ 00-595S	00-595S Total	20.75	3.50
+ 00-596	00-596 Total	4.50	0.00
+ 00-6102	00-6102 Total		
+ 00-912	00-912 Total		
+ 00-963	00-963 Total	2,043.75	280.00
+ 00-964	00-964 Total	49.00	2.00
+ 00-964B	00-964B Total	0.50	0.00
+ 00-965	00-965 Total	13.50	0.00
+ 00-966	00-966 Total	27.00	2.00
+ 00-967	00-967 Total	170.25	29.75
+ 00-968	00-968 Total	51.75	11.50
+ 00-TESTIMP	00-TESTIMP Total	95.00	0.00
+ 01-101	01-101 Total		

Figure 2-8. Data Analysis with OLAP

CONCLUSIONS

Historical data records a company's past performance and contains predictive information that is important for the company's future projects. The collection of historical data requires good planning for current and emerging data needs and formal and efficient data collection procedures. This research shows that the selection of data collection technique is determined by the characteristics of the data in terms of its source, structure, quantity, and significance. Characteristics of a good data acquisition system are cost efficiency, reliability, and flexibility in meeting current and future data needs.

A comprehensive data acquisition solution, including computerized timesheet systems, CAD-based quantity surveying, questionnaire surveys, and time studies, was implemented to collect labour expenditure data, product definition data, activity duration, and project information. A data warehouse system and an OLAP server were developed to facilitate the organization and retrieval of data and data analysis. The project results in improvements being made to timekeeping and document management. It also resulted in a high quality data set for productivity analysis. This makes the company well-positioned to discover the strategic value of its data assets and further capitalize on its investment in the data acquisition system. Historical data collected from the data acquisition system has been used for modeling the productivity of steel drafting and shop fabrication. The data required for ANN modeling of steel drafting productivity, which is discussed in Chapter 3, were primarily collected from the CAD-based quantity surveying, OTS, and the online questionnaires. The SLTS, CAD-based quantity surveying and time studies have helped in modeling shop labour productivity and the steel fabrication process, as well as developing and validating a virtual shop model for productivity analysis and production planning, which is discussed in Chapters 4, 5, and 6.

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CHAPTER 3: MODELING STEEL DRAFTING PRODUCTIVITY[1]

INTRODUCTION

Productivity studies during the construction phase of a project have been quite successful, as exhibited in many publications. However, little effort has been expended in the area of engineering productivity at a time when design tools, work processes, and project cost and schedule constraints are continuously changing (CII 2001). In the context of this research, engineering refers to the design of public works, such as bridges or plants, and other large facilities (Merriam-Webster 2003). In the engineering field, the term "productivity" becomes difficult to understand in relation to engineers. Standard engineering productivity measurements must be established and applied to present day work processes before significant improvement and predictability of performance can be made (CII 2001).

By definition, productivity is the relationship between quantities of output and input. The measurement of engineering project scope or the output is the basis for measuring engineering productivity. Project scope definition involves subdividing the overall project deliverables into smaller and more manageable components. A survey 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 (Diekmann and Thrush 1986). Essentially, this method treats the output of the design process as any paper design

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[1] *A version of this chapter has been accepted for publication. ASCE, Journal of Construction Engineering and Management.*

document such as a drawing or specification. The scope for a new project is defined subjectively based on data collected 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 Aid Design (CAD) tools, a particular representation of the physical design deliverables as documents is no longer relevant.

Project scope definition is the reference point for measuring productivity, developing estimates and schedules, coordinating teamwork, applying control strategies, and evaluating engineering performance. 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. Estimating engineering productivity is a highly subjective process, as the engineering productivity is influenced by many factors. For example, the scope and complexity of the project, the design team qualification and efficiency all contribute to the process. Tracking effort dedicated to each detailed level deliverable is not economically feasible or efficient. As a result, accurately estimating and controlling engineering productivity is a challenge, without groundwork in defining productivity measurements and producing quantitative evaluations of influencing factors.

In spite of some awareness of problems in measuring engineering project scope and productivity, there have been only limited studies in response to the industry's growing need. This is shown through the literature review on engineering productivity provided in Chapter 1. This research was first focused on how engineering project scope can be quantitatively measured. A method, the Quantitative Engineering Project Scope Definition (QEPSD), was developed to standardize the measurement of engineering project scope within a CAD environment. Based on the quantitative measurement of engineering project scope, an drafting productivity measurement system was established for steel drafting projects. In this system, ANN was proposed to model drafting productivity. The research was conducted in conjunction with the collaboration company. The historical data collected from the implemented data acquisition system, which is described in Chapter 2, were used to develop the productivity measurement system.

QUANTITATIVE ENGINEERING PROJECT SCOPE 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.

Engineering design creates and transforms ideas and concepts into a product definition that will satisfy customer needs. Engineering hours represent a major resource for design inputs in the design process. 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 design output can be viewed as information. For example, the output of steel drafting is a complete set of fabrication drawings, erection drawings, and specifications. 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. 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 the research in quantifying engineering project scope.

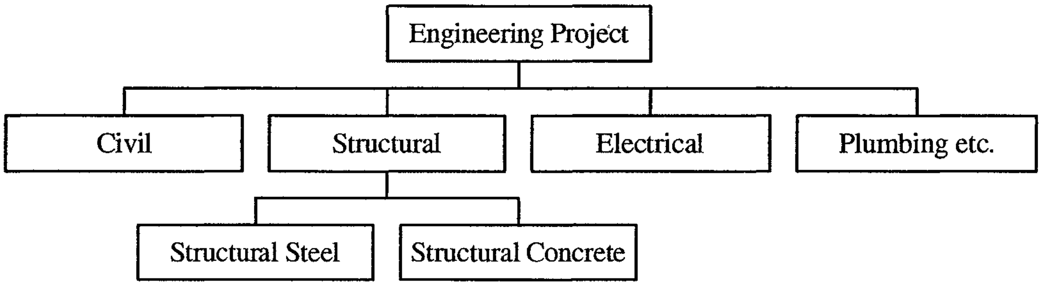
Scope Definition Based on Design Complexity

In a construction project, the project scope is defined by the quantities of construction items within each labour discipline that can be easily measured, such as the volume of earth hauled, 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 in the constructed facility. The engineering output can be measured naturally based on the quantity of design items, such as a beam or a window. 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 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 design 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.

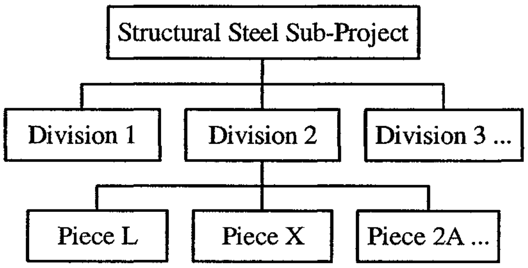
This is analogous to a "unitization" scheme used in quantifying industrial fabrication shop work (Alfeld 1988).

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 project environment variables, such as crew qualification and the quality of pre-project 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 are described in the section titled "Modeling drafting productivity using ANN" of this chapter.

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 Figure 3-1. The WBS in Figure 3-1(a) divides the project at the design discipline level first. This is the level that 91% of companies focus upon for project control, as reported by CII (CII 2001). 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. Figure 3-1(b) is the product model for structural steel design. The structural steel design sub-project can be further divided into divisions representing different physical locations, each of these divisions containing many steel pieces with certain material requirements.



(a) Project breakdown structure



(b) Product breakdown structure

Figure 3-1. Work Breakdown Structure for Project Scope Definition

This WBS model is a structured approach to manage the project scope, but does not necessarily result in a quantitative measure of the work scope. 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 function.

Design Category

The first step toward a measurement of design item complexities is to group similar design items within a specific 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, 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:

$C_1, C_2, C_3 \ldots\ldots C_m$ is a set of mutually exclusive and exhaustive categories so that $C_i \cap C_j = \Phi$ and $C_1 \cup C_2 \cup C_3 \ldots\ldots \cup C_m$ is the entire design item space. The design item classification is to assign a design item, $p_j \{p_j : j = 1 \ldots\ldots n\}$, to one of M categories $\{C_i : i = 1 \ldots\ldots m\}$, 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. Project managers were asked to participate in defining and verifying the design categories. The developed drafting category list consists of 30 categories, as shown in Column 2 in Table 3-1. The collaborating company has standardized the naming convention used by draftspersons to describe steel pieces based on these defined categories.

Table 3-1. Design Categories for Steel Drafting

ID (1)	Description (2)	Complexity variable (3)	a (4)	b (5)
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

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 the category C_j is given by:

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

A complexity function f must be defined for each design category. Experienced engineers can 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 into three categories, as shown in Column 2 of Table 3-1: "Handrail – straight," "Handrail – sloping," and "Handrail – circular." A dominant complexity variable is identified for each category. Column 3 of Table 3-1 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 steel piece is measured by a single design item.

Based on the draftsperson's experience 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 can be defined as:

$$f_j\ (x_j) = a_j + b_j x_j \qquad (2)$$

Where a_j is the base complexity value for category C_j, and b_j is the coefficient for the complexity variable x_j. A standard design item can be defined as an abstract unit of measurement. The project scope 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 drafting process involves multiple stages of development, review, and revision. To facilitate the definition of a_j and b_j in Equation 2, the drafting process of a drafting item is broken down into wire frame modeling, Bill Of Material (BOM), 2D drawing, electronic drawing (E-drawing), checking, and administration, and the drafting process of a fitting is 2D drawing, checking, and administration. Tables 3-2 and 3-3 illustrate the definition of a_j and b_j according to the defined process model. First, the wire frame modeling of a column is set to 1. Other activities involved in design the column and fittings of this column are evaluated based on a comparison with the wire frame modeling activity, as shown in Columns 2 to 6 of Table 3-2 and Columns 1 to 3 of Table 3-3. The summation of evaluations made at the process level for the column category is shown in Column 7 of Table 3-2 and Column 4 of Table 3-3. This process can be repeated for other drafting categories. As shown in Column 7 of Table 3-2, the evaluation of a simple column without fitting shows a value of 9.9. Dividing Column 7 of Table 3-2 and Column 4 of Table 3-3 by 9.9, a_j and b_j can be derived. Column 8 in Table 3-2 and Column 5 in Table 3-3 show the a and b values. Parameters a and b defined for each drafting category are shown in Columns 4 and 5 of Table 3-1. 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 the definition of drafting unit by scrutinizing the quantification procedure used to define it.

Table 3-2. Parameter *a* Definition for Complexity Functions

Category	*a*							
	Wire Frame (1)	BOM (2)	2D Dwg. (3)	E-Dwg. (4)	Check (5)	Admin. (6)	Total (7)	*a* (8)
Column	1.00	0.50	5.00	1.00	1.50	0.90	9.90	1.00
Beam	2.00	0.50	5.00	1.00	1.70	1.02	11.22	1.13
Girder	10.00	0.50	5.00	1.00	3.30	1.98	21.78	2.20
Bracing	4.00	0.50	5.00	1.00	2.10	1.26	13.86	1.40
Girt	2.00	0.50	5.00	1.00	1.70	1.02	11.22	1.13
Purlin	2.00	0.50	5.00	1.00	1.70	1.02	11.22	1.13

Table 3-3. Parameter *b* Definition for Complexity Functions

Category	*b*				
	2D Dwg. (1)	Checking (2)	Admin. (3)	Total (4)	*b* (5)
Column	5.00	1.00	0.60	6.60	0.67
Beam	4.00	0.80	0.48	5.28	0.53
Girder	10.00	2.00	1.20	13.20	1.33
Bracing	4.00	0.80	0.48	5.28	0.53
Girt	5.00	1.00	0.60	6.60	0.67
Purlin	4.00	0.80	0.48	5.28	0.53

To illustrate the result from the unit measure, a sample complexity factor table is shown in Table 3-4. A bracing in the bracing category with two fittings is 2.46 drafting units, according to Table 3-4. The total adjusted quantity of a project output, or project scope, in drafting unit is given by:

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

Where Q_{total} is the project scope measured by drafting unit. q_i is the complexity of a piece p_i measured by drafting unit, which is defined in Equations 1 and 2. n is the total number of pieces in a steel drafting project.

Table 3-4. Sample Complexity Factor Table

Category	**a**	**b**	**Complexity variable value (Number of Fittings)**			
			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
Girder	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

Automation of the 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 tools are used in almost every engineering design discipline. The proposed QEPSD method is designed to work in a CAD environment. The data required for measuring design output are normally recorded in a CAD model. 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.

The collaborating company uses specialized CAD drafting software, StruCAD, for its steel drafting work. Product data were extracted from CAD models and stored in a database system. The complexity evaluation algorithm was built using Structured Query Language (SQL), and was integrated into the database system. Over a million steel pieces from past projects were quantified into drafting units over the course of our study. This information was used to validate the QEPSD method and define work scope of future projects, which are discussed in the following sections.

QEPSD VALDIDATION

The proposed conceptual model aims at quantitatively measuring the engineering project scope for construction projects. It relies on experienced engineers to define the design category, complexity variables, and complexity functions. To verify its capability and accuracy, the model must be tested on actual projects. 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 are work-hours. A correlation analysis was performed to compare the relative effectiveness of different measurement units.

Data from a total of 59 steel drafting projects were collected for the correlation analysis. Scatter diagrams were constructed for each measurement unit and correlation coefficients were calculated and compared, as shown in Table 3-5. 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. A t test at the 95 percent level shows that the correlation 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. The value rankings following this are the quantity of drawings, the weight of steel, and the 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 of steel.

Table 3-5. Results of the Correlation Analysis

	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

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 work-hours required. An explanation of the residual is expected by other project environment variables and overall project complexity factors. This is discussed in the section of modeling drafting productivity using ANN.

PROJECT SCOPE DEFINITION WITH THE QEPSD METHOD

It is impossible to know what the exact quantity of work will be until after the fact, so engineers must determine a project scope using only the information available at the time. The proper approach for quantifying project scope in 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 at the project planning stage were discussed.

For some drafting disciplines working at the construction document phase, their work scope may be fully defined at the project planning stage. For example, in some 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 take-off 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.

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 experience 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 project 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 ANN models (Creese and Li 1995), may be used to estimate a new project's scope. A comprehensive discussion of these estimating techniques falls outside the scope of this research. 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 projects using historical data is illustrated later in this chapter.

MODELING DRAFTING PRODUCTIVITY USING ANN

Based on the measurement of project scope using QEPSD method, a productivity measurement system was proposed to measure and analyze drafting productivity. The measurement system is illustrated in Figure 3-2. The productivity measurement system is comprised of measures of input resource, output product, engineering productivity, and input influencing factors, and a productivity model. Man-hours represent the major resource of input to engineering design. Project outputs are measured by design unit, which can be defined for each design discipline using the QEPSD method, such as the drafting unit for steel drafting discipline. In this research, the drafting productivity is measured by man-hours per drafting unit. Factors that affect engineering productivity can be identified for each design discipline.

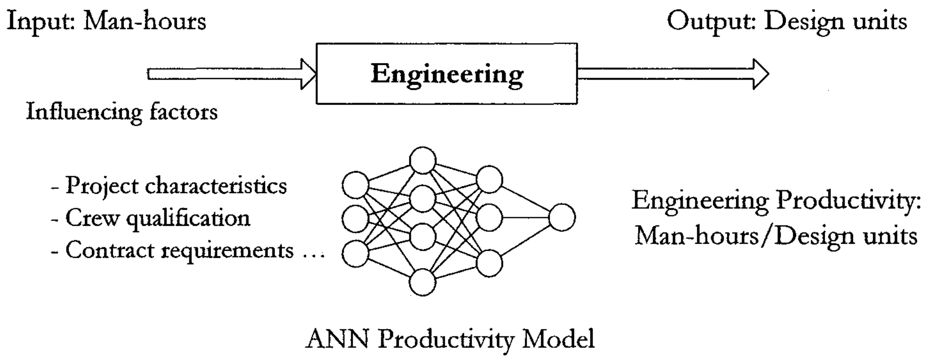


Figure 3-2. Engineering Productivity Measurement System

Engineering productivity is influenced by a variety of factors. The relationship between these factors and engineering productivity cannot be given in a precise and explicit fashion. ANN was proposed to develop the productivity model in the engineering productivity measurement system. A literature review on ANN is provided in Chapter 1. Modeling steel drafting productivity using ANN is described in the following sections.

Identification of Influencing Factors

Influencing factors that affect drafting productivity were collected through literature reviews, interviews, and surveys among estimators, project managers, and engineers. A survey has also been conducted in an online steel drafting and fabrication community. A number of factors regarding the project overall complexity, crew qualification, and working condition are considered relevant to drafting productivity. Several factors that are initially included were dropped out of analysis after examining the collected data, in which slight variations were observed due to the consistent practice, such as drafting method and project location. Factors that describe the complexity of a project in terms of individual design items, such as the percentage of bracings and the percentage of handrails, are not considered as influencing factors due to the use of the QEPSD method in measuring project scope at the design item level. Eventually, seventeen factors that affect drafting productivity were identified from the study, as shown in Table 3-6.

Table 3-6. Influencing Factors for Steel Drafting Productivity

Factor	Data Type	Option and Remarks
Project type	Binary	Structural/plate work/both
Work scope	Binary	Supply only/supply & erect
Contract type	Binary	Lump sum/unit price
Piece cloning	Raw	Percentages of unique pieces over all pieces
Dynamic structure	Binary	Yes/No
Fire proof	Binary	Yes/No
Special fall arrest provision	Binary	Yes/No
Overall complexity	Rank	1 very high, 3 average, 5 very low
Detailers' Qualification	Rank	1 very low, 3 average, 5 very high
Crew size	Binary	1-2, 3-5, 5+
Client	Raw	Index derived from historical data
Engineer firm	Raw	Index derived from historical data
Engineering standards	Rank	1 very low, 3 average, 5 very high
Administration	Raw	Percentages of administration hours over total hours
Overtime	Raw	Percentages of overtime hours over total hours
Subcontract	Raw	Percentages of subcontracts
Total work quantity	Raw	Quantity in drafting unit

Data Collection

The model definition process requires the availability of accurate historical data of both the input factors as well as the corresponding productivity values. Many companies cannot take advantage of productivity modeling due to the lack of accurate, consistent, and comprehensive productivity data from past projects. An online office timesheet system, which is described in Chapter 2, was used to record engineers' hour allocation to steel drafting projects. Project outputs were measured by drafting unit as described previously.

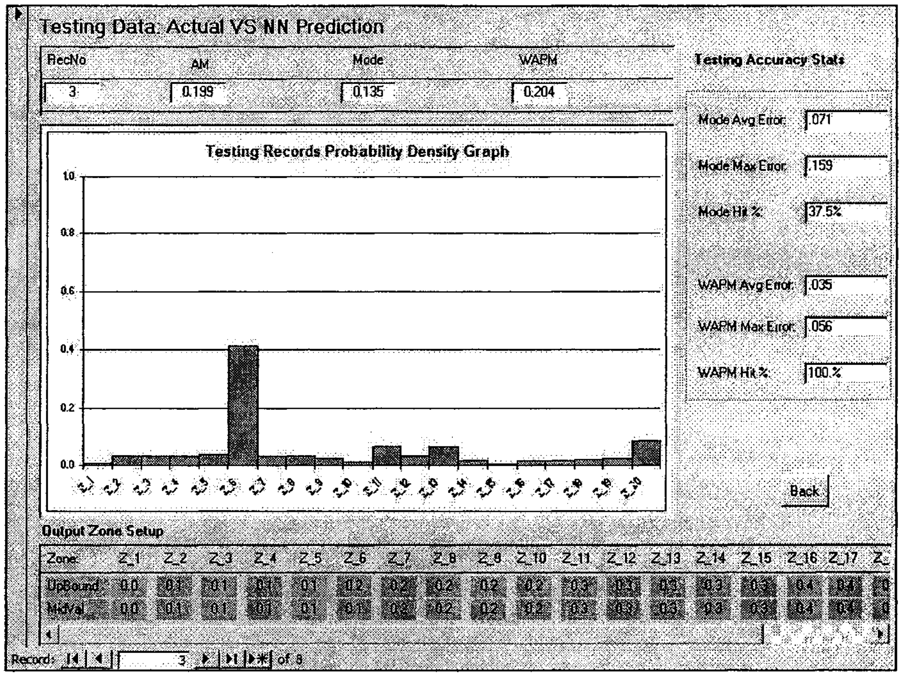
Historical data were aggregated in a data warehouse system. Values of influencing factors for historical projects were collected as much as possible from the company's existing information system, to reduce the subjectivity. For undocumented quantitative data and all other qualitative data, questionnaires, which were generated from the data warehouse system, were used to collect project-specific information. A description about the questionnaire can be found in the section titled "Online questionnaires" in Chapter 2. At the current phase of our research, a total of 59 jobs in the previous 3 years were included for ANN modeling.

ANN Training and Validation

During the stage of ANN modeling and training, various network structure, input models, output models, and training algorithms were investigated This includes multilayer feed-forward networks with different configurations trained using back-propagation and the learning algorithm presented in the Probability Inference Neural Network (PINN) (Lu et al. 2000). Through training and testing based on the drafting productivity data, PINN was found to have the best performance in terms of prediction accuracy and was finally utilized in this research. PINN was developed and successfully used for modeling labour productivity of pipe spool fabrication (Lu et al. 2000). The PINN model was proved to be effective in dealing with high dimensional input-output mapping with multiple influential factors. It is a classification-prediction combined neural network model based on Kohonen's LVQ concept (Kohonen 1995), but integrated with a probabilistic approach. It has four layers: an input layer, a Kohonen classifier, a Bayesian layer, and an output layer. The outcome of the PINN model at the output layer is a probability density function reflecting the likelihood of the target variable occurring in a given zone. This gives the estimator a sense of uncertainty in the predicted result. The mode of the distribution or its mean can serve as point predictions.

Three input data types are used to define PINN input factors (Lu et al. 2000). Raw is used simply for quantitative input factors, like total project quantities and percentages of overtime. Rank is used to convert subjective factors, like project overall complexities, into numeric format. And binary is used to group textual factors into numeric formats, like project types and contract types. An input factor of the raw or rank type corresponds to one input node at the input layer and an input factor of the binary type corresponds to a number of input nodes depending on the number of groups for the factor. The PINN input data is normalized and scaled between 0 and 1 at the input layer. The PINN model for steel drafting has a total of 26 input nodes. The input factors and their data types are shown in Table 3-6. The output range is divided into 18 output zones, each with an equal width of 0.024. Five processing elements are assigned to each output zone.

The training of the PINN Model utilized 51 randomly selected records of the available 59 drafting projects. The other 8 records were kept for testing. The process was repeated three times to confirm that the network is stable. Figure 3-3 shows an output for a test record, indicating the likelihood of productivity occurring in each zone. The network predictive capability is shown in Figure 3-4. For confidentiality reasons, productivity values shown in this figure were scaled. The model predicted the productivity to within 20% of the actual value on average 75% of the time. The accuracy of this predictive model is also expected to be improved by collecting more training data.



Testing Data: Actual VS NN Prediction

RecNo	AM	Mode	WAPM
3	0.199	0.135	0.204

Testing Accuracy Stats

Mode Avg Error: .071

Mode Max Error: .159

Mode Hit %: 37.5%

WAPM Avg Error: .035

WAPM Max Error: .056

WAPM Hit %: 100.%

Output Zone Setup

Zone:	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_10	Z_11	Z_12	Z_13	Z_14	Z_15	Z_16	Z_17
UpBound:	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4
MidVal:	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4

Record: 3 of 8

Figure 3-3. Output of the PINN Model

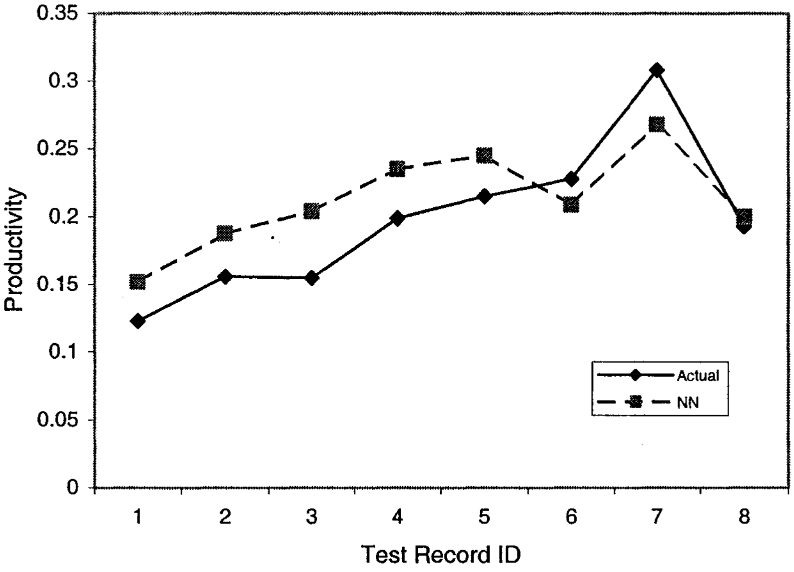


Figure 3-4. PINN Model Output versus Actual Productivity Values

The application of ANN in modeling drafting productivity help estimators to have better understanding of the available project information and the possible productivity performance that could achieve. The predicted distribution and point-prediction values give the estimator more confidence in the predicted result. In combination with personal experience and preference, drafting productivity for a new project can be determined.

Sensitivity Analysis of the ANN Model

In this section, "What if" analysis is conducted to demonstrate the sensitivity of the drafting productivity to input factors. Various scenarios can be formulated by changing input values. The response of the PINN model can then be compared against that of an experienced estimator for the purpose of model validation. Besides the "What if" analysis, the pairwise comparison method was utilized to measure the relative magnitude of impact of input factors on drafting productivity based on estimators' experience (Allouche and Song 2003). The result shows the top three influencing factors are fire proof, engineer standards, and dynamic structure.

The base case scenario is taken from the test data set. The actual productivity of this project is 0.228 hour per drafting unit, and the network output is 0.209 hour per drafting unit. In the base case, the steel structure is not a dynamic structure and does not require fire proof. The engineering standard is evaluated as 3, which means an average level of detail is given in the client engineering drawings. Three scenarios were formulated based on the base scenario by changing only the value of one of the three inputs, which are fire proof, dynamic structure, and engineering standards, while keeping all other factors unchanged. Scenario 1 examines the productivity that can be achieved if the steel structure requires fire proof. Similarly, Scenario 2 examines the productivity if the steel structure is dynamic structure and

Scenario 3 examines the productivity if the project has better engineering standards which can be evaluated as 5. The productivity values predicted by the PINN model for these three scenarios are 0.241, 0.225, and 0.201 hour per drafting unit. Compared to the base case scenario, Scenario 1 shows that the productivity measured by hour per drafting unit is increased by 15.38% due to the requirement of structure fire proof. The productivity of Scenario 2 has an increase of 7.7% due to the dynamic nature of the structure. The better quality of engineering standards in Scenario 3 contributes to the 3.9% decrease of the productivity value of the base case scenario. The direction and magnitude of these changes matches the estimator's expectation. The sensitivity of other input factors can be examined in a similar manner, and are not elaborated further due to space limit.

CASE STUDY

The selected project is a unit price contract, involving detailing the 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 also 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 take-off 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 tonnes, in which 41.11 tonnes were drawn by the collaborating company, and 79.39 tonnes 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 3-7. For the selected project, the quantities measured by weight in tonnes 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 man-hours per tonne (Column 4), in which the complexity of each unit-price category and profits were accounted for by his or her experience. Thus, the unit cost for a unit-price category is the product of the productivity and a pre-defined hourly rate.

This estimating problem can be approached alternatively using historical data to determine the unit cost for each unit-price category and the total project duration. A total of 216 similar types of projects were quantified and stored in a database system using the QEPSD method customized 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 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 for each category (Column 7) is the product of the mean value in Column 6 and the weight of each category in Column 3.

Table 3-7. Case Study: A Unit Price Contract Steel Drafting Project

ID (1)	Category description (2)	Weight (ton) (3)	Productivity (hr/ton) (4)	Est. hours (hr) (5)=(3)X(4)	Unit per ton (unit/ton) (6)	Quantity (unit) (7)	Est. hours (hr) (8)	Productivity (hr/ton) (9)=(8)/(3)
1	Rolled Shapes 15-31 kg/m <2744 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 <2744 mm	3.46	16.53	57.19	Normal(32.82,12.38)	113.39	52.16	15.07
3	Rolled Shapes 62-100kg/m <2744 mm	0.29	14.46	4.19	Normal(12.34,4)	3.62	1.67	5.74
4	Rolled Shapes 32-61 kg/m >2744 mm	14.37	14.39	206.78	Normal(11.25,2.71)	161.69	74.38	5.18
5	Rolled Shapes 62-100kg/m >2744 mm	3.32	12.48	41.43	Normal(5.49,1.8)	18.22	8.38	2.52
6	Rolled Shapes 101-150kg/m >2744 mm	5.90	9.83	58.00	Normal(5.46,2.31)	32.21	14.82	2.51
7	Bracing - WT section < 2744 mm	1.16	27.20	31.55	Normal(86.07,43.03)	99.50	45.77	39.46
8	Bracing - WT section > 2744 mm	2.43	24.13	58.64	Normal(25.39,13.96)	61.65	28.36	11.67
9	Girt <30 kg/m > 2744 mm	0.17	22.54	3.83	Uniform(19.2,27.2)	4.04	1.86	10.93
10	Girt >30 kg/m > 2744 mm	0.42	16.14	6.78	Uniform(3.2,7.75)	2.31	1.06	2.53
11	Web Stiffeners W14 to 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		1560.00	717.62	

The ANN drafting productivity model was used to predict the productivity value as described previously. The ANN input data for this project are shown in Table 3-8. The estimated productivity is 0.46 hour per drafting unit. The estimated hours 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 productivity value. For bidding purposes, the productivity measured in work-hours per drafting unit is converted to man-hours per tonne in Column 9.

Table 3-8. ANN Input Data for the Sample Project

Factor	Value	ANN input data
Project type	Industrial	0 0 1 (Binary input)
Work scope	Supply only	1 0 (Binary input)
Contract type	Unit price	0 1 (Binary input)
Piece cloning	8%	8%
Dynamic structure	No	1 0 (Binary input)
Fire proofed	No	1 0 (Binary input)
Special fall arrest provision	Yes	0 1 (Binary input)
Overall complexity	Average	3
Detailers' Qualification	Average	3
Crew size	3-5	0 1 0 (Binary input)
Client	X	0.258
Engineer firm	Y	0.276
Engineering standards	Average	3
Administration	12%	12%
Overtime	6%	6%
Subcontract	63%	63%
Total work quantity	1560.00	1560.00

The Monte Carlo simulation technique was used to evaluate the risk and uncertainty of the estimate (Ahuja et al. 1994). The man-hours of each category were calculated as the product of the productivity in man-hours per unit, the weight, and the unit-weight ratio. The experiment was implemented in Microsoft Excel. Figure 3-5 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 hours, and a 90 percent confidence level that the total hours is between 614.67 and 829.30 hours. The eightieth percentile of the estimated project completion time are 792.56 hours.

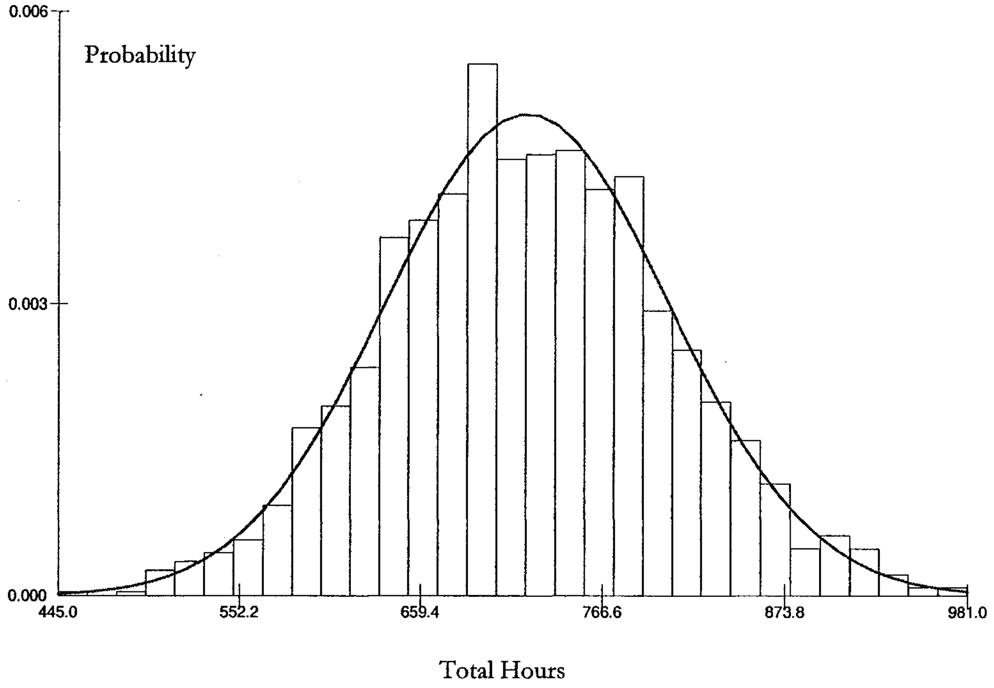


Figure 3-5. Probability Density Function for Project Total Hours

After the competition of this project, QEPSD measured the project scope as 1537.01 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 hours. This is inside the 90 percent confidence interval. The eightieth percentile indicates an overestimate of 17.16 percent 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 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.

CONCLUSIONS

The research on drafting productivity identified the lack of quantitative method in measuring project scope and productivity of design engineers. The measurement at the design item level suggested by the QEPSD method 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 man-hours;
- The complexity can be quantified 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 the QEPSD method. Engineering productivity can be conveniently measured by man-hours per design unit. ANN models the relationship between influencing factors and engineering productivity and streamlines the productivity estimating process. The productivity measurement system also addresses the need of project control, performance evaluation and improvement. These project management functions need to be revisited and updated accordingly with the new measurement system. The following discussion highlights the implications and benefits of adopting the proposed system in regard to:

- **Project Control:** During the 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 progress reporting. 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 man-hours per unit of work. However, it does not measure the design effectiveness, which can 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.
- **Productivity Improvement:** The productivity model contains information about what influencing factors cause productivity to change. The identification and sensitivity analysis of those factors allows for a better understanding of engineering productivity and relative importance of the factors affecting it. Based on this information, guidelines can be developed to improve productivity.

The engineering productivity measurement system 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 estimating. It improves the common understanding of engineering productivity. It holds significant potential as a force in improving the project management process. The proposed system will be applied to different design disciplines, and its applicability will be further verified.

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CHAPTER 4: MODELING THE STEEL FABRICATION PROCESS[1]

INTRODUCTION

Steel has been an important component in buildings, bridges, and other structures for more than a century. Structural steel is largely fabricated off-site, then erected and assembled on-site. "Steel fabrication" refers to the production of steel pieces through a series of operations, which include detailing, fitting, welding, and surface processing in a fabrication shop according to the steel engineer's design. Material handling and inspection activities occur frequently during the fabrication process.

The complexity of the steel fabrication process is due primarily to the uniqueness of steel products and the high product mix. There is a large variety of steel pieces produced, in terms of geometry and processing requirements; however, the total production volume is usually small. This characteristic distinguishes the steel fabrication process from most other manufacturing processes where identical products are produced *en masse.* A steel fabrication shop is a production system, possessing a number of workstations with different processing capabilities, in order to respond to the variety of steel product types. Steel fabrication operations require a variety of machines and labour disciplines in order to produce the many different kinds of unique steel pieces.

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[1] *A version of this chapter has been submitted for publication. Journal of Simulation Modeling and Practice.*

Generally, estimating and scheduling of a fabrication project is based primarily on personal experience, information from drawings, and knowledge of the status of the shop. However, given the complexity of steel products; the large number of recourses, activities, and their interactions; and the possible combinations of all these variables, an accurate analysis of such a production system can be extremely difficult. It is generally risky to make decisions based on "gut instinct" alone. Network-based tools such as CPM/PERT are used by fabricators for project planning and control at the project level. The shortcomings of these tools arise due to modeling assumptions, or due to incapability to deal with uncertainty, resources interaction, or activity relationships. These shortcomings limit their capabilities to describe activities at a process level (Pritsker 1986); thus they are not useful for production analysis at the shop floor. Also, although researchers have introduced many analytical optimization-based scheduling algorithms (Hopp and Spearman 2001), most of these algorithms are highly simplified and static in nature, which limits their direct applicability in managing industrial fabrication shops. The complex nature of the fabrication process, the industry's growth, and the adoption of new fabrication technologies and materials require advanced and effective tools capable of analyzing the fabrication process.

Simulation models can represent real-world systems at almost any level of detail in order to provide as accurate a representation of the system as possible. This research proposes an approach to building virtual shop models for the purpose of analyzing the productivity of the steel fabrication process. A virtual shop model is a computer model representing a steel fabrication shop in the real world. This model can be used for production planning and productivity analysis in a steel fabrication shop.

As described previously, each steel piece has unique features and is different in terms of fabrication complexity. It consumes different amount of labour hours for each activity, such as detailing, fitting, welding, and painting. Unitization scheme, which is described in Chapter 3 in measuring steel drafting project scope, may be applied to uniformly measure the work quantity of steel fabrication. However, unlike steel drafting, the productivity data of fabrication activities can be collected through time studies. This means that the complexity of steel products, the working environment, and activity duration can be explicitly modeled in a simulation model. This approach is more accurate than unitization scheme due to its capability in modeling productivity at the individual piece level, which will be described in Chapter 5. This chapter discusses the virtual shop modeling system, which is a platform for building virtual shop models.

STEEL FABRICATION PROCESS

Steel fabrication produces steel components and assembles them together as steel pieces according to fabrication drawings. A fabrication drawing provides information about all the steel components that make up a steel piece: the material list, piece dimensions, other important dimensions such as hole locations and spacing, and welding and painting specifications. Steel fabrication in a typical fabrication shop involves detailing, fitting, welding, surface preparation, surface protection, and shipping, as shown in Figure 4-1.

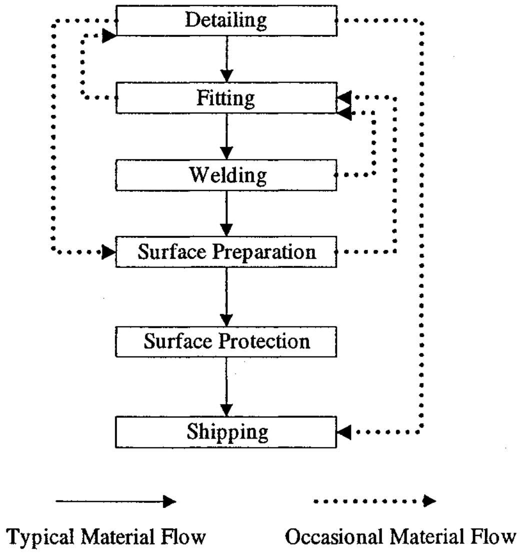


Figure 4-1. Steel Fabrication Process

Detailing involves a number of machining operations, such as cutting, holing, and grinding, to shape steel components as specified in fabrication drawings. Cutting raw material to the required size is usually the first operation. There are a number of cutting methods that can be applied, such as sawing, shearing, flame or plasma cutting, depending on the material type and dimension. Certain sawing machines, such as hacksaw, cutoff saw, and band saw are more suitable for cutting steel sections. Shearing is limited to cutting steel plates. Flame or plasma cutting can make both straight cuts and curved shapes, as well as complex profiles. Holing is required for steel components that need to be bolted. Holes can be made either by drilling or punching. Drilling creates smooth and precise holes by rotating and advancing the cutting edge of drill bit through the steel material. Holes can also be rapidly punched using properly sized dies. Punching is especially useful where square holes are specified, but the process is limited by the hole's tolerance requirements and the material's thickness. Grinding and finishing operations may also be required to remove burrs and scales from steel components. With the introduction of Computer Numeric Control

(CNC) technology, much of the detailing work is handled by the automated CNC equipment (e.g. beam drilling system and plate burning system). The use of CNC equipment has greatly increased the productivity of detailing.

After all the steel piece components are detailed, they are stored in storage areas, and are ready to be assembled together either by a welded connection or a bolted connection, as specified in the fabrication drawing. At fitting stations, fitters review the main component for compliance, according to the fabrication drawing, and retrieve other detail components from the storage areas. For a welded connection, fitters fit and tack-weld detail components to the main component in order to assemble the steel piece temporarily until the final welding.

Fitted pieces are passed to welding stations for final welding according to the welding specifications. Most welds made on structural steel and heavy plates are either groove welds, joining surfaces on the same plane, or fillet welds, joining perpendicular edges.

Surface processing is normally required for protecting steel pieces from oxidization and corrosion. This process includes surface preparation and protection. Steel pieces must be cleaned prior to applying any protective coating. Surface preparation removes mill scale, rust, paint, and other surface contaminants on steel pieces using blast cleaning equipment. Once pieces are cleaned, they can be painted or galvanized to protect the steel surfaces. Surface protection is prepared in accordance with corresponding specifications. Finished pieces are shipped to the construction site for erection.

During the steel fabrication process, raw materials and steel pieces are handled and moved by bridge cranes, jibs, conveyor systems, and guided carts. Inspection and checking activities are also carried out at each stage of the fabrication process to ensure product quality.

There are many exceptions to this general process description. On many occasions, steel pieces are moved from the initial stage directly to shipping if no welding is required (e.g. base plates). Other pieces could potentially move back and forth between fitting, welding, and surface preparation. Occasionally, pieces can move from fitting back to detailing, such as in the case where match drilling is required. Typical and occasional flows of steel materials are illustrated in Figure 4-1.

MODELING SYSTEM STRUCTURE

A virtual shop model capable of capturing the complexity of steel products, resources, activities, their interactions, and the uncertainties in a steel fabrication shop would be of great value to steel fabricators. Based on currently available simulation tool designs (Banks 1996), the proposed virtual shop modeling system would extend the capabilities of these designs to address the unique requirements of modeling the steel fabrication process. The system supports the process of building and deploying a virtual shop model by supporting steel product modeling, process modeling, and fabrication facility modeling.

The steel fabrication process is complex because steel products are themselves complex. Steel fabrication includes a limited number of operations; however, steel products are quite varied, thus making their processing and routing requirements within a steel fabrication facility different from one product to another. This observation has resulted in a distinction between the study of steel product and the study of the fabrication facility where steel products are produced. The overall modeling system consists of the Product/Process

Modeling System (PPMS) and the fabrication Facility Modeling System (FMS). The system structure is illustrated in Figure 4-2.

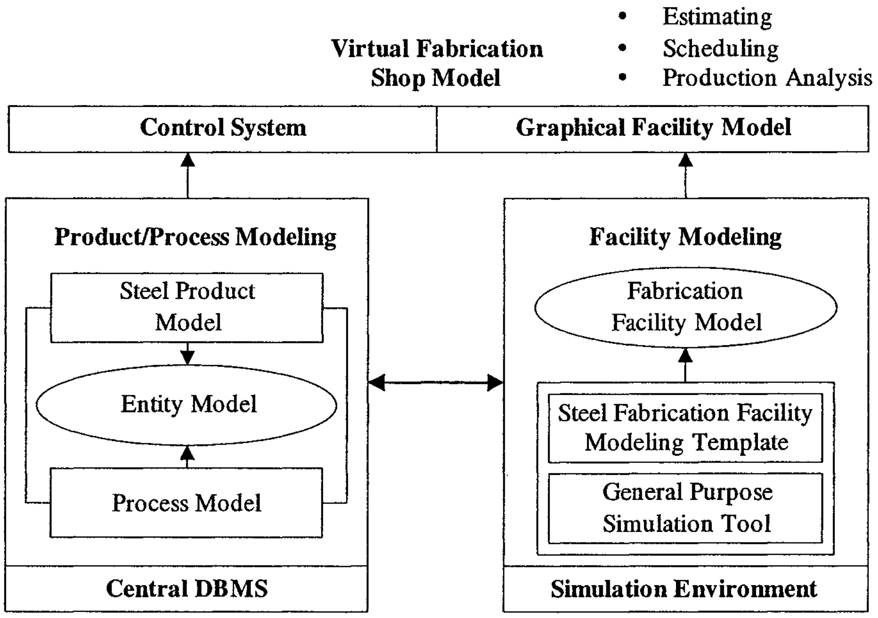


Figure 4-2. Virtual Shop Modeling System Structure

PPMS creates a mechanism to define steel products, model the general fabrication process, and set up relationships between the product model, the process model, and the fabrication facility model. Product and process model data are integrated and attached to a combined product/process model, called an "entity model", which will be introduced later to the fabrication facility model in order to drive the simulation experiments. The PPMS is implemented in the central database, which is a relational Database Management System (DBMS). It can interface with CAD systems and external planning systems to facilitate the definition of steel products and master production schedules. The control system is the central control panel for users to compile and analyze data stored in the DBMS.

The FMS enables users to virtually reproduce a steel fabrication facility, including fabrication shops, working stations, storage areas, equipment, labour, movement paths, and their attributes and layouts, as a computer model. Facility modeling elements in the steel fabrication facility modeling template can be used to build a facility model. A general-purpose simulation tool is used to extend the flexibility and power of the customized template for modeling micro-processes within each modeling element. The facility model also serves as a graphic interface for the virtual shop model. Relevant data in the PPMS and the FMS are synchronized at different modeling stages.

PRODUCT MODELING

In a steel fabrication project, the steel structure is normally decomposed into steel pieces and their detail components. Steel components are fabricated and assembled to make steel pieces. Steel components or fittings are the most basic elements of a steel structure, and are modeled as products in the virtual shop modeling system. Steel products are defined by the product model and the process model. Steel products are "smart" elements which carry product definitions and process plan information.

Product Model

The product model carries all product definition data, including a product's physical attributes and Work Breakdown Structure (WBS) information. Examples of physical attributes include a steel component's material type, size, weight, connection method, and the quantity and size of holes. The WBS is frequently used for project management. It systematically decomposes a project into measurable elements. A typical WBS used during the fabrication stage is shown in Figure 4-3. A project is first divided into divisions representing different physical locations. The typical steel pieces and their components are detailed on fabrication drawings. Drawings are grouped by a shop manager into batches, called load lists, before they are issued to working stations. A load list consists of a collection of drawings that must be fabricated and shipped together. This decision depends on many factors including: site logistics, shipping weight, and physical restrictions. The definition of load list schedules is inputted by users into the model system.

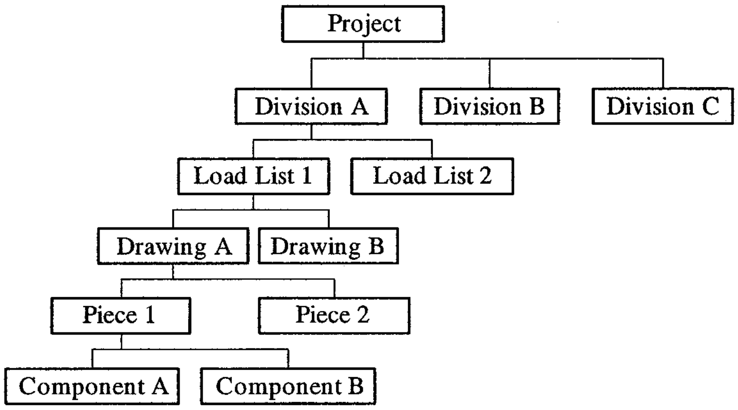


Figure 4-3. Work Breakdown Structure

Process Model

There are several fabrication operations that a steel fabrication facility can perform, such as detailing, fitting, welding, and painting. A steel component may require one or more of these operations. The process model defines the plan for the fabrication of a steel component, specifying the operations and their sequence. The process model also defines resources required for these operations, specifying a list of working stations, where steel components can be processed, for each fabrication operation. Table 4-1 shows an example of a steel component's process plan. Stations and station controllers are defined in the facility model, which is described in the section titled "Fabrication Facility Modeling". The process model also carries traveling source and destination information for steel components to be routed in the shop. In short, the process model connects the product model to the fabrication facility model.

Table 4-1. A Sample Process Plan

Operation	Station controller	Station list	Sequence
Detailing	WSG_C_Detailing	BDL600; BDL750; BDL1250	1
Fitting	WSG_C_Fitting	Fit1; Fit2; Fit3; Fit4; Fit5; Fit6	2
Welding	WSG_C_Welding	Weld1; Weld3; Weld5; Weld6	3
Painting	WSG_D_Painting	PaintA; PaintB	4

Entity Model

Steel components are routed and processed through a fabrication shop. Within the context of a virtual shop model, they are represented by a flow entity. The entity model combines the product model and the process model. The structure of the entity model is illustrated in Figure 4-4. The concepts of product model, process model and entity model were implemented in the central database. A CAD model captures a vast amount of product definition data in an electronic format. A software module was designed and implemented to automate the process of extracting and mapping data from a CAD model to the product model. This is described in detail in the section titled "CAD-base quantity surveying" in Chapter 2. The database also stores a definition file of the facility model, which is defined in the FMS, to facilitate the definition of the process model. Product definition and process plan data of steel components is stored in the central database.

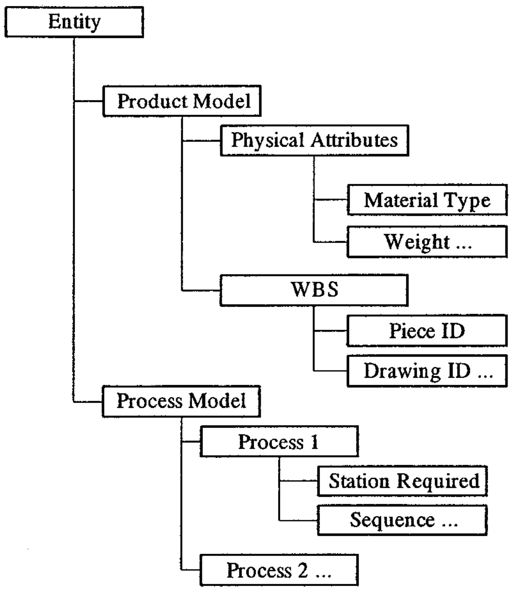


Figure 4-4. Entity Model

The virtual shop modeling system is unique in the representation of steel products. Normally, "products" in a production system are modeled as identical entities which flow through a network of activities in a simulation model. In the virtual shop model, steel products are modeled as unique entities. Each entity is characterized by its attributes, which represent its unique physical features. Entities are also "smart" entities because each entity carries its process plan which specifies the entity's routing in the virtual shop model.

Computer-Aided Process Planning

The process model only provides a structure in order to store process plan information. The user must provide the information itself. Generally, a production engineer examines each fabrication drawing and then uses his/her experience and knowledge of production facilities, equipment, processes, and tooling in order to produce a process plan for each product. Due to the high product mix and high volume of production in a fabrication shop, the process planning can be extremely time-consuming. The process is also quite error-prone as a result of the manual nature of the process. This research proposes the application of Computer Aided Process Planning (CAPP) to simplify this process. CAPP systems represent production knowledge in the form of internal data structures and procedures so that planning decisions can be made by a computer (Banks 1998).

Figure 4-5 shows schematically the use of CAD systems, CAPP, and a virtual shop model in developing a virtual fabrication environment which integrates the engineering, planning, and fabrication processes. The main objective in developing CAPP for use in steel fabrication projects is to assist production engineers in generating process plans for a virtual shop model. The virtual shop modeling system extracts product data stored in CAD models to the product model as described previously. The modeling system then applies production rules captured in the CAPP system to each product in order to generate a preliminary process plan. This plan contains routing information that specifies operations, operation sequences, station controllers, and lists of working stations. Production engineers can verify and update these generated preliminary plans before they are submitted to the virtual shop model for processing.

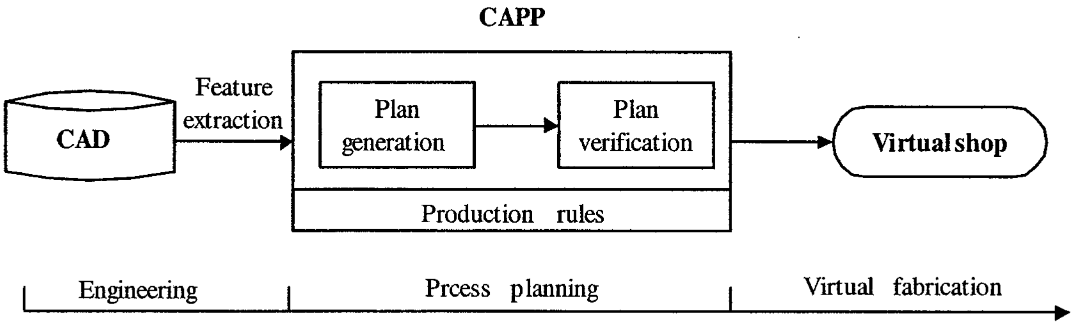


Figure 4-5. Virtual Fabrication Environment

The most important aspect of the CAPP system is the organization of production rules. There are two categories of classification for production rules: static rules and dynamic rules. Static rules are based on the static product feature, equipment capacity, or any other pre-determined production restriction. Due to the dynamic nature of the shop environment and the presence of uncertainty, there are dynamic rules for determining a process plan, such as various dispatching and scheduling rules. The virtual shop modeling system captures dynamic rules and embeds them in the FMS and applies them during the execution of simulation experiments. The CAPP system captures only static rules. It formulates static rules in the form of "If-then" rules and specifies them for a particular fabrication shop. A knowledge structure was defined to help users to organize and manage these production rules. For example, the structure for steel fabrication relates process-planning rules to the category of steel structure member and the raw material type. Table 4-2 shows example rules for "Beam" category and "W shape" material type. If a component is part of a beam, and the material type is "W"-shaped, then the first operation will be detailing. If the material depth is larger than 600-mm, only the station "BDL1200" will be capable of handling this component, so it is recorded in the detailing station list. When the depth is less than 600-mm, both "BDL600" and "BDL1200" are capable of performing the detailing operation. They are both recorded in the detailing station list. If the connection type of this beam is a welding connection, then fitting and welding will be required with an operation sequence number as 2 and 3, respectively.

Table 4-2. Static Production Rules

Category: Beam			
	Material type: W shape		
	Condition	**Value**	**Action**
	Material type="W"	True	Detailing=1
		False	Quit
	Material depth>600mm	True	Detailing station list=BDL1200
		False	Detailing station list =BDL600; BDL1200
	Connection type="Welding"	True	Fitting=2 and welding=3
		False	Welding=0

FABRICATION FACILITY MODELING

The FMS is a combination of the customized steel fabrication facility modeling template and a general-purpose discrete-event simulation tool.

Steel Fabrication Modeling Template

The design of this customized modeling tool employees the Special Purpose Simulation (SPS) approach (AbouRizk and Hajjar 1998). SPS enables a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain using visual modeling tools that have a high degree of resemblance to actual systems. The template for steel fabrication was implemented in *Simphony* (Hajjar and AbouRizk 2002). *Simphony* is a simulation platform for building special-purpose simulation models. *Simphony* allows users to implement highly flexible simulation tools supporting graphical, hierarchical, modular, and integrated modeling. Various fabrication equipments, labour disciplines, and material handling systems involved in the steel fabrication process, and their interactions, were studied systematically to extract common modeling elements. The implemented SPS template for steel fabrication includes ten modeling elements:

product, plant, shop, station, resource, storage, path, in port, out port, and a drawing tool. Sample graphic representations of modeling elements used by this template are demonstrated in Figure 4-6. A brief description of these elements is available in Table 4-3.

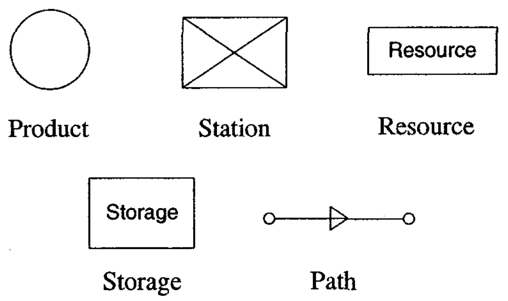


Figure 4-6. Graphic Representations of Modeling Elements

Table 4-3. SPS Modeling Elements for Steel Fabrication

Element	Description
Product	The product element imports products defined by the entity model in the central database into the facility model. It then releases products according to the dispatching schedules. The product element also offers basic services, such as searching process plans, probing travel paths, and routing for products.
Plant	This element represents a fabrication facility. It is the parent of all shop elements. Shop models are built as sub-models of the plant element.
Shop	The shop element represents a fabrication shop, the details of the shop are built as a sub-model of the shop element. Multiple shops can be modeled.
Station	The station is a location where a fabrication process can be performed on products. The station controller, a dummy station, models the foreman's basic decision-making capabilities in job dispatching and station selection.
Resource	The resource element represents equipment or labour in working stations and material handling systems. It can model interruptions and track utilizations.
Storage	The storage element models buffer areas in the shop where steel products can stay and wait for stations, storages, paths, or other resources.
Path	The path element, along with the storage element, defines the shop material handling system. Paths are routes that products travel through from a source location to a destination.
In port	The in port element redirects simulation entities to a lower level sub-model of product, station, storage, or path. The in port element supports batching and assembling functions.
Out port	The out port element sends simulation entities from a lower level sub-model to the parent element. The out port element supports un-batching function.
Drawing tool	The drawing tool element can create layout gridlines and import plant and shop layout drawings from a CAD system.

Figure 4-7 illustrates conceptually how a virtual shop model works. Steel components defined in the database system are introduced by the product element to the facility model, and are further distributed to a shop element where the first operation can start, as specified by their process model. As a default, a steel component always travels to a station controller first. The station controller is a dummy station element that manages a group of stations performing the same operation. The station controller decides which component should be dispatched for processing first, and which station will be selected to perform this processing. The user can specify decision rules that control the behaviour of the station controller. For example, the dispatching rules could be based on First-In First-Out (FIFO) or component priority, and the station selection rules could be random, alternative, or based on station priority, probability, shortest queue length, or shortest waiting time. After the processing at one station, the steel component searches for the next operation from its process plan, and probes the traveling route checking the availability of storage spaces, paths, and required material handling resources. If the search is successful, the steel component will travel through the material handling system and will be routed to the next station controller; otherwise it queues at the current location and waits for services. Stations, paths, and storage areas can be single, batch, or assembly, in terms of their processing mode. Each of them keeps a work list where they search for jobs. Advanced control logic can be defined by users using the scripting tool offered in *Simphony*. Upon the completion of a simulation experiment, statistics collected for steel components, stations, resources, and the material handling system are exported to the central database for output reporting and further analysis by users.

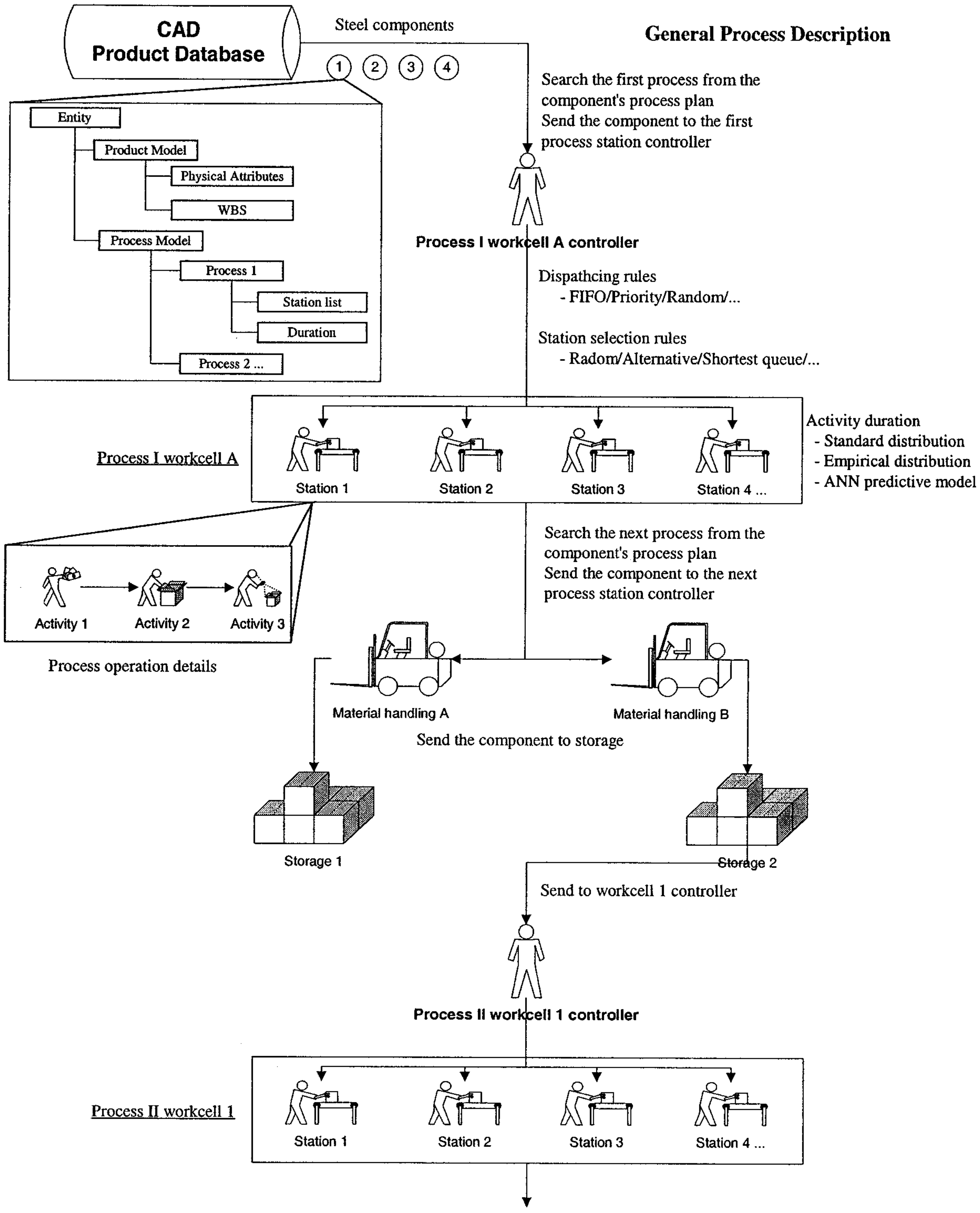


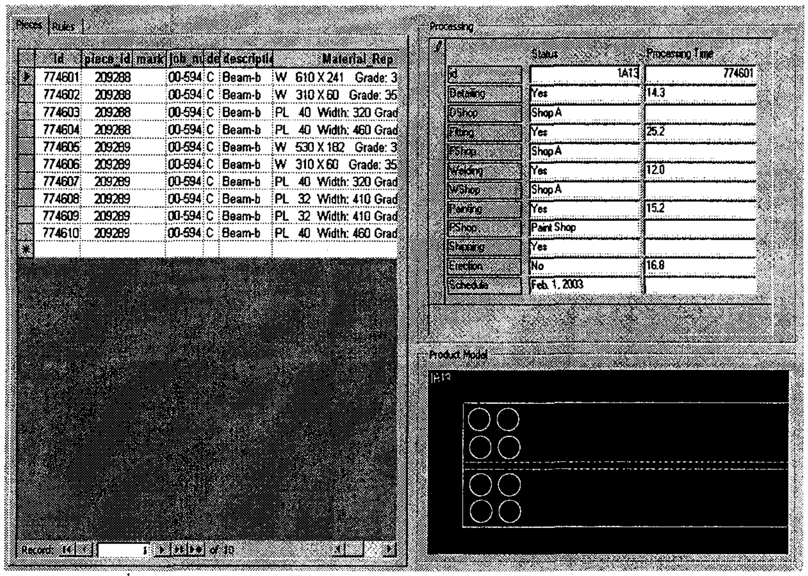
Figure 4-7. General Simulation Process

General Purpose Simulation Tool

The general-purpose simulation tool allows users to describe micro-processes within a modeling element included in the steel fabrication modeling template. The general-purpose simulation tool utilized is the Common Template in *Simphony* (AbouRizk and Mohamed 2000). The Common Template features most of the required functions for general-purpose modeling that could be found in stand-alone general-purpose simulation software. Using the basic constructs in the Common Template, an advanced user can model the details of those basic fabrication shop modeling elements. For example, users can build detailed models of a station performing loading, unloading, and machining operations. This tool has been used by the authors to custom-build advanced station models. These detailed station models were stored in a steel fabrication station library, and can be reused for future projects. In short, proper use of the general-purpose tool can greatly extend the flexibility and power of the customized fabrication modeling template.

CONTROL SYSTEM

Large amounts of data are created and manipulated in the virtual shop model, such as product definition data, fabrication facility configurations, processing rules, and simulation outputs. Data are modeled and stored in the central database. The control system is a set of user interfaces defined to facilitate the management of model information by users. For example, an interface was designed to facilitate quantity take-off and process model definition, as shown in Figure 4-8. The database and the control system create an open structure for the virtual shop model to interface with other existing applications, such as estimating systems, inventory control systems, and CNC control programs. For example, in the case study, which is discussed later, an existing scheduling system was linked to the virtual shop model. Users can create load lists and develop master project schedules in the scheduling system, and this information is automatically shared by the virtual shop model. The control system comes with basic simulation output reporting functions, such as resource utilization and component processing duration reports. Advanced reports such as bar chart schedules or shop loading diagrams can be custom-built, or alternatively, output data can be exported to other applications for further analysis.



Id	piece_id	mark	job_n	de	descriptio	Material_Rep
774601	209288		00-594	C	Beam-b	W 610 X 241 Grade: 3
774602	209288		00-594	C	Beam-b	W 310 X 60 Grade: 35
774603	209288		00-594	C	Beam-b	PL 40 Width: 320 Grad
774604	209288		00-594	C	Beam-b	PL 40 Width: 460 Grad
774605	209289		00-594	C	Beam-b	W 530 X 182 Grade: 3
774606	209289		00-594	C	Beam-b	W 310 X 60 Grade: 35
774607	209289		00-594	C	Beam-b	PL 40 Width: 320 Grad
774608	209289		00-594	C	Beam-b	PL 32 Width: 410 Grad
774609	209289		00-594	C	Beam-b	PL 32 Width: 410 Grad
774610	209289		00-594	C	Beam-b	PL 40 Width: 460 Grad

	Status	Processing Time
Id	1A13	774601
Detailing	Yes	14.3
DShop	Shop A	
Fitting	Yes	25.2
FShop	Shop A	
Welding	Yes	12.0
WShop	Shop A	
Painting	Yes	15.2
PShop	Paint Shop	
Shipping	Yes	
Erection	No	16.8
Schedule	Feb. 1, 2003	

Figure 4-8. Sample User Interface for Product Modeling

CASE STUDY

The developed virtual shop modeling system was applied to model a steel fabrication facility. The fabricator needs a proper planning tool that will enable them to manage the shop in a proactive rather than reactive manner. The scope of the case study was to model detailing operations in Shop B and Shop C, and fitting, welding, and material handling operations in Shop C. Stations in these shops are configured to handle structural steel, such as columns, beams and bracings. There are six detailing stations, six fitting stations, and six welding stations. Figure 4-9 shows a schematic layout drawing of Shop C. Materials are handled by three 10-ton bridge cranes and a number of fixed jibs.

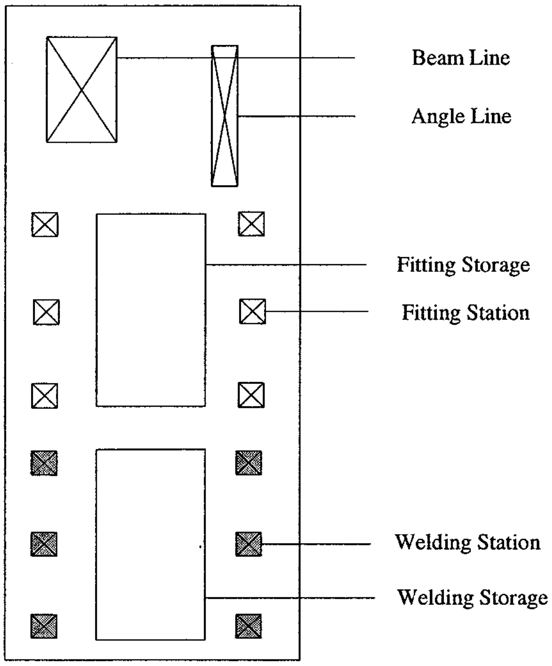


Figure 4-9. Schematic Layout Drawing of Shop C

The CAD system used by the drafting department of the company is StruCAD, which is a specialized system for steel drafting. Entity model data are gathered automatically from the StruCAD system. The fabrication facility was modeled using the steel fabrication modeling template. Detailing stations are equipped with CNC machine tools, including beam lines, plate punch and plasma cutting systems, plate drill and plasma cutting systems, angle lines, and burning table systems. Virtual machining station models were built and detailed using the Common Template in *Simphony* (Song 2003). Figure 4-10 shows screenshots that illustrate the hierarchy structure of the virtual shop model. Form left to right, these screenshots are of plant, shop, and station models.

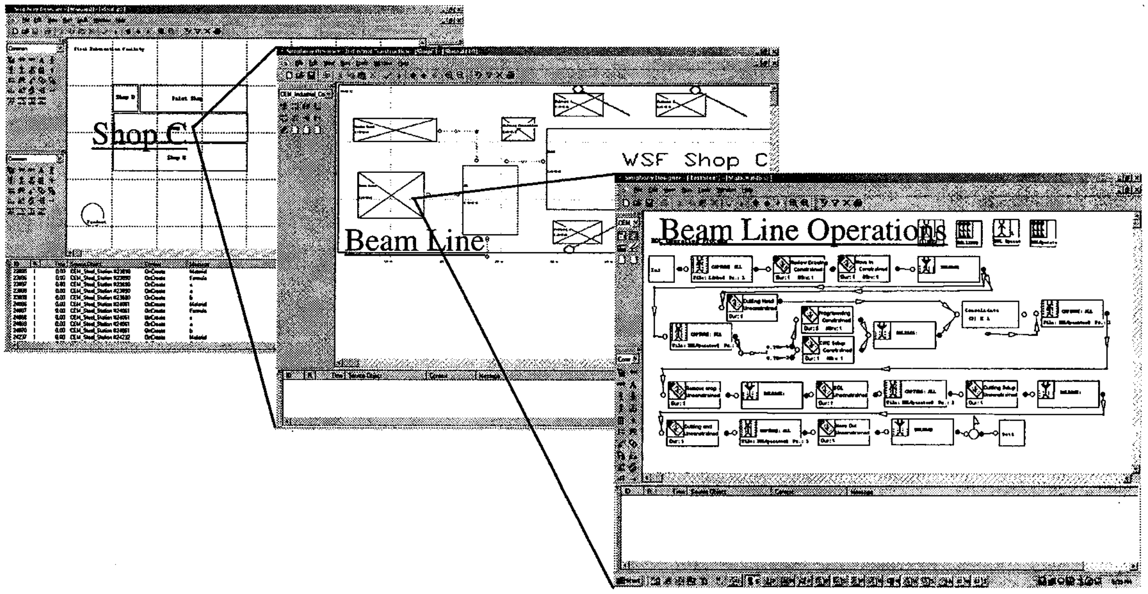


Figure 4-10. Virtual Shop Model Hierarchy

The fabrication of 120 steel pieces was simulated using the virtual shop model. The simulation experiment showed that the average total duration for shop fabrication was 1777.8 minutes, with a standard deviation of 65 minutes. The 90% confidence interval for the duration is from 1564 to 1884 minutes. The actual duration collected from the company's shop timesheet system was 1875 minutes. The value of the total duration from the simulation experiment is relatively lower than that of the actual duration. A possible explanation is that the virtual shop model does not explicitly model the shop information flow and its delay, such as scheduling, drawing transmission, team coordination, and supervision. In general, the virtual shop model can be used to represent the fabrication shop operations. WSF's other shops will use the same strategy for modeling and validation. The ultimate objective is to model the whole fabrication facility for project planning.

CONCLUSIONS

The developed modeling system is intended as a platform for building virtual shop model for steel fabrication capable of capturing steel products, resource interactions, and uncertainties in an industrial shop environment. Besides normal uses of simulation modeling in new system design and bottlenecking analysis, users can also perform scheduling tasks using this model. It can also be used in the day-to-day operation of a fabrication facility. The model complements other planning and scheduling systems in order to validate plans and confirm schedules. It provides steel fabricators with the ability to evaluate the system's capacity for new orders, unforeseen events such as machine downtime and changes in operations. It assists shop superintendents in determining the work quantity, the required duration, and workloads of each resource.

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CHAPTER 5: MODELING UNCERTAINTY WITH AN INTEGRATED SIMULATION SYSTEM[1]

INTRODUCTION

Construction projects are often characterized by a high degree of uncertainty due to the influence of numerous factors. A major contributor to uncertainty in any construction project is the timing or scheduling of its activities (Carr 1979). Uncertainty about activity durations is often a result of uncertainty existing in the work scope definition, physical features of the facility to be constructed, working environment, resource allocation, and activity constraints. Uncertainty may also lie in subjective and vague decision-making regarding the selection of construction methods, activity dependence relationships, inspections, and activity execution and activation (Ayyub and Gupta 1994; Zhang et al. 2003).

The performance of a construction project in terms of time, cost, and quality is subject to a large degree of fluctuation due to the presence of uncertainty. For an operation in an open area, the productivity achieved in poor weather conditions is considerably lower than that achieved in favorable weather conditions. For industrial shop fabrication, the expected productivity and decisions about assembly routing change considerably due to significant variations in terms of physical features and the complexity of an assembly. To create a reliable project plan, all uncertain elements that may affect the progress of the

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[1] *A version of this chapter has been submitted for publication. CSCE, Canadian Journal of Civil Engineering.*

project must be identified and accounted for. Some of the uncertainty may be reduced or even removed when additional information becomes available, while some remains outside the control of the project management team. Ignoring or excluding uncertainty from the project plan may cause schedule delays and cost overruns.

Uncertainty can be identified by domain experts with knowledge about, and experience with, the specific type of a given construction project. Uncertainty and its impact are usually considered subjectively in a project plan. Thus, how well the plan accounts for uncertainty depends upon the experience and skill of the project planner. However, due to the complex nature of uncertainty, the intuitive consideration of the combined impact of uncertainty often fails to produce reliable project estimates (Ahuja and Nandakumar 1984).

Identifying and classifying uncertainty, in order to model and subsequently reduce uncertainty is an important aspect of project planning. This research described an approach that systematically studies uncertainty in steel fabrication following three steps. First, the nature and types of uncertainty are identified. Second, an integrated simulation framework that combines simulation and Artificial Neural Network (ANN) modeling techniques is proposed to quantitatively model the uncertainty in a project, and its impact on project performance. Third, the identification and measurement of uncertainty are used to direct uncertainty reduction efforts. In the following section, previous studies in modeling uncertainty in construction projects are reviewed.

LITERATURE REVIEW

Identifying uncertainty and understanding its characteristics are the first steps toward modeling and reducing it. Uncertainties that affect construction project performances globally and those that are specific to a particular construction process have both been studied intensively in the last several decades. Some of the significant factors include weather, space congestion, crew absenteeism, design changes and rework, economic conditions, learning curve, and labour unrest (Ahuja and Nandakumar 1984). Many studies that model construction productivity have identified influencing factors that are specific to a certain construction activity, such as excavation (Chao and Skibniewski 1994), formwork (Portas and AbouRizk 1997), and pipe spool fabrication and installation (Lu et al. 2000). Thereafter, we will refer to these influencing factors as "uncertainty variables" in the context of modeling uncertainty. The definition of uncertainty variables may remain inconclusive due to the unique nature of the construction industry. However, the nature and types of uncertainty should be studied to offer a guideline for the industry in identifying uncertainty variables so that proper techniques can be employed to quantify their impact and proactive measures can be taken to reduce any negative impact.

Modeling uncertainty is likely the most pervasive and the most difficult aspect of analyzing a construction system. Many quantitative techniques based on classic set theory, probability theory, fuzzy set theory, and artificial intelligence were explored in order to evaluate quantitatively these uncertainty variables and their combined effects. These techniques can be conceptually divided into two categories: Aggregate Input-process Method (AIM) and Separate Input-process Method (SIM) (AbouRizk and Sawhney 1993). AIM models the aggregated effects of all elements of predictable and unpredictable uncertainty using a statistical distribution function representing the variation of activity duration or decision-making (AbouRizk and Sawhney 1993). This distribution function incorporates all past knowledge with similar situations and all uncertainty variables. Random samples are generated based on this distribution during simulation experiments. Carr (1979) recognized that many of uncertainty variables are shared between project activities. Therefore, activity durations are not independent of each other. However, an underlying assumption of most AIM methods is the independency of activity durations.

Therefore, it is advantageous to model explicitly the occurrence of uncertainty variables, and quantify their impacts on project performance in order to improve the accuracy of the overall project plan. When data are available for uncertainty variables, SIM methods can be used to model the influence of uncertainty variables using mathematical functions, elemental data, and other statistical distributions and random input processes (AbouRizk and Sawhney 1993). Carr (1979) developed a model for uncertainty determination (MUD) to quantify uncertainty in a project schedule. The duration of each activity is sampled from a distribution that contains the effects of variables that are independent of calendar dates. Random variables which are dependent on calendar date, such as weather, are determined randomly. The sensitivity of each activity to these variables is also incorporated into the simulation of the project CPM network to evaluate the impact of these variables. Wales and AbouRizk (1996) described a combined discrete-event and continuous simulation method for project planning. A project CPM network is first implemented in a discrete-event simulation model. Next, mathematical and statistical methods are used to model continuous weather processes. And a neural network model is used to estimate the impact of weather conditions on productivity as a multiplier. Zhang et al. (2003) proposed the application of fuzzy logic to discrete-event simulation in dealing with uncertainty in construction operations. The quantity of resources required to activate an activity are modeled with fuzzy sets in linguistic terms. The duration of the activity, which varies with the quantities of resources involved, is then determined through the fuzzy rule-based model.

Uncertainty variables exist not only in the constantly changing working environment, but also in the physical complexity of the product, which is the facility to be constructed. The need for increased project planning accuracy is ever increasing along with the complexity of construction projects, especially those in the industrial construction sector. The complex interactions among controllable and uncontrollable variables and their combined and correlated effects on project performance must, therefore, be further investigated.

TYPES OF UNCERTAINTY

Uncertainty classification in construction projects is necessary to allow project engineers to follow a structured methodology to identify uncertainty variables and select proper techniques to model them. In this regard, studies of uncertainty in structural engineering were found to be helpful in understanding the origins and nature of uncertainty in the context of construction projects.

Uncertainties in construction can be conceptually classified into objective and subjective types according to their origins (Ayyub and Gupta 1994). According to Ayyub and Gupta (1994), sources of objective uncertainty include physical randomness, statistical uncertainty, lack of knowledge, and model uncertainty. Subjective uncertainty originates from expert-based assessment of system parameters, empirical determination of cause-effect relationships among system parameters, and other human factors, such as human and organizational errors and conflicting information (Ayyub and Gupta 1994).

Uncertainty in construction may lie in either the complexity of a facility or the working environment in which the facility will be constructed. Accordingly, the uncertainty variables can be classified into product-related uncertainty and environment-related uncertainty. Uncertainty variables can be defined as controllable or uncontrollable (Flanagan and Norman 1993). Controllable variables are those that engineers can manipulate or feel confident about, even though they may vary over time and space. Deterministic analysis can be used to model the occurrence of controllable variables, such as shift arrangement and resource allocations. Probabilistic analysis can be conducted to represent the occurrence of uncontrollable variables which are out the control of engineers. The combined effect of controllable and uncontrollable variables, if any, must also be studied. Within a defined system boundary, one can easily identify many cause-effect relationships. For instance, activity duration depends on the outcomes of various factors that affect it. Thus the uncertain activity durations can be modeled by their influencing factors. From this perspective, uncertainty variables can be classified as dependent variables and independent variables. The cause-effect relationships can be treated as subsystems and are modeled separately (Ayyub and Gupta 1994). Applications of this system decomposition and modeling of cause-effect relationships can facilitate the modeling of complex construction project systems and increase the overall model accuracy.

Engineers can identify critical issues by discovering the sources of uncertainty variables in order to reduce the negative impact of uncertainty. Accordingly, uncertainty variables can be classified as reducible and irreducible types (Georgopoulos 1995). Reducible uncertainties are those that can be reduced or even removed by means of collecting additional information about a project or using advanced modeling techniques. Uncertainty variables that are inherently random due to their nature are considered to be irreducible.

MODELING UNCERTAINTY

AIM is often the only option in modeling uncertainty when uncertainty variables and their effects cannot be identified. As discussed above, many studies show that variables that affect construction projects or a specific construction process can be identified, and data can be collected from historical projects or time studies. This suggests the use of SIM methods to model uncertainty. The project planning scope can be extended in order to incorporate more relevant uncertainty variables that reflect cause-effect relationships. Appropriate techniques can be applied to model the occurrence of these variables and their combined effects on project performance explicitly, ensuring information available at the time of planning will be efficiently utilized to generate the best possible results. The proposed framework for modeling uncertainty follows this approach.

Integrated Simulation System

Simulation has been proposed as an indispensable problem-solving methodology for modeling complex construction processes (Halpin and Riggs 1992). Uncertainty variables can be effectively captured in a simulation model in order to model their occurrence and analyze the impact of uncertainty associated with a construction project. With the increasing complexity of construction projects, simulation models are expected to be powerful and flexible enough to capture and model all major uncertainty variables. An integrated construction simulation system is proposed for this purpose. The conceptual framework of the system is illustrated in Figure 5-1.

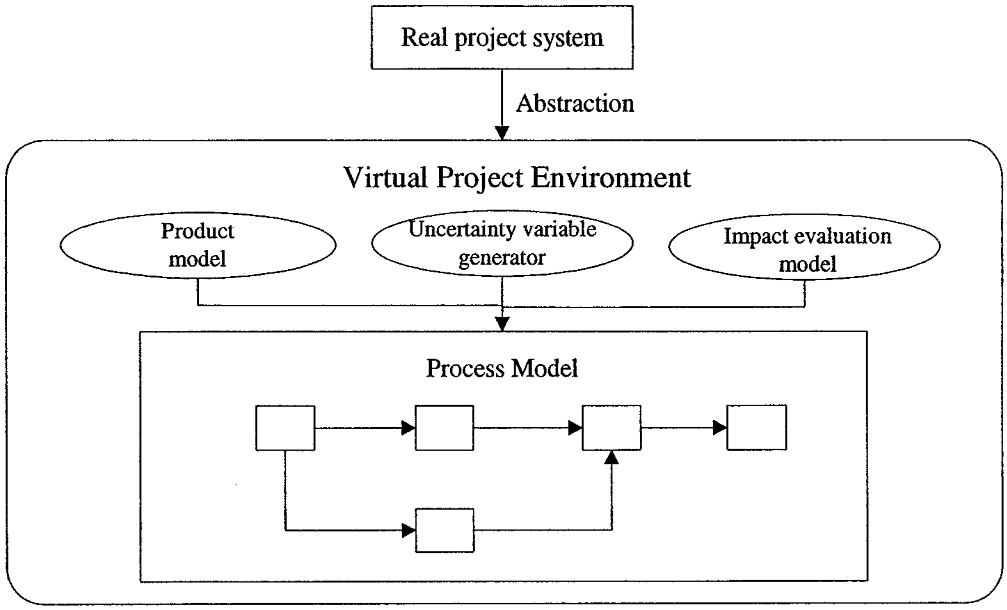


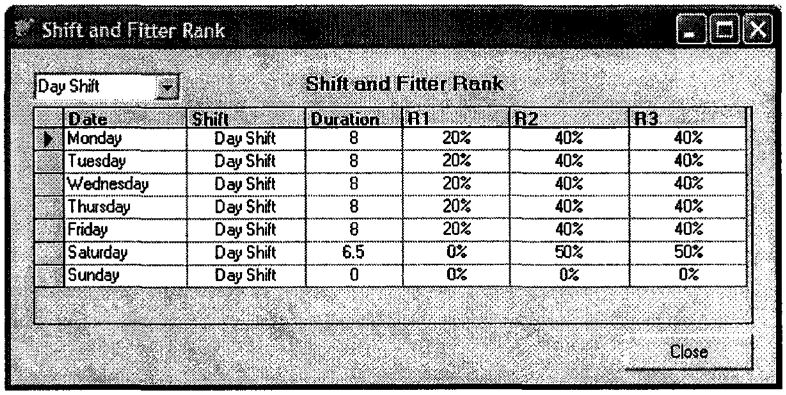
Figure 5-1. Integrated Construction Simulation System

A real construction project can be abstracted and represented by a model in the virtual project environment. The virtual project environment consists of the product model, process model, uncertainty variable generator, and impact evaluation model. The selection of construction methods and the productivity which can be achieved depends greatly on the physical features of the facility. The product model stores all product definition data, including physical attributes and processing information for each work package of the targeted facility. A CAD model of the facility, which captures product definition data in an electronic format, can be conveniently mapped to the product model. If no detailed product definition is available, deterministic values or stochastic distribution techniques can be used to represent the key physical features of work packages. The process model resembles a conventional resource-interaction simulation model that stores information regarding construction methods, resources, construction activities, and their sequence. Uncertainty variables can be defined using statistical distribution models or precise stochastic models.

The uncertainty variable generator is a collection of such models. An engineer can define statistical distributions using historical data or personal experience. For more on the use of precise stochastic uncertainty generation models, the reader is referred to the methodology presented by Wales and AbouRizk (1996).

The nature and magnitude of the impact of uncertainty variables on project performance is modeled by a collection of impact evaluation models. However, it becomes difficult to model the cause-effect relationship between uncertainty variables and project performance directly using a simulation model, due to the complex nature of these variables. Furthermore, the effects of these variables are not intuitively determinable. It is also difficult to incorporate these effects into an analytic model. Therefore, in the proposed system, ANN is proposed to develop the impact evaluation model for approximating the complex cause-effect relationship when relevant historical data are available or can be collected. A review on ANN is provided in Chapter 1.

This modeling approach is applied to the virtual shop model described in Chapter 4 to model uncertainty involved in a fabrication shop environment. In the virtual shop model, uncertainty variables are defined in the uncertainty variable generator. Some temporal variables are modeled using the Common Template offered in *Simphony* (AbouRizk and Hajjar 1998; AbouRizk and Mohamed 2000), such as the eight-hour day shift followed by the ten-hour night shift arrangement. A set of user interfaces was defined to facilitate the management of these variables. Figure 5-2 shows an example of an interface designed to facilitate defining work shift and the percentage mix of fitters' rank. A study on the steel fitting operation is used to illustrate the neural network modeling. The steel fitting operation involves fitters fit and tack-weld detail components to a steel piece temporarily for the final welding operation. The same modeling strategies may also be developed for approximating other forms of cause-effect reasoning by following the same approach presented herein.



Shift and Fitter Rank

Date	Shift	Duration	R1	R2	R3
Monday	Day Shift	8	20%	40%	40%
Tuesday	Day Shift	8	20%	40%	40%
Wednesday	Day Shift	8	20%	40%	40%
Thursday	Day Shift	8	20%	40%	40%
Friday	Day Shift	8	20%	40%	40%
Saturday	Day Shift	6.5	0%	50%	50%
Sunday	Day Shift	0	0%	0%	0%

Figure 5-2. An Example Interface for Defining System Parameters

ANN Modeling for the Steel Fitting Operation

The purpose of this study is developing an ANN model to predict the steel fitting duration based on the complexity of a steel piece and the working environment. This involves identifying influencing factors that affect steel fitting, collecting productivity data, and training and testing the ANN model. The trained ANN model is eventually incorporated into the virtual shop model.

Data Collection

Over the course of this study, two brainstorming sessions were held. The first session included researchers, the shop production manager and the fitting foreman, while the second session included researchers, the fitting foreman and fitters. Factors influencing the fitting operation were identified through the first session. Product-related variables include piece weight, piece length, the number of cutouts, and the number of fittings. Work environment-related variables include fitter rank and working shift. Table 5-1 shows a description of the identified factors and their ANN input data types. The data types are described in the section titled "ANN Training and Validation" in Chapter 3.

Table 5-1. Influencing Factors for Steel Fitting Productivity

Factor	**Data Type**	**Option and Remarks**
Piece weight	Raw	Piece weight
Piece length	Raw	Piece length
No. of cutouts	Raw	Number of copes and blocks
No. of fittings	Raw	Number of detail fittings
Fitter rank	Binary	Ranked by experience; 1- Apprentice, 2- Journeyman Fitter I, 3- Journeyman Fitter II
Shift	Binary	Day shift/night shift

The second brainstorming session defined a method for data collection, and developed a partnership between researchers and both the fitting foreman and fitters, which subsequently proved to be very helpful during the data collection process. To facilitate this process, a stamp was designed, as shown in Figure 5-3. The foreman stamps a fitting drawing then passes it to a fitter. The fitter records the required information onto the stamp and return the drawing when he or she finishes fitting a piece. The required information from fitters includes their rank, the start and finish time of a fitting operation, and time loss due to interruptions and reworks. CAD models supplied all other product-related information, such as piece weight, length, and number of fittings. 131 data points were collected from WSF Shop C. The data were statistically analyzed for significance and consistency. Summaries of the collected data are shown in Tables 5-2 and 5-3. For confidentiality reasons, fitting duration data were scaled.

Fitter Rank	1	2	3
Lost Duration			
Mistake Correction Duration			
	Date	Time	
Start	/ / 2003	:	am pm
End	/ / 2003	:	am pm

Figure 5-3. Data Collection Stamp

Table 5-2. Summary of the Collected Fitting Data

Factor	Min	Max	Mean	Std. dev.
Weight (Kg)	5.00	2915.00	401.84	609.79
Length (m)	0.15	14.13	4.58	3.31
Number of fittings	1.00	33.00	5.70	4.82
Number of cutouts	0.00	6.00	1.33	1.42
Fitting duration (min)	5	212	39.01	28.16

Table 5-3. Fitter Rank and Shift

Factor	Description	Total
Fitter experience	Rank 1	34
	Rank 2	56
	Rank 3	41
Shift	Day	95
	Night	36

ANN Training and Validation

The developed ANN model is a back-propagation network with nine input nodes, two hidden layers, and one output node at the output layer. The output of the network is the fitting duration. *Neuroshell 2* (NeuroShell 2 2000) was used to train the network. 111 data points were randomly selected and 20 data points were reserved for testing. The training results are summarized in Table 5-4, and are accompanied by a description extracted from *Neuroshell 2*. Figure 5-4 shows the network predictions plotted against the actual duration values for the test data points. The average absolute error is 0.75 minute and the maximum absolute error is 38.9 minutes for the test data set. Considering the wide duration range, the trained network is considered relatively accurate in predicting the fitting duration with a satisfactory margin of error.

Separate ANN models can be constructed for each cause-effect reasoning, and included in the collection of impact evaluation models. These trained models can be integrated with the process model. In the case study, the trained neural network model was compiled as a Dynamic Link Library (DLL) file using *NeuroShell 2* and included and referred by the virtual shop model in *Simphony* during run-time.

Table 5-4. ANN Training Results

Coefficient	**Value**	**Description**[1]
R Squared	0.86	Coefficient of multiple determinations is a statistical indicator usually applied to multiple regression analysis. It compares the accuracy of the model to the accuracy of a trivial benchmark model wherein the prediction is just the mean of all of the samples. A perfect fit would result in an R squared value of 1, a very good fit near 1, and a very poor fit less than 0.
Correlation Coefficient r	0.93	(Pearson's Linear Correlation Coefficient) This is a statistical measure of the strength of the relationship between the actual vs. predicted outputs. The r coefficient can range from -1 to +1. The closer r is to 1, the stronger the positive linear relationship, and the closer r is to -1, the stronger the negative linear relationship. When r is near 0, there is no linear relationship.
Mean Squared Error	182.03	This is the mean over all patterns in the file of the square of the actual value minus the predicted value, i.e., the mean of $(\text{actual - predicted})^2$
Mean Absolute Error	10.21	The mean over all patterns of the absolute value of the actual minus predicted, i.e., the mean of (actual – predicted)
Min Absolute Error	0.00	The minimum of (actual – predicted) of all patterns.
Max Absolute Error	46.39	The maximum of (actual – predicted) of all patterns.

[1] Extracted from *NeuroShell 2 User Manual* (NeuroShell 2 2000)

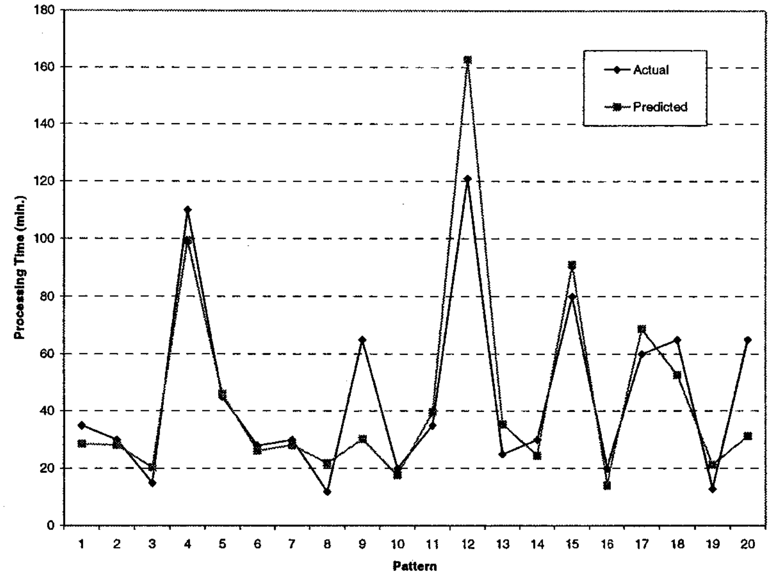


Figure 5-4. Actual vs. Predicted Fitting Duration for Test Data Points

Integrated Model Experiment Algorithm

The experiment algorithm of the integrated simulation system embedded with ANN models can be summarized as the following steps:

1. Set work packages' attributes based on product definition data captured in the product model and release these work packages as flow entities to the process model.
2. Update the values of environment-related variables according to their corresponding uncertainty variable generation models.
3. Simulate the execution of construction operations until an impact evaluation, such as determining activity duration, is required.
4. Recall the corresponding ANN model in order to generate an output based on the values of product-related variables and the current values of environment-related variables.
5. Update the progress of those activities affect by the change of working environment.

6. Continue the simulation until all works packages are processed.

This algorithm models effectively the correlation among activity durations as discussed by Carr (1979). Activities of a construction project are normally conducted in the same environment. The sharing of uncertainty variables results in a correlation among activity durations. Multivariate (or joint) probability distributions (Law and Kelton 2000) can model this correlation statistically without excessive scrutiny of the causes. However, this modeling method can be inaccurate and time-consuming due to the complex nature and amount of correlations existing in activity durations. In the proposed method, influencing factors and their effects are modeled explicitly for predicting activity durations. Variables can be declared as global simulation variables whenever necessary, thereby sharing their occurrence and impact simultaneously with all activities that may be affected. Activity durations can then be determined by ANN models, rather than randomly sampling the durations from statistical distributions.

Performance Comparison

In order to evaluate the performance of the model, the proposed integrated model was compared to a simulation model, which uses a fitted statistical distribution in modeling the fitting duration. The test examines the effect on the estimate of mean system performances when using different simulation input modeling methods.

For the fitting case study, the 131 data points used originally for ANN modeling were used to develop a standard statistical distribution. A beta distribution, Beta (1.31, 13.16), with a lower bound as 1 and an upper bound as 480 was developed and validated using BestFit (BestFit 1999). Figure 5-5 shows both the histogram of the sample data and the probability density function of the fitted Beta distribution.

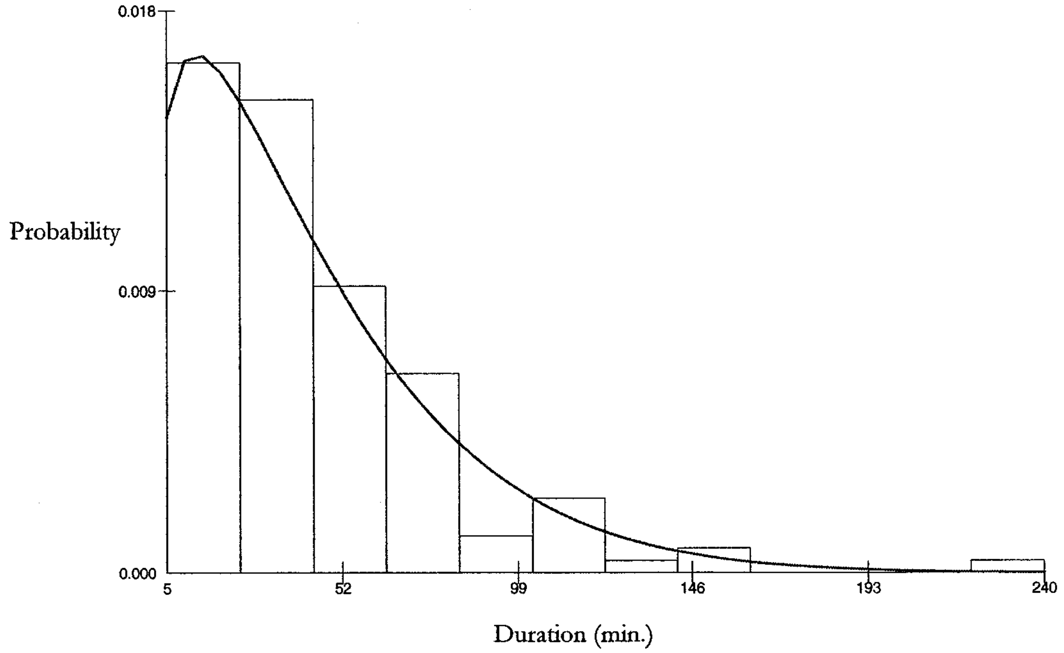


Figure 5-5. Histogram and the Fitted Beta Distribution

A sample of 120 steel pieces was collected for the performance comparison. In Scenario 1, the developed ANN model for steel fitting was embedded into the virtual shop model. It is assumed that all ANN inputs are known. In Scenario 2, the fitted Beta distribution was used as an input for the virtual shop model. Finally, in Scenario 3, the actual fitting duration was used in the virtual shop model; this scenario can be used as a base case for comparison. All configurations and inputs of the virtual shop model, except the fitting duration, were kept the same in all scenarios for the purposes of an objective comparison. The system performance examined is the total duration of fabrication and the queue length of two bottlenecking storages in the fitting and welding areas of Shop C.

The results of the experiments are shown in Table 5-5. Compared to Scenario 3, Scenario 1 predicts all performance measures more accurately than Scenario 2. Specifically, Scenario 1 predicts the total duration with a relative error of –3.6%, while Scenario 2 results in a relative error of 12.2%. This experiment shows that by explicitly modeling uncertainty variables and their effects using ANN, the project performance estimates can be improved dramatically.

Table 5-5. Model Performance Comparison

NO.	Total Duration (min)			Fitting Storage			Welding Storage		
	Avg.	Std. Dev.	95% Interval	Avg.	Std. Dev.	95% Interval	Avg.	Std. Dev.	95% Interval
1	1765	91	(1586,1943)	31.6	0.7	(30,33)	22.7	1.4	(20,25)
2	1904	151	(1609,2199)	33.5	2.2	(29,38)	19.6	3.3	(13,26)
3	1756	69	(1620,1891)	31.2	0.5	(30,32)	22.4	0.6	(21,24)

REDUCING UNCERTAINTY

The accuracy of a project plan is achieved by reducing uncertainties. Uncertainty can be reduced by collecting and analyzing relevant information about uncertainty variables. A sensitivity analysis of uncertainty variables reveals the magnitude of their impact upon project performance. This analysis suggests a prioritization of data collection effects in order to reduce uncertainty.

Table 5-6 shows the sensitivity analysis performed for the fitting case study using *NeuroShell 2*. The contribution factor is a rough measure of a variable's relevance in predicting the network's output relative to other input variables within the same network. The higher the contribution factor, the more a variable contributes to the prediction. The results show that the number of fittings is the most influencing factor, followed by the fitter's rank.

Table 5-6. Contribution Factors for ANN Inputs

Inputs	Contribution factors
Number of fittings	0.25
Fitter rank	0.23
Number of cutouts	0.22
Shift	0.12
Length	0.11
Weight	0.08

Three scenarios were tested and compared to show the effect of differing amounts of information and of different modeling techniques upon the variability of model outputs. The scope of the experiment is limited to a study of the total fitting duration for 50 steel pieces. In scenario 1, it is assumed that there is no information available for these 50 pieces, so the fitted Beta distribution is used to represent the fitting duration. In Scenarios 2 and 3, the trained ANN model is used to predict the fitting duration. In Scenario 2, it is assumed that all input data, except the number of fittings for each piece, are provided for these 50 pieces. The number of fittings of a piece is considered as an uncertainty variable and modeled by a statistical distribution developed based on historical data. Similarly, in Scenario 3, it is assumed that only weight information is missing for these 50 pieces, and that the weight distribution is represented by a statistical distribution developed based on historical data. The model for each scenario was run 200 times. During simulation runs, for Scenarios 2 and 3, random samples are generated based on these statistical distributions for each piece, then fed to the ANN model to predict the fitting duration. Probability density functions of the total duration derived from these three scenarios and the actual total duration are plotted in Figure 5-6. The effect of reducing uncertainty with an increasing amount of information can be easily identified. Scenarios 2 and 3 were found to predict the total duration more accurately than Scenario 1. The variability of the total duration is quite different for each scenario. The standard deviation is 226, 78, and 62 for Scenarios 1, 2, and 3, respectively. A comparison of Scenario 1 with Scenarios 2 and 3 shows that the variability of the total duration is dramatically reduced as information about the steel pieces and the working environment increases. Also, the variability of the total duration due to the uncertainty in the number of fittings is larger than the variability due to the uncertainty in weight in this case. The uncertainty in input variables possessing higher output contributions tends to increase the variability of the output more than other minor variables.

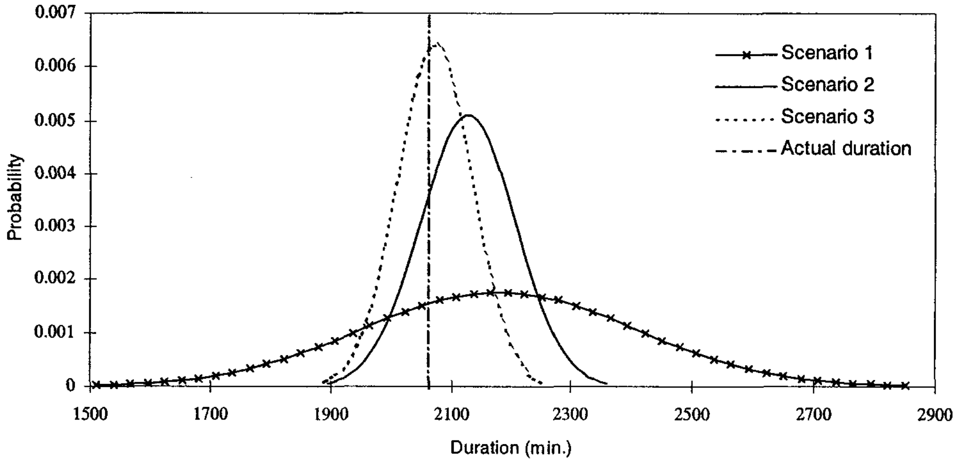


Figure 5-6. Sensitivity of the Amount of Information to the Tôtal Fitting Duration

CONCLUSIONS

The ability to estimate the uncertainty associated with a construction project accurately and reliably is key to the successful planning and completion of a construction project. Contractors can benefit greatly from the reduction and control of uncertainty prior to commitment. The research describes a methodology to help engineers identify, model, and reduce uncertainty inherent in construction projects. With the appropriate information regarding identified uncertainty variables, the impact of these variables to the project's performance can be evaluated by the proposed integrated simulation system.

There are different forms of uncertainties, including vagueness and ambiguity. Each of uncertainty modeling theories, such as probability theory and fuzzy set theory, captures a different form of uncertainty and they should be combined to deal with the modeling of a real system. Future research will identify and apply appropriate modeling techniques to model other forms of uncertainty in construction projects.

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CHAPTER 6: VIRTUAL SHOP SYSTEM FOR PRODUCTION PLANNING[1]

INTRODUCTION

Steel construction projects are often fast paced. On-site construction time is reduced by fabricating steel pieces off-site prior to erection (AISC 1999). Steel fabrication requires careful planning and close coordination with other activities, such as steel design and approval, material procurement, delivery, and erection to ensure a streamlined, delay-free process. A number of factors, including the project complexity, labour and equipment allocation and efficiency, shop status, production policies, quality of scheduling and supervision, engineering design, coordination with erection schedules, and contract specifications, greatly affect the fabrication process and its productivity. Competitive pressures also force steel fabricators to disrupt schedules in-progress in order to accommodate frequent requests from key customers for changes in design and/or delivery schedules (Karumanasseri and AbouRizk 2002).

The main objectives of managing a fabrication shop are on-time delivery, short customer lead-time, and maximum utilization of resources. To achieve these objectives, it is important to balance these potentially conflicting objectives with considerations of the influencing factors that affect the steel fabrication productivity. Traditionally, long-term planning of an industrial shop, which includes determining the plant layout and new

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[1] *A version of this chapter has been submitted for publication. ASCE, Journal of Computing in Civil Engineering.*

equipment investments, relied much upon the production engineers' experience. For short-term project planning, a production engineer would create a realistic Master Production Schedule (MPS) for the project at hand. On the shop floor, experienced shop superintendents attempt to complete the jobs completed by the delivery date estimated in the MPS. Network-based tools, such as Critical Path Method (CPM), are used by steel fabricators for project-level planning and control. These methods are not effective for making decision on the shop floor due to assumptions and an inability to deal with the presence of uncertainty, the interaction of resources, and complex relationships between activities, which limit the methods' ability to describe details at the process level (Pritsker et al. 1997). Many analytic optimization-based scheduling algorithms have been introduced (Hopp and Spearman 2002); however, most of these algorithms are highly simplified and static in nature, which limits their direct applicability to industrial fabrication shops for the purposes of productivity analysis and production planning. The effectiveness of current practices depends greatly upon the engineers' experience. Often, the human mind is incapable of grasping the combination of factors at one time. Thus, it is generally both unstable and risky to make decisions based on "gut instinct" alone.

Most long-term and short-term planning problems found in a fabrication shop have a strong experimental component: a good plan is normally developed by comparing various alternatives. This axiom has motivated the author to develop a new planning methodology for steel fabrication shops, namely, "experimental planning". A virtual shop system, which was developed using the virtual shop modeling system described in Chapter 4 and system integration techniques, enables production engineers to conduct experiments that will facilitate decision-making. The following section describes the proposed experimental planning method. The third section outlines the architecture of the virtual shop system, and the supporting techniques utilized. The capacity of the virtual shop model and of the experimental planning concept are demonstrated using several case studies.

EXPERIMENTAL PLANNING

Production planning takes into account a number of factors, and acts in the light of complex, dynamic, and uncertain realities. Production engineers are responsible for making decisions regarding process, personnel, and production strategy, in a planning horizon that ranges from long-term strategic planning to short-term day-to-day scheduling. For example, questions arise concerning the risks and benefits of investing in new fabrication technologies, the radical changes of practice found in some of the new approaches, such as the lean manufacturing system, the impact of job sequencing and priority to the MPS, and the impact of labour skill and the quality of supervision on productivity. An accurate quantitative answer to these questions is extremely difficult to give, due to the numerous influencing factors, their interactions and combined effects, and the presence of uncertainty.

Production planning is generally perceived to be somewhat speculative rather than an experimental science. However, the complexity of planning does not prevent experienced engineers from using their experience and knowledge to identify influencing factors, to form an imaginary scenario and its alternatives, to evaluate empirically the performance of these alternatives against established evaluation criteria, and to produce an acceptable schedule. This observation shows that certain aspects of planning are akin to experimentation procedures used in the natural sciences. An essential feature of any science is the application of hypotheses, experimentation, and analysis for the purpose of developing knowledge (Davis and Holt 1993). A hypothesis is an educated guess regarding the relationship between cause and effect. Experimentation is the search for these cause and effect relationships in nature. A conclusion enables researchers to apply their findings in order to produce a desired effect. Likewise, production planning has the potential to develop knowledge through experimentation. This research argues that experimentation is an important approach for production planning.

As experimentation within a real production system is potentially risky, inefficient, or simply impossible, this approach to experimentation did not offer an effective solution for production planning. Computer simulation, on the other hand, allows a simulated shop's performance to serve as a vehicle for experimentation. The virtual shop system, described later in this chapter, employs simulation, ANN, and real data gathering techniques to develop a fine-grained simulation model. The virtual shop system generates a synthetic and immersive experience for the user to explore an interactive virtual production environment. It provides a flexible tool allowing users to design, model, and evaluate possible future scenarios while considering various related factors and their expected influence upon production performance. Users can create and define a shop model in an intuitive, graphical, and collaborative way, perform "what-if" analyses, and analyze "how-to-achieve" questions. Experimenting in a computerized environment rather than a real system makes systematic experimentation possible, easy and, ultimately, profitable. Specifically, experimentation in production planning can employ a general procedure that may be summarized as follows:

1. Identify measures of performance.

State the objective of the experiment, such as prediction, optimization, and sensitivity analysis. In the light of this objective, identify the criteria for measuring performance, such as cycle time and resource utilization.

2. Identify independent variables and data collection.

Identify system variables affecting the production performance, such as job dispatching rules and resource allocation. Determine an operating range of values for each variable.

3. Development of alternatives

There are always alternatives to any course of action because of the operating range of system variables. Either use experience or follow appropriate experimental design methods, such as factorial design or Design Of Experiment (DOE) (Law and Kelton 2000), to develop alternatives.

4. Experimentation

Perform the experiment and evaluate the alternatives in the virtual shop model. Record the system variables and their effect on system performance.

5. Comparisons and conclusion

Analyze and summarize the experiment's data. This exercise will show the trends related to the effect system variables have upon system performance. Based on these trends, inferences and conclusions can be drawn. The user may repeat Steps 3 and 4 in order to determine the most satisfying solution. The alternative that produces the solution most responsive to the desired objectives will be chosen as the solution to the problem being studied.

THE VIRTUAL SHOP SYSTEM

System Architecture

A three-tier architecture is proposed for the virtual shop model system. As illustrated in Figure 6-1, the system has a database tier, an application logic tier, and a user interface tier. The primary consideration in developing this three-tier architecture is to offer users an integrated, collaborative, and user-friendly environment for experimental planning, and to cope with the potential alterability of shop configurations and various component models in meeting the ongoing requirements of users.

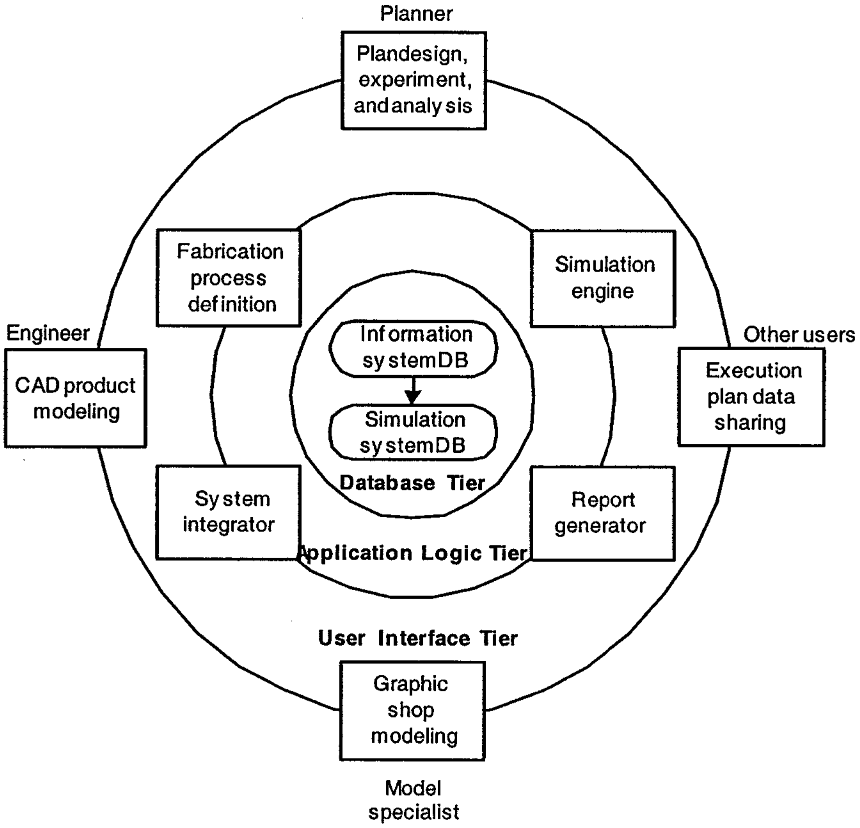


Figure 6-1. Virtual Shop Model Architecture

The database tier stores data required for the operation of the virtual shop model, as well as for the output of simulation experiments. Simulation input data collected through time studies and shop information systems are aggregated and sorted in a data warehouse.

The application logic layer consists of the fabrication facility definition, the simulation engine, the system integrator, and a report generator. The fabrication facility model is a virtual representation of the steel fabrication shop, which defines shop facilities and the fabrication process. The virtual shop modeling system described in Chapter 4 can be used to model a fabrication facility. The simulation engine provides basic services for discrete-event simulation, such as queuing and event scheduling. *Simphony* (Hajjar and AbouRizk 2002) is the simulation engine of the virtual shop model. The application logic tier is unique to each fabrication facility. Fabrication facility models must be defined for different fabrication facilities that vary in terms of layout, resource configurations, and production policies. The system integrator contains software modules for integrating the virtual shop model with external applications, such as CAD systems, scheduling, and animation applications. The report generator stores scripts that enable the generation of simulation experiment reports.

The outmost tier of the architecture is the user interface tier, which consists of a number of user interfaces that interact with end-users, including shop planners, design engineers, model specialists, and other shop employees. The graphic shop modeling tool allows a simulation specialist to build and maintain a sophisticated shop model that planners can reuse. Because the fabrication shop and its processes may be subject to frequent changes, the modeling tool allows a model specialist to modify the shop layout, resources, and the fabrication process easily in order to represent the latest shop configurations. The complex fabrication process definition is transparent to virtual shop users. The model definition is stored in the application logic tier, hiding the shop configuration, its complicated process logic, and tedious data acquisition tasks from planners and other users. The CAD system used by design engineers is an integral part of the virtual shop model, since the steel structure is initially modeled as a digitized CAD product model. The product model represents the steel structure modeled in the virtual shop model. After the CAD product model is created and imported into the virtual shop, planners can use customized user interfaces to create process plans and manipulate resources and inventory. Experiments can be conducted to test the various configurations of production plans to assist in the decision-making process. The final execution plan and other relevant information can be shared by other shop employees.

Simulation has reached a technological level providing users with the simplicity, flexibility, and integration capabilities necessary for the development of a fully digital simulation environment (Murphy and Perera 2001). The following sections describe the strategies used in developing the virtual shop system, including data-driven simulation, data modeling, system integration, and visualization.

Data-Driven Simulation

In the shop facility model, the production logic is separate from the system parameters, which include product definition, process plans, resource allocation, and production rules. The production logic is stored in the application logic tier, which is shared by users. System parameters are translated as input parameters which the production engineers can interactively change using self-explanatory user interfaces, for example, adding or subtracting resources, and changing dispatching rules without having to interact with any programming work. It provides a data-driven approach for building simulation models and offers a "user access" feature for model customization (Kulvatunyou and Wysk 2001). This approach reduces a considerable amount of effort in model maintenance. Only when the shop facility and production logic undergo radical changes in the production system, would model specialists be required to update the shop facility model in the application logic tier through the graphic simulation modeling interface.

Data Modeling and Collection

The quality of a simulation model does not only depend upon the detail and quality of the model logic it presents, but also upon the quality of input data. Acquiring data is an important stage in developing the virtual shop model. Data collection can be extremely time-consuming for large-scale models mainly due to the manual process (Robertson and Perera 2001). The focus of this study is to identify the sources of input data and to automate the data collection process. In the context of modeling shop fabrication, primary sources of input data are the CAD product model, time studies, and existing business information systems.

The use of CAD tools has been primarily restricted to the pre-construction phase. However, there are many benefits to using CAD for automating existing technical construction services, such as the presentation of estimates and schedules or the development of simulation models (Mahoney and Tatum 1994). A CAD model creates a great opportunity to automate the collection for product definition data. Detail information on how product definition data are modeled and extracted from CAD models is described in the section titled " Product Modeling" in Chapter 4. Time studies are still an indispensable approach to collecting simulation input data. Time studies are described in the section titled "Time Studies" in Chapter 2.

Most companies have invested heavily in the development of their information systems. Information systems store valuable and accurate historical and current business data. An information system is normally built around a central DBMS, where all relevant company and project data are stored. It enforces business policy company-wide and ensures that all data are validated and maintained consistently. This information is readily available and accurate, and provides an effective means of collecting the simulation data required by the virtual shop model. Figure 6-2 illustrates the information systems and data that can be extracted for the virtual shop model. The information created and maintained in various information system components, such as project management, engineering, shop production, purchasing, quality assurance, and human resource, is easily accessible through the central DBMS. Information relevant to the virtual shop model includes general project information, MPS, drawing revision and approval, current shop load, resource status and maintenance, inventory level, production quality and rework, and labour tracking. Data are extracted and stored in a data warehouse system, from which data can be accessed by the virtual shop model. The central DBMS can easily reflect changes in these information systems so that the virtual shop model is always running on the latest shop configurations. Historical productivity data can also help to validate the virtual shop model. Interfacing the virtual shop model with a company's existing information system allows fast data access without the need for database specialists, simplifies the procedure of estimating model parameters, and enhances the accuracy and reliability of simulation modeling and experimentation.

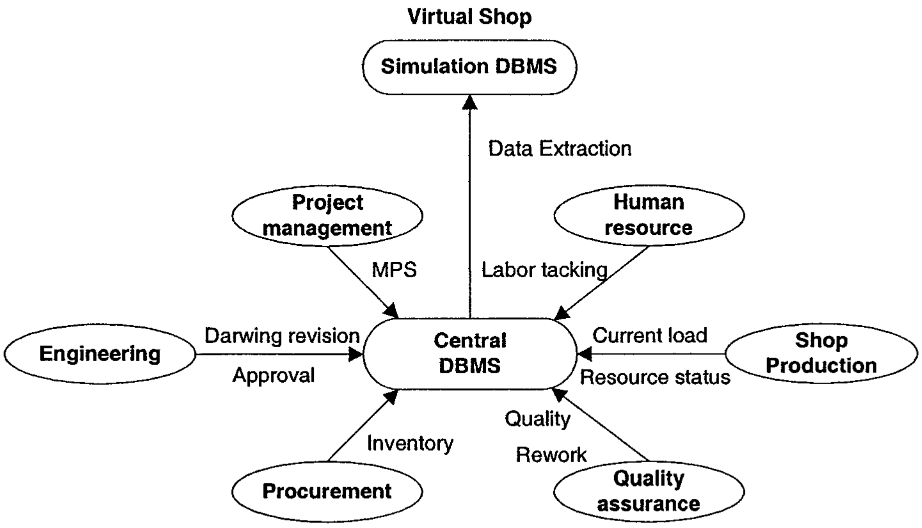


Figure 6-2. Data Collection from Existing Information Systems

System Integration

An important aspect of experimentation is the collection and presentation of simulation outputs. The virtual shop model uses a process approach to simulation modeling. A process is a sequence of interrelated events separated by intervals of time that describes the entire experience of an "entity" as it flows through a system (Law and Kelton 2000). In the context of the virtual shop model, the process corresponds to a steel component's routes and history as it moves through a virtual shop model. This information is recorded during a simulation experiment and later exported to the simulation database. Because the data are collected at the most detailed level of the WBS and at its operational level, the system is sufficiently flexible to report at any higher project level. By interfacing with other existing planning applications, the virtual shop model presents results of immediate relevance to the target users in a familiar and natural manner. System integration is achieved at the database level by sharing data in the simulation database with external applications. This capability is demonstrated later in this chapter through the integration of the virtual shop model with Microsoft Project.

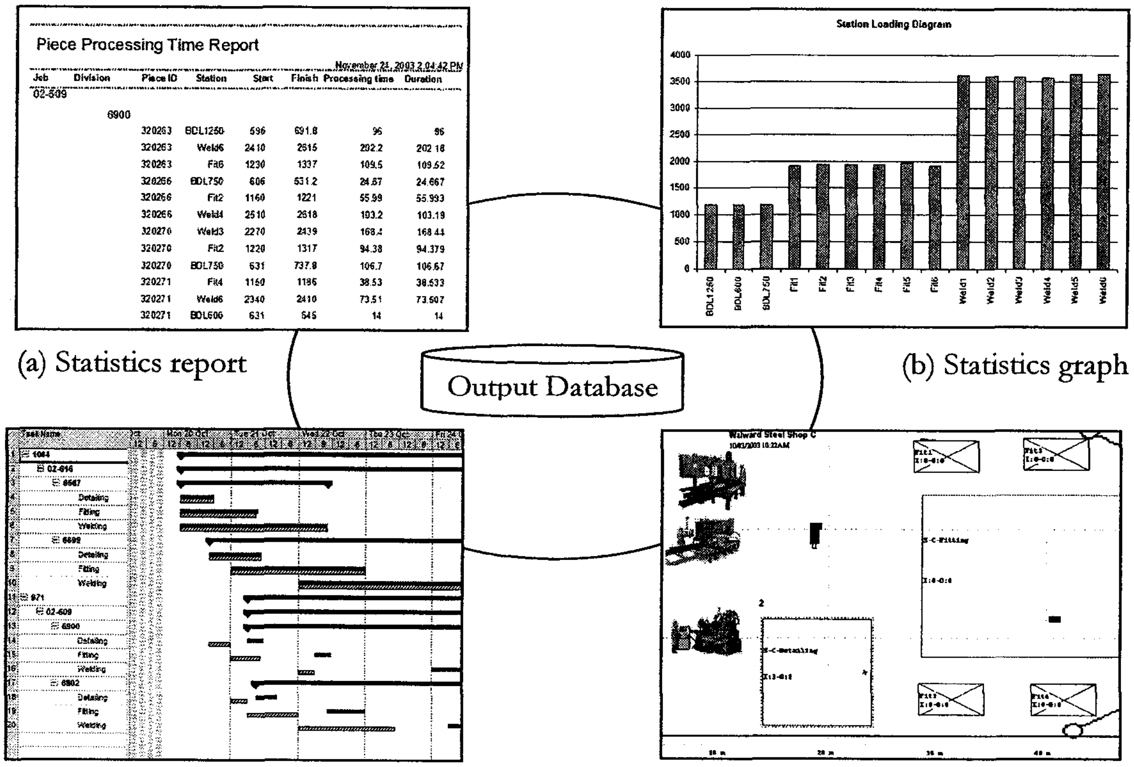
Fabrication Process Visualization

Animation is one of the reasons for the increased use of simulation modeling. The capability to visualize the production process can help users verify and validate simulation designs, enhance their understanding of the production process, and gain confidence in the simulation model. A two-dimensional animation function was built into the SPS template for steel fabrication. Thus, the animation model can be created simultaneous with the construction of the virtual shop model. The animation runs in a post-process mode, which means that the animation acts as a playback of a simulation run.

VIRTUAL SHOP PROTOTYPE SYSTEM

The prototype virtual shop model developed for Waiward Steel Fabricator Ltd. (WSF) is used to illustrate the modeling concept. Detailed information about the virtual shop model is provided in Chapters 4 and 5. Stored Structural Query Language (SQL) procedures were developed to extract relevant business data to the simulation database. User interfaces were developed for production engineers to create job orders, process plans, and to assign dispatching priorities. Outputs of the virtual shop model are stored in the simulation database and presented in various statistical reports and graphs, such as the steel piece processing time report and the working station loading diagram, as shown in Figure 6-3 (a) and (b). Integration with the Microsoft Project was developed based on the Microsoft Project object model. Project schedules, such as Figure 6-3 (c), are automatically created after simulation runs. Microsoft Project gives users a handful of opportunities in further manipulating these schedules. A screenshot of the virtual shop animation is shown in

Figures 6-3 (d) and 6-4. The animation shows steel pieces, working stations, storages, bridge cranes, and visualizes the shop fabrication process.



Piece Processing Time Report

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Job	Division	Piece ID	Station	Start	Finish	Processing time	Duration
02-509							
	6900						
		320263	BDL1250	596	691.8	96	96
		320263	Weld6	2410	2615	202.2	202.18
		320263	Fit6	1230	1337	109.5	109.52
		320266	BDL750	606	531.2	24.67	24.667
		320266	Fit2	1160	1221	55.99	55.993
		320266	Weld4	2510	2618	103.2	103.19
		320270	Weld3	2270	2439	168.4	168.44
		320270	Fit2	1220	1317	94.38	94.379
		320270	BDL750	631	737.8	106.7	106.67
		320271	Fit4	1160	1186	38.53	38.533
		320271	Weld6	2340	2410	73.51	73.507
		320271	BDL606	631	645	14	14

(a) Statistics report

(b) Statistics graph

(c) Project schedule

(d) Animation

Figure 6-3. System Outputs

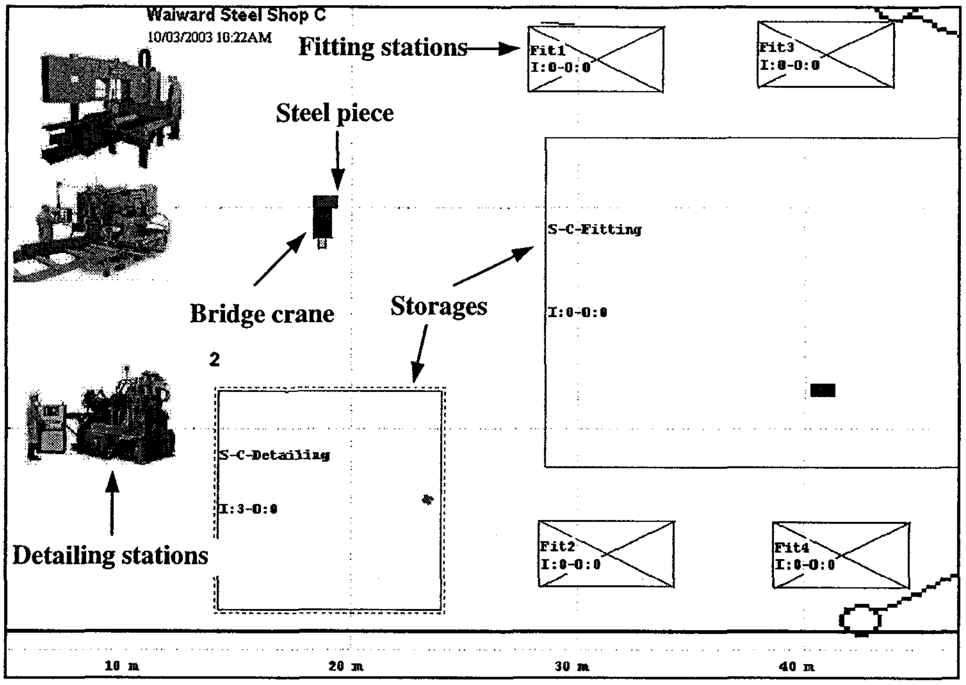

Figure 6-4. Virtual Shop Animation

CASE STUDIES

Case studies are used to illustrate the capability of the prototype virtual shop model in modeling steel fabrication, as well as the potential benefits of the experimental planning method. The performance of a steel fabrication shop is affected by factors that stem both from within the fabrication shop and from the external environment that interacts with the shop. The first two case studies quantify the influences of labour efficiency and the quality of supervision, which are identified as internal factors. The third and fourth case studies illustrate how external factors, such as change orders and rush orders, affect shop performance. All case studies model the detailing, fitting and welding of 317 pieces from Job 02-616, which contains Division 6567, and Job 02-609, which contains Divisions 6900 and 6902. The pieces will be detailed, fitted, and welded in WSF Shop B and Shop C using the stations assigned for these particular job orders.

Labour Efficiency

In this case study, the focus is on the effect of a fitter's skill level and the shift arrangement on the fitting duration and quality, rather than on the overall shop performance. Based on the qualification and experience, fitters are classified into different skill levels. Two skill levels are considered in this case study: level 1, which is high, or level 2, which is low. The shop can operate on an 8-hour day-shift, or on an 8-hour day-shift and a 10-hour night-shift. The four scenarios that result from the factorial design were studied using the virtual shop model. Figure 6-5 shows the total fitting time and the production quality, as measured by rework hours. The result shows that a higher skill level contributes to improved productivity. In this case, production quality does not seem to be affected much by skill level and shift arrangement. Although introducing multiple shifts can be an economical way of accomplishing more work within the same period of time, the shift that follows a regular shift is less productive.

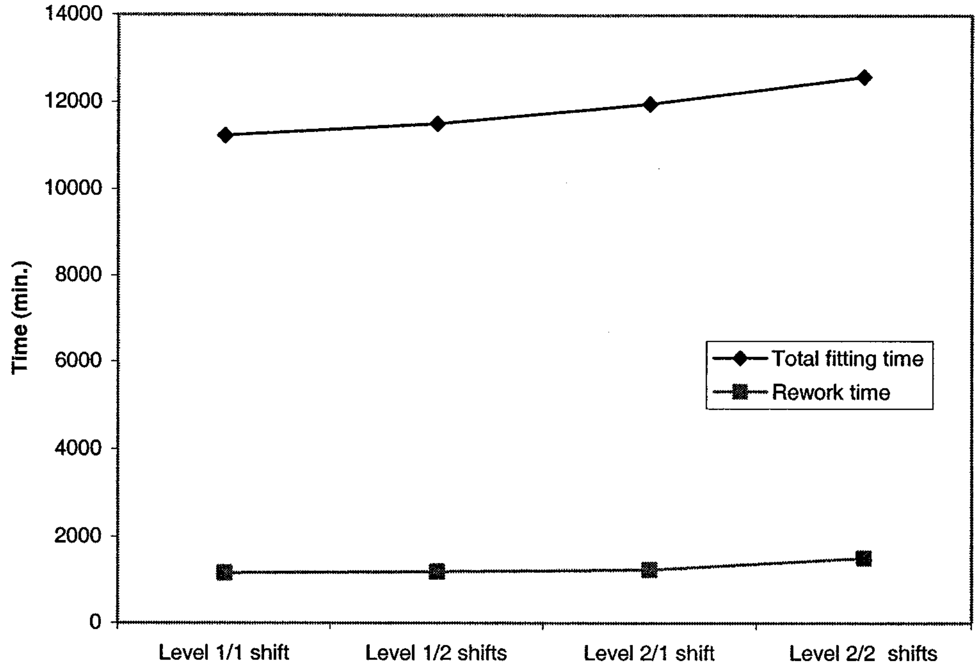

Figure 6-5. Skill Level, Shift Schedule and Steel Fitting

Quality of Supervision

Quality of supervision is often cited in the literature as one of the major factors affecting productivity. The quality of supervision is largely reflected by the foreman's scheduling skill in coordinating working stations and balancing their loads. For example, an experienced foreman would specify assignments based on the balanced working stations' processing time in order to reduce in-process inventory and to maximize resource utilization. This practice corresponds to the use of a "shortest waiting time" rule to loading working stations. A less experienced foreman may lack the ability to estimate the waiting time at each working station. In that case, the "shortest queue length" rule, which is based on a simple count of the number of steel pieces in a station's waiting queue, may be used. In a worst-case scenario, steel pieces can be sent "randomly" or "alternatively" to a working station regardless of any dynamic context. These scenarios correspond to the "random" rule and the "alternative" rule to loading working stations. In this case study, the rules used by the detailing, fitting, and welding foremen are assumed to be the same as those used in the following four scenarios. The rules used in Scenarios 1, 2, 3, and 4 correspond to the "random", "alternative", "shortest queue length", and "shortest waiting time" rule respectively. Figure 6-6 shows the average total duration and its 95% confident interval for each of the four scenarios. The "shortest waiting time" rule has the lowest average total duration and minimum variance among the other three rules. When compared to the "random" and "alternative" rules, the "shortest queue length" rule has a shorter total duration as well as a marked reduction in variance. The performance under the "random" or "alternative" rules is inefficient and unstable. A high product mix in steel fabrication causes considerable variations in processing time and helps to explain this result. In short, supervisors with greater experience of the product and process can greatly enhance the production performance.

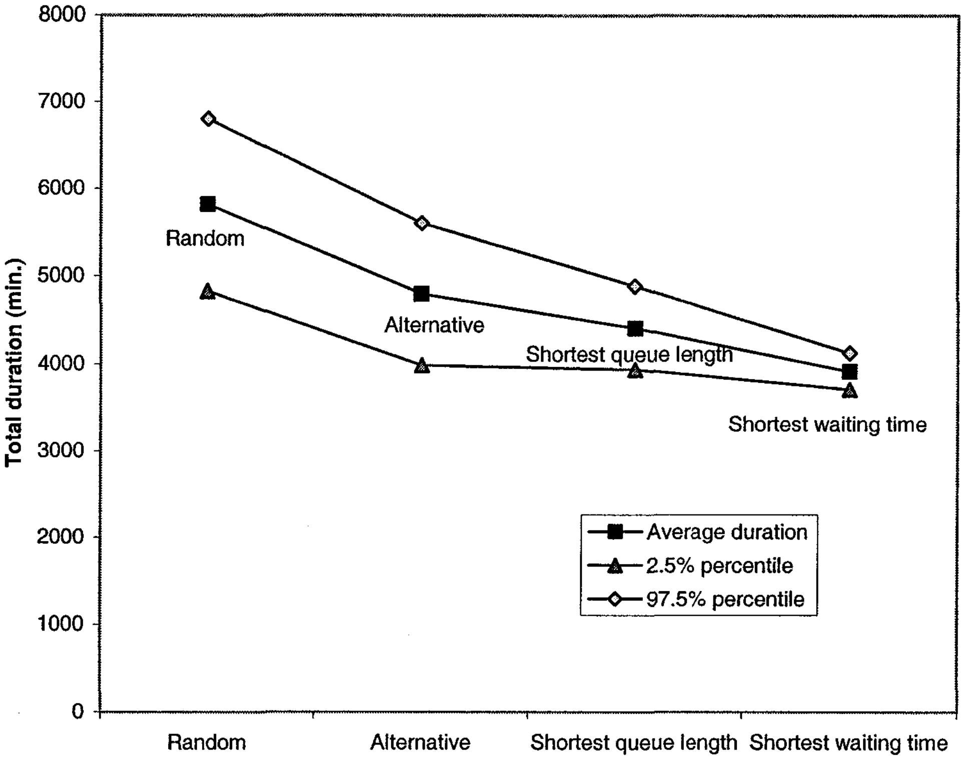

Figure 6-6. Scheduling Rules and the Total Duration

Change Order

Engineering changes inevitably affect shop performance. After fabrication drawings are issued to the shop for fabrication, they may be cancelled due to revisions in project scope. Labour hours are wasted on fabricating cancelled steel pieces prior to their cancellation. A cancellation also affects other jobs because of an increased WIP level and lengthened queuing time. Little quantitative research has been done on the impact of change upon production performance. A quantification of the cancellation and its timing to the shop performance was thereby attempted. Assume that 50% of the steel pieces in Division 6567 are cancelled. Experiments were made to study the subsequent effects upon the cycle times of two other divisions. It is assumed that a steel piece may be cancelled anytime during processing and queuing, except in the material handling phase. Figure 6-7 shows the cycle times of Division 6900 and 6902 and the waste time of Division 6567 due to the cancellation at different cancellation time. This experiment shows that cancellations not only cause direct labour-hour loss but also have a ripple effect on the overall shop performance. The latter a cancellation is issued, the more wasted time is spent upon cancelled pieces, and the longer average cycle time the other two divisions will experience.

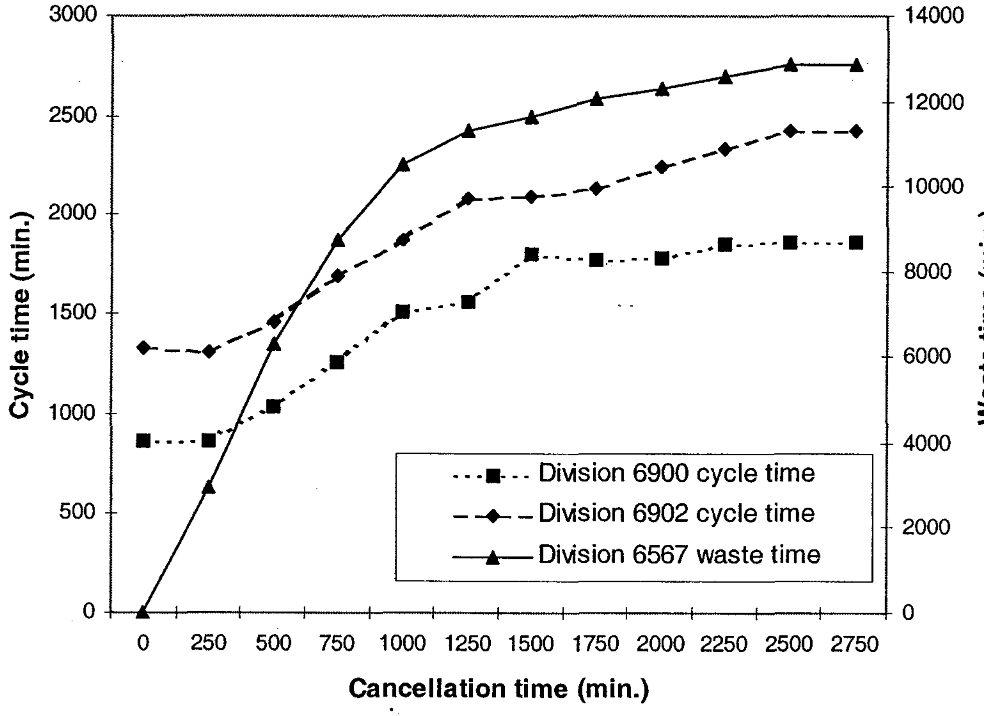

Figure 6-7. Cancellation and its Timing

Rush Order

Rush orders are also a factor in interrupting shop performance. This is due to external factors such as scope changes and erection schedule changes. Normally, a shop superintendent sets a priority to a new rush order to be processed so that the due date can be met. Given the existing shop load, the rush order will delay other existing job orders.

Assume a new Division 6699 must be fabricated after Division 6567, and before Divisions 6900 and 6902. Priorities are set for Divisions 6567, 6699, 6900, and 6902 ranked from the highest to the lowest. The priorities of steel pieces within each division are assumed to be the same in this case study. Figure 6-8 compares the original schedule and the updated schedule. Divisions 6900 and 6902 will be delayed, and average cycle times will be increased due to the rush order on Division 6699.

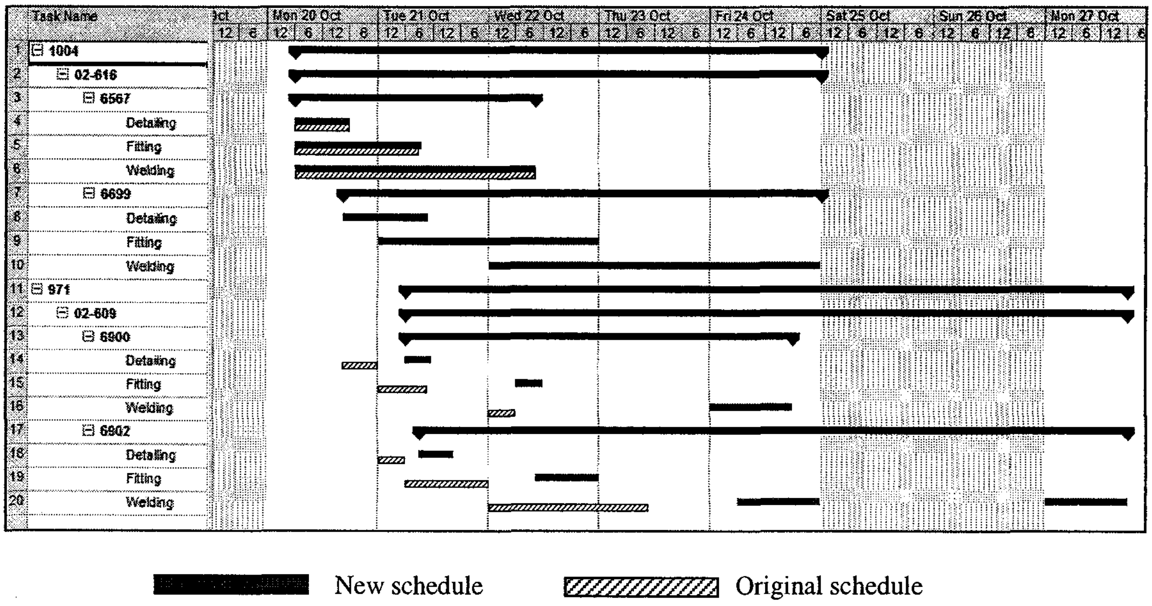

Figure 6-8. Evaluation of Rush Orders

For all case studies, the response of the virtual shop model is compared against that of an experienced production engineer at the collaborating company. The virtual shop model was found to give a similar magnitude of impact as that of an experienced production engineer speculated for these four case studies.

CONCLUSIONS

Industrial shop, product, processes, material, and fabrication technologies are growing ever more complex. Production engineers who attempt to manage and plan an industrial shop without scientific management techniques must trust to luck, intuition, or what they did in the past. Although expert experience will continue to be indispensable in production planning, the proposed experimental planning employs practices from the experimental science, as compared to the traditional approach of relying solely on personal experience. The virtual shop model is a media to conduct experiments when experimentation with the real project is not feasible. The virtual shop mimics the behavior of the actual shop, which makes it easy for production engineers to understand and trust. Experimentation with the proposed virtual shop environment can illustrate the likely effects of various alternative plans. A good plan and desired production performance can thus be achieved through "trial and error". Although the direct application of this proposed approach is to steel fabrication shop, the concept of experimental planning can be applied to other construction job shop planning. Future work is still required to further integrate the virtual shop model with other modeling techniques and information systems for the design and analysis of simulation experiments. This integration will eventually lead to the development of a fully digitized steel fabrication environment for advanced project planning and control.

Certainly, simulation modeling is no panacea. Realistic simulations may be prohibitively expensive and time consuming. However, subsequent planning and shop reconfiguration would be of higher quality because many more questions can be answered with deliberate experimentation, sensitivity, and optimization studies. The three business directives of "faster, cheaper, and better" can be achieved with the proper use of simulation modeling techniques. Given the intricacy of the project environment, it is believed that experimental methods will play an increasingly important role in production planning.

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CHAPTER 7: CONCLUSIONS

SUMMARY AND CONCLUSIONS

Productivity is a fundamental piece of information involved in many construction project management functions, such as estimating, scheduling, and project control. Appropriate measuring, planning, controlling, and subsequently improving of productivity is of great importance to the success of steel fabrication projects. The primary objective of this thesis research is to develop a methodology to measure and analyze the productivity of steel fabrication projects using simulation and ANN modeling techniques. Productivity was systematically studied through a process of data collection, measurement, and modeling. This research has addressed: (1) how to effectively collect productivity data in steel fabrication projects in the light of the state-of-the-art and on-site practices; (2) how to measure the work scope and productivity of steel drafting engineers; (3) how to measure the productivity of steel fabrication process; and (4) how to quantify the effect of productivity-influencing factors on project performance.

Data Acquisition for Productivity Modeling

The current and emerging data needs for productivity modeling and the current data collection practices were review. The research classified productivity data according to source, format, and structure. Various data collection technologies were then reviewed for their abilities and benefits in collecting a specific category of data. The research also addressed processes and tools that improve the sharing and management of data, such as data archiving and data collection procedures. A comprehensive data acquisition solution, consisting of computerized timesheet systems, CAD-based quantity surveying, time studies, and questionnaire surveys was designed and implemented to collect product definition data, labour expenditures, activity durations, and qualitative data. A data warehouse system was developed to facilitate the organization and retrieval of data for any further analysis.

Historical data records a company's past performance and contains predictive information that is important for the company's future projects. The collection of historical data requires good planning for current and emerging data needs and formal and efficient data collection procedures. This research shows that the selection of data collection technique is determined by the characteristics of the data in terms of its source, structure, quantity, and significance. A good data acquisition system must be cost effective, reliable, and flexible in meeting current and future data needs.

Measuring and Estimating Drafting Productivity

This research established an engineering productivity measurement system and proposed a neural network modeling approach for estimating steel drafting productivity. A conceptual model, termed Quantitative Engineering Project Scope Definition (QEPSD) was proposed to standardize the measurement of engineering project scope in a CAD environment. QEPSD quantitatively measures engineering project scope at a discipline level in terms of the quantity and complexity of design items. The proposed method was applied to the steel drafting discipline. A new measurement unit, drafting unit, was developed to measure drafting project scope. Historical projects were analyzed using the QEPSD method to extract predictive information for scope definition of future projects. With the ability to quantitatively measure work scope, drafting productivity can be conveniently measured by man-hours per drafting unit. ANN was proposed to model the relationship between drafting productivity and its influencing factors. Productivity-influencing factors were identified through literature review, interviews, and surveys among estimators and project managers. The data collected through the implemented data acquisition system were used to train and validate the ANN model. The developed model can be used to predict the drafting productivity of future projects. This approach in measuring drafting productivity leads to an increased utilization of untapped values in historical data to improve the accuracy of project scope definition and estimating, which will otherwise heavily rely on the personal experience of project managers. The research also shows the potential benefits of adopting the proposed approach in other engineering project management functions, such as scheduling, project control, and performance evaluation.

Standard engineering productivity measurements must be established before significant improvement and predictability of engineering performance can be made. Work quantity of design projects should be measured in terms of design complexity involved. This research shows that a properly defined productivity measurement can potentially improve the overall project management process.

Modeling the Steel Fabrication Process

This research developed a simulation-based virtual shop modeling system for the productivity analysis of steel fabrication projects. As a first step, a virtual shop modeling system was designed and implemented as a platform for building virtual shop models. The system is a tool for modeling steel products, fabrication operations, and shop facilities. A CAD product model was used to represent the features of a steel structure and its components in the virtual shop model. A computer-aided process planning system was designed to capture production rules and knowledge to assist engineers in generating process plans. A special-purpose simulation tool for steel fabrication was developed to model steel fabrication facilities.

This research systematically studied uncertainties in an industrial shop environment through a process of classifying, modeling, and reducing uncertainty. The research classified uncertainties involved in a production system according to their characteristics. This classification guided the modeling and reducing of uncertainty. The developed virtual shop modeling system was enhanced to represent various uncertainties in steel products and the shop environment. The ANN modeling technique, which plays a significant role in the simulation model, was used to model activity duration based on the identified productivity influencing factors and data collected through a time study project conducted in the fabrication shop. The ANN-embedded virtual shop model was proven to be more accurate than traditional approaches in modeling activity durations using statistical distributions. A sensitivity analysis of uncertainty variables reveals the intensity of their impact on project performance, and indicates, where the data collection efforts should be focused and prioritized in order to reduce uncertainty.

The ability to estimate the uncertainty associated with a construction project accurately and reliably is key to the successful planning and completion of a construction project. Contractors can benefit greatly from the reduction and control of uncertainty prior to commitment. With the appropriate information regarding identified uncertainty variables, the impact of these variables to the project's performance can be evaluated by appropriate modeling techniques, such as simulation and ANN.

Virtual Shop System for Production Planning

This research proposed the concept of experimental planning, which allows engineers to experiment with plans and analyze production performance in a virtual shop environment. A three-tier system architecture was developed to offer users an integrated, collaborative, and user-friendly virtual environment for experimental planning, and to meet the users' ongoing need to cope with the potential changeability of shop configurations and various component models. The research presents a flexible simulation data collection framework based on the developed data acquisition system and other existing business information systems. By interfacing with external planning applications, the virtual shop model presents experiment results in a manner that is of immediate relevance to the target users. The integration of the virtual shop model into a company's overall information framework provides users with a virtual project execution environment for running experiments and solving problems that they encounter during day-to-day operations.

Industrial shop, product, processes, material, and fabrication technologies are growing ever more complex. Although expert experience will continue to be indispensable in production planning, computer simulation provides a scientific tool to assist decision-making. The direct application of this proposed approach is to steel fabrication shop, however, the concept of experimental planning can be applied to other construction job shop planning. Given the intricacy of the project environment, it is believed that experimental methods will play an increasingly important role in production planning.

In conjunction with an Edmonton-based steel fabrication company, the data acquisition system was implemented to collect productivity data. Prototype systems of the proposed engineering productivity measurement system and virtual shop model were also implemented at the involved company. The engineering productivity measurement system has proven to be effective in quantitatively measuring and analyzing the productivity of engineers as knowledge workers. The virtual shop model has exceptional capabilities in modeling dynamics and uncertainties in an industrial shop environment for productivity analysis. The results of the research help engineers to quantify the productivity of steel fabrication projects and assist them in improving the accuracy of predicting future performance. The research on process-level productivity also demonstrated its potential benefits to current project planning and control practices. It laid a solid foundation for future endeavours in building a production-oriented project planning and control system for the steel fabrication industry. The problems addressed in this research regarding productivity modeling are common to the fabrication industry. The productivity modeling methodology presented herein has been successfully applied to steel fabrication projects for the collaborating company. Its fundamental approach will be applied to other fabrication companies to further verify its applicability.

PROPOSAL FOR FUTURE RESEARCH

Steel construction projects are often fast-paced and require careful planning and close coordination of steel design and detailing, shop fabrication, and site erection to ensure a streamlined, delay-free process. Fabricators are also under enormous competitive pressures for continuous improvement to enhance their productivity. It is of great benefit for engineers to have an integrated system to plan and control steel construction projects taking advantage of results from the research on productivity modeling. The thesis research has been focused primarily on shop fabrication at the process level. It addressed fundamental problems with how the work scope and productivity of the steel fabrication process can be measured and forecasted. A production-oriented project planning and control system based on the virtual shop model is envisioned as the direction for future research. This system would model, at the project level, the entire supply chain of steel construction projects ranging from engineering, to shop fabrication, to site erection.

The production-oriented system will allow production engineers develop reliable production plans and their alternatives based on the available project information. Experiments can then be conducted in the virtual shop model to quantitatively measure the performance of each alternative and select the most satisfactory solution. Once the project begins, project progress and expenditure reporting will be automated, taking advantage of the existing data acquisition system. This automated process will enable the continuous monitoring of the project's execution and allow actions to be taken proactively based on any reported deviation. The virtual shop system will also be a test bed for new production concepts and ideas for improving productivity, avoiding risky, costly, or inefficient experiments on the real system. To achieve these benefits, a number of issues must be addressed, including developing a simulation meta-model, formulating a production-oriented project planning and control framework, and applying lean principles for productivity improvement.

Simulation Meta-Modeling

The current virtual shop models the complex steel fabrication processes at a very detailed level using discrete-event simulation. Two issues associated with this characteristic of the virtual shop model limit its use in certain forecasting situations. First, the current model is not tolerant of input data deficiencies. For example, the accuracy of the system outputs will be greatly compromised when detailed steel product data are not available.

Detailed design information of many steel construction projects may not be available at the project planning stage, which prevents any direct measure of the final project scope. Secondly, the virtual shop model is computationally expensive. Simulation experiments may not be efficient enough to be used in situations when a quick response from the model is required. The limitation of costly and slow responses from the virtual shop model also prevents the exploration of all input-parameter combinations.

A simulation meta-model simplifies the simulation model and approximates its behaviour using an analytic function. It exposes the fundamental nature of the system input-output relationships. This makes the simulation meta-model flexible in dealing with different situations in terms of the availability of useable information. The meta-model can also be used as a proxy for the full-blown simulation model in order to get at least a rough idea of what would happen for a large number of input-parameter combinations. A non-linear simulation meta-model must be developed to approximate the virtual shop model. Methodologies must then be developed to use the meta-model or a combination of the meta-model and the virtual shop model to support decision-making with incomplete project information and increase the efficiency of the virtual shop model.

Production-Oriented Project Planning and Control System

Although the thesis research proved that simulation and ANN were effective in modeling productivity, it does not provide an overall approach for planning and controlling a steel construction project. They are only building blocks that will be enhanced and integrated into a project planning and control framework. The thesis research addressed the problem of how productivity can be quantitatively measured and modeled. The project planning and control system will address how productivity can be planned, controlled, and improved. The existing project scheduling system will be re-designed to conform to the new project planning and control framework based on the virtual shop model. The virtual shop model and various existing project information systems will be integrated into this framework. The existing data acquisition system will be enhanced by developing additional automated data acquisition applications, especially those at the shop floor. The new project control model will be based on the virtual shop model and will be fed by the automated progress reporting facilities. Appropriate project control techniques for steel construction projects must also be identified and used to measure the project progress and forecast future performance.

Lean Principles for Productivity Improvement

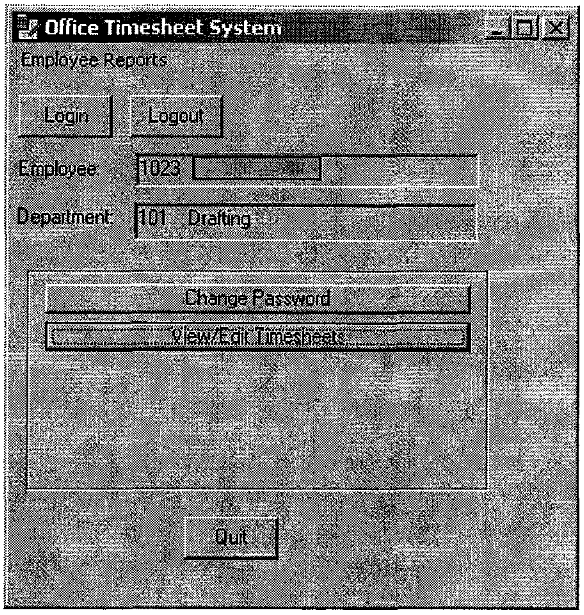
Continuous productivity improvement is one of the most important goals for every construction company. Future research must utilize the developed virtual shop model, coupled with process improvement guidelines, in an attempt to enhance the overall system performance. Potential areas for productivity improvement in the steel supply chain and within each production process can be identified using lean production principles. A generic approach must be developed to facilitate the process of testing, evaluating, and implementing productivity improvement efforts. The virtual shop model must be used to verify these improvement efforts before they are implemented in the real system. Risks and costs associated with changes in the production environment can thus be reduced to a minimum.

APPENDIX A: TIMESHEET SYSTEM AND DATA PROCEDURES

The computerized timesheet system focuses on collecting labor expenditures of office and shop employees on various activities and project components. The timesheet system contains two modules: Office Timesheet System (OTS) for office employees and Shop Labor Tracking System (SLTS) for shop employees. Employees use the systems to allocate their hours on a daily basis. Department supervisors use the systems to approve the timesheets for their subordinates and generate departmental reports. The systems are used by accountants to make overtime adjustments and produce detailed company-wide reports. Different functionalities/permissions are provided to each user depending on their status as determined by the system administrator. This section provides information with a focus on how ordinary employees use the system to record time expenditures.

OFFICE TIMESHEET SYSTEM

Run the OTS program, and log into the program by selecting department, employee name, and entering password. The main user interface is shown in Figure A-1.

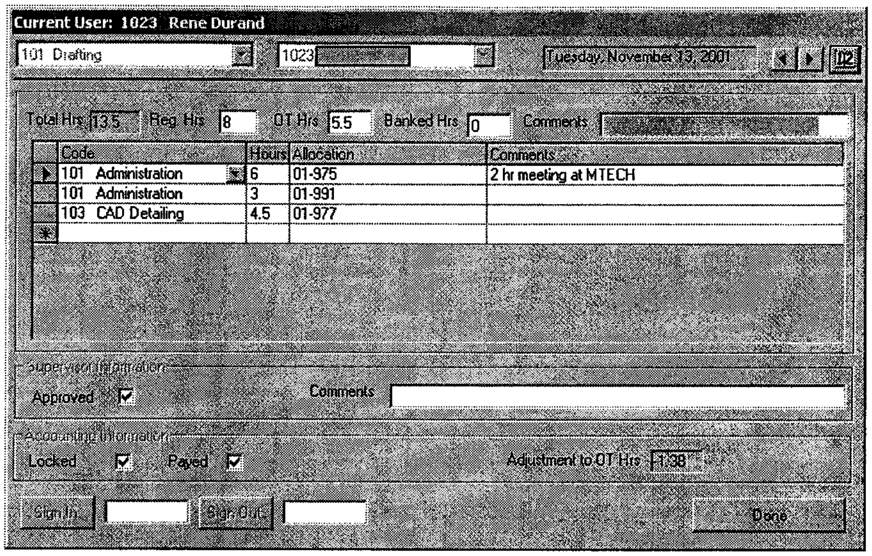


Employee: 1023

Department: 101 Drafting

Figure A-1: Main User Interface

By clicking "View/Edit timesheets" button, users can access the timesheet form, as shown in Figure A-2. The timesheet shows the basic employee information. The data grid allows edit and display the detailed breakdown of the daily activities and hours. The "Code" column allows for the specification of the activity code as defined for each department, such as CAD detailing, revision, and checking for the drafting department. The "Allocation" column displays where the hours are allocated. By clicking the drop down button of the "Allocation" column, users can browse through projects and allocate his/her hours to a particular project component, such as a job, division, or even a drawing. The task selection dialog box is shown in Figure A-3. If their hours do not associate with any specific project component, users can allocate them to "Non-job codes", such as training, vacation, and doctor appointment using the task selection dialog box.



Current User: 1023 Rene Durand

101 Drafting

1023 [redacted]

Tuesday, November 13, 2001

Total Hrs 13.5 Reg Hrs 8 OT Hrs 5.5 Banked Hrs 0 Comments

Code	Hours	Allocation	Comments
101 Administration	6	01-975	2 hr meeting at MTECH
101 Administration	3	01-991	
103 CAD Detailing	4.5	01-977	

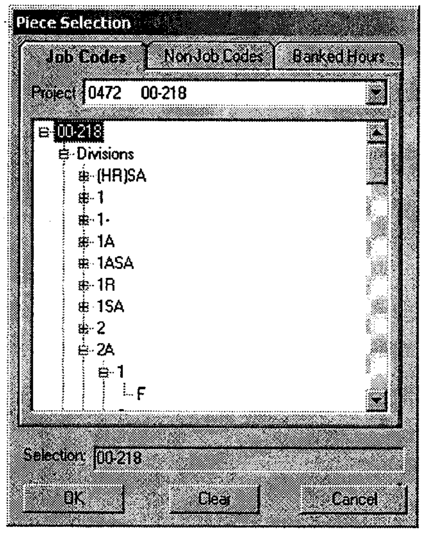
Supervisor Information

Approved ☑ Comments

Accounting Information

Locked ☑ Payed ☑ Adjustment to OT Hrs -1.38

Figure A-2: Electronic Timesheet



Piece Selection

Project 0472 00-218

- 00-218
  - Divisions
    - (HR)SA
    - 1
    - 1-
    - 1A
    - 1ASA
    - 1R
    - 1SA
    - 2
    - 2A
      - 1
        - F

Selection: 00-218

Figure A-3: Task Selection Dialog Box

By default, as detailed time allocation records are added, the total hours are adjusted, regular hours and overtime hours are calculated automatically according to the company policies. Users can browse to other date by clicking the calendar button and check their time allocation. A timesheet summary report showing the timesheet information for a specified period is available in the main user interface by clicking the "Employee Reports" menu. Department managers validate and approve the timesheets for employees in their department. Accountants can access the approved timesheet information for certain adjustments, overtime hours allocation, and generation of appropriate reports for payroll or job costing purposes.

SHOP LABOR TRACKING SYSTEM

The SLTS system comprises specially formatted timesheets, barcode-based time terminals, an automated timesheet processing module, SLTS program, timesheet archiving module, and supervisor program. Figure A-4 shows the time reporting and validation process involving shop employees, superintendents, and accountants.

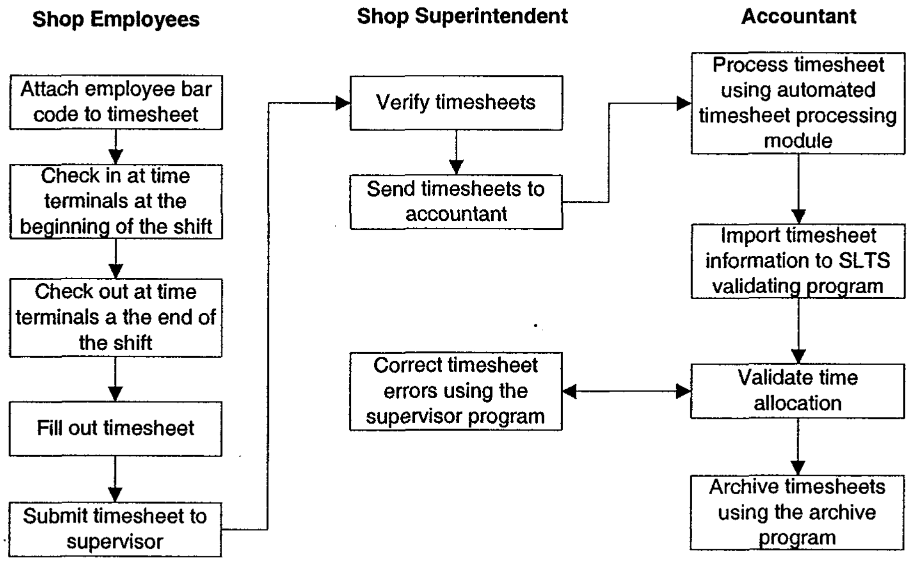


Figure A-4: Time Tracking Process

Shop Employee Time Reporting

Figure A-5 shows a daily paper-based timesheet used by shop employees to report their hours. Shop employees are required to affix the pre-printed barcode label to the top left corner box of the timesheet to identify themselves. At the beginning of a shift, employees can check in by scanning their barcode label through the barcode reader attached to the "Check In" time terminals located in the shop. If the entry is valid, employee name, check in time information and messages, if any, will be displayed on the time terminal, as shown in Figure A-6. Similarly, employees checks out at the end of their shift at "Check Out" time terminals.

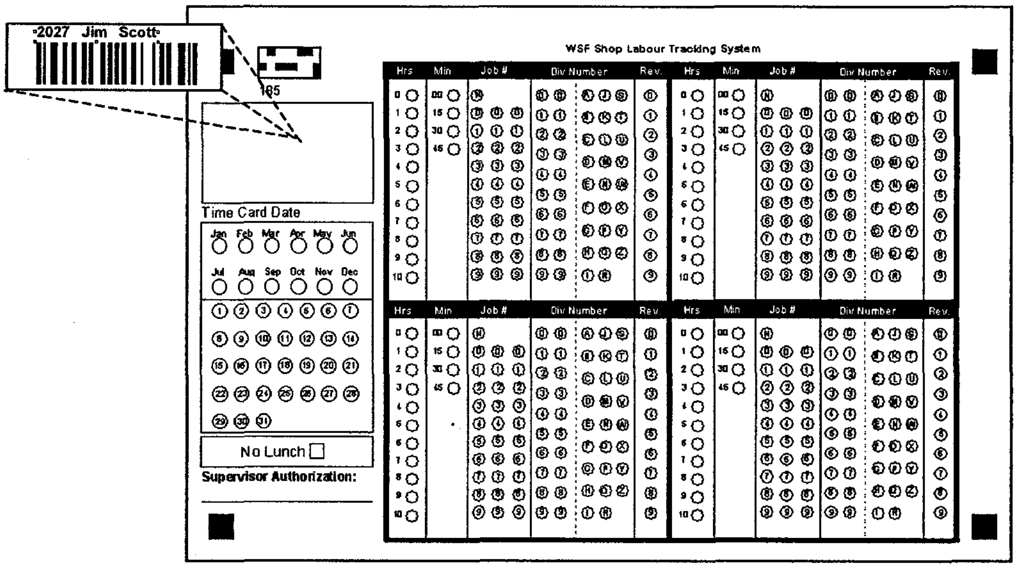
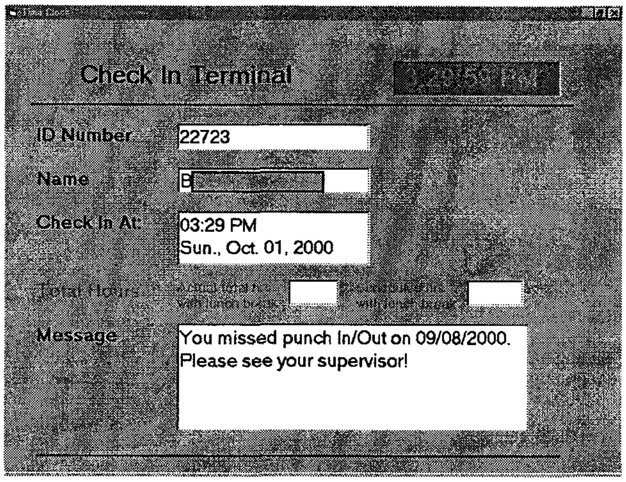


Figure A-5: Timesheet and Identification Barcode



ID Number: 22723

Name: B[redacted]

Check In At: 03:29 PM
Sun., Oct. 01, 2000

Total Hours:

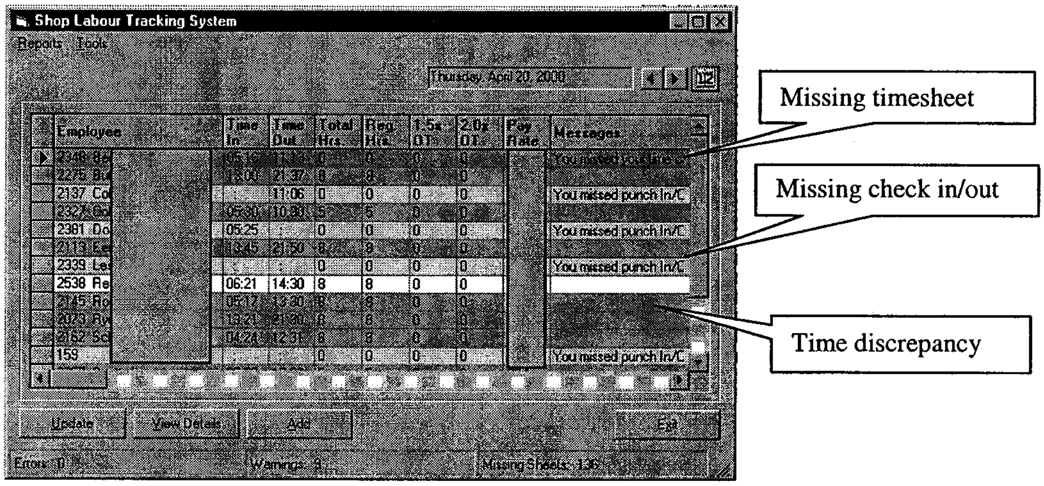
Message: You missed punch In/Out on 09/08/2000.
Please see your supervisor!

Figure A-6: Time Terminal Program

Employees are required to fill out the timesheet, as shown in Figure A-5, using pens or pencils. The card date column records the date of a timesheet. If no lunch break is taken during a shift, the "No Lunch" option should be marked. There are four sections which can be used to report time allocation. Mark the duration of an activity in the "Hrs" and "Min" columns. Use the "Job#", "Div Number", and "Rev" columns to record time allocation to a specific job, division, and revision. Extra timesheets can be used to report time allocations, if needed. Submit the timesheet to the shop superintendent for sign-off.

Timesheet Processing and Verification

The accountant receives timesheets on a daily basis from shop superintendents. Timesheets are processed in a third-party optical recognition software, TeleForm Reader® and TeleForm Verifier®. Timesheets are scanned and interpreted using the reader program. The verifier program highlights questionable data entries and allows the accountant to confirm or manually modify timesheet data. Verified timesheet data are saved in a text file, which contains employee information, timesheet date, working hours and their allocation. This information is then imported into SLTS to match with employees' check in/out time collected from the time terminals. To import the timesheet information, run the SLTS program, select "Import" from the "Tools" menu, and follow the wizard to import the text file into the program. The SLTS program automatically applies company policies and check and highlight exceptions, such as missing check in/out, missing timesheets, wrong job and division numbers, and any discrepancy between the actual hours and the reported hours for the accountant's further investigation. Figure A-7 shows the main interface of the SLTS program, highlighted time records, and warning messages. Shop superintendents work with the account to correct these exceptions using the shop supervisor program. This program shows all exceptions at a shop superintendent's desktop computer and allows him/her to work seamlessly through the company's computer network with the accountant to manage time records. A screenshot of the program is shown in Figure A-8.



Employee	Time In	Time Out	Total Hrs	Reg. Hrs	1.5x OT	2.0x OT	Pay Rate	Messages
2348 Be	05:16	11:10	0	0	0	0		You missed your time c
2275 Bu	13:00	21:37	8	8	0	0		
2137 Co	:	11:06	0	0	0	0		You missed punch In/C
2327 Go	05:30	10:30	5	5	0	0		
2381 Do	05:25	:	0	0	0	0		You missed punch In/C
2113 Ee	13:45	21:50	8	8	0	0		
2339 Le	:	:	0	0	0	0		You missed punch In/C
2538 Re	06:21	14:30	8	8	0	0		
2145 Ro	05:17	13:30	8	8	0	0		
2073 Ry	13:21	21:30	8	8	0	0		
2152 Sc	04:24	12:31	8	8	0	0		
159	:	:	0	0	0	0		You missed punch In/C

Errors: 0

Warnings: 8

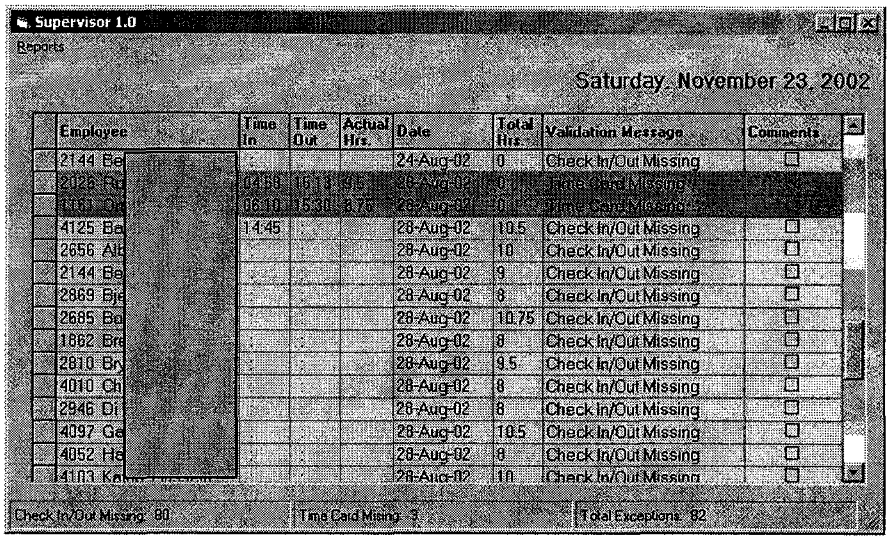
Missing Sheets: 136

Missing timesheet

Missing check in/out

Time discrepancy

Figure A-7: SLTS Program



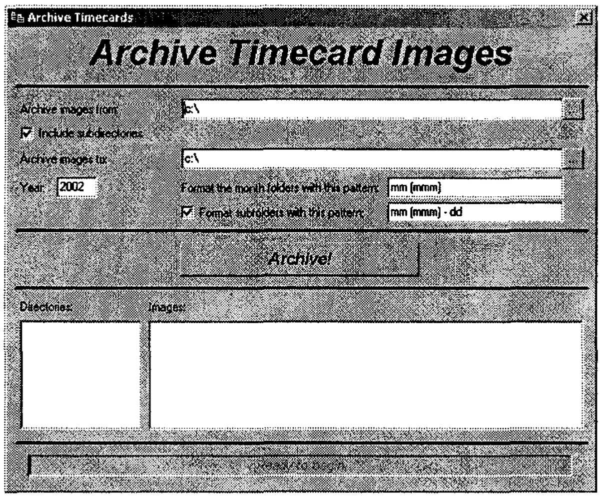
Saturday, November 23, 2002

Employee	Time In	Time Out	Actual Hrs.	Date	Total Hrs.	Validation Message	Comments
2144 Be[redacted]	:			24-Aug-02	0	Check In/Out Missing	☐
2026 Ru[redacted]	04:58	16:13	9.5	28-Aug-02	0	Time Card Missing	☐
1161 Or[redacted]	06:10	15:30	8.75	28-Aug-02	0	Time Card Missing	☐
4125 Ba[redacted]	14:45	:		28-Aug-02	10.5	Check In/Out Missing	☐
2656 Alb[redacted]	:	:		28-Aug-02	10	Check In/Out Missing	☐
2144 Be[redacted]	:	:		28-Aug-02	9	Check In/Out Missing	☐
2869 Bje[redacted]	:	:		28-Aug-02	8	Check In/Out Missing	☐
2685 Bo[redacted]	:	:		28-Aug-02	10.75	Check In/Out Missing	☐
1862 Bre[redacted]	:	:		28-Aug-02	8	Check In/Out Missing	☐
2810 Bry[redacted]	:	:		28-Aug-02	9.5	Check In/Out Missing	☐
4010 Ch[redacted]	:	:		28-Aug-02	8	Check In/Out Missing	☐
2946 Di[redacted]	:	:		28-Aug-02	8	Check In/Out Missing	☐
4097 Ga[redacted]	:	:		28-Aug-02	10.5	Check In/Out Missing	☐
4052 He[redacted]	:	:		28-Aug-02	8	Check In/Out Missing	☐
4103 Ka[redacted]	:	:		28-Aug-02	10	Check In/Out Missing	☐

Check In/Out Missing: 80 | Time Card Mising: 3 | Total Exceptions: 82

Figure A-8: Shop Supervisor program

Upon the completion of timesheet import and verification, timesheets images generated by TeleForm Reader® are archived in the company's file server for future reference using the archiving program. Specify the location of timesheet images and the location for the archive, and click the "Archive" button to archive selected timesheets, as shown in Figure A-9.



Archive images from: c:\
☑ Include subdirectories
Archive images to: c:\
Year: 2002
Format the month folders with this pattern: mm (mmm)
☑ Format subfolders with this pattern: mm (mmm) - dd
Ready to begin.

Figure A-9: Timesheet Archiving Program

APPENDIX B: HISTORICAL STEEL DRAFTING PRODUCTIVITY DATA

The development of the neural network model for steel drafting productivity requires the availability of past project productivity values as well as the values of the corresponding productivity influencing factors. Influencing factors for historical projects were collected as much as possible from the company's existing information system to reduce the subjectivity. Questionnaires were used to collect undocumented quantitative data and all other qualitative data. At the current phase of the research, a total of 59 jobs in the previous 3 years were included for ANN modeling. The 17 influencing factors, productivity, and their values for these 59 jobs are shown in Tables B-1 and B-2. For confidentiality reasons, productivity values shown here were scaled. A description of the influencing factors is available in the section titled "Identification of influencing factors" in Chapter 3.

Table B-1. Steel Drafting Productivity Data (1)

ID	Project type	Work scope	Contract type	Dynamic structure	Fire proof	Fall arrest	Crew size	Crew quality	Overall complexity
1	Both	Supply only	Lump sum	Yes	Yes	Yes	5+	3	3
2	Both	Supply only	Lump sum	Yes	Yes	No	5+	3	3
3	Structural	Supply only	Lump sum	No	Yes	No	1-2	4	1
4	Both	Supply only	Lump sum	Yes	Yes	No	5+	3	3
5	Both	Supply only	Unit price	Yes	Yes	Yes	5+	2	3
6	Both	Supply only	Lump sum	Yes	Yes	Yes	5+	3	3

ID	Project type	Work scope	Contract type	Dynamic structure	Fire proof	Fall arrest	Crew size	Crew quality	Overall complexity
7	Both	Supply & erect	Lump sum	Yes	Yes	Yes	5+	3	3
8	Both	Supply only	Unit price	Yes	Yes	No	5+	2	2
9	Both	Supply only	Unit price	Yes	No	Yes	5+	4	3
10	Both	Supply only	Unit price	Yes	No	Yes	5+	4	3
11	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
12	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	4
13	Plate work	Supply & erect	Unit price	Yes	Yes	Yes	3-5	3	3
14	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
15	Plate work	Supply only	Unit price	Yes	Yes	Yes	3-5	3	3
16	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
17	Both	Supply only	Unit price	No	Yes	Yes	5+	4	3
18	Structural	Supply only	Unit price	Yes	Yes	Yes	1-2	3	3
19	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
20	Both	Supply & erect	Lump sum	Yes	Yes	Yes	5+	3	3
21	Both	Supply & erect	Unit price	Yes	No	Yes	5+	4	2
22	Both	Supply only	Unit price	Yes	Yes	No	5+	3	3
23	Structural	Supply only	Unit price	No	Yes	No	1-2	3	1
24	Both	Supply only	Lump sum	Yes	Yes	No	5+	3	3
25	Both	Supply only	Unit price	Yes	Yes	No	5+	2	2
26	Both	Supply only	Unit price	Yes	Yes	No	5+	3	2
27	Both	Supply only	Unit price	Yes	Yes	No	5+	3	2

ID	Project type	Work scope	Contract type	Dynamic structure	Fire proof	Fall arrest	Crew size	Crew quality	Overall complexity
28	Both	Supply only	Unit price	Yes	Yes	No	5+	3	2
29	Both	Supply only	Unit price	Yes	Yes	No	5+	3	2
30	Both	Supply only	Unit price	Yes	Yes	No	5+	3	2
31	Both	Supply & erect	Lump sum	Yes	No	Yes	5+	3	3
32	Structural	Supply & erect	Lump sum	No	Yes	Yes	1-2	3	2
33	Structural	Supply only	Unit price	No	Yes	No	1-2	3	1
34	Both	Supply & erect	Lump sum	No	Yes	No	5+	5	1
35	Structural	Supply & erect	Lump sum	No	Yes	No	1-2	4	1
36	Both	Supply only	Unit price	Yes	Yes	No	5+	3	4
37	Both	Supply only	Unit price	Yes	Yes	Yes	5+	4	3
38	Both	Supply & erect	Lump sum	Yes	Yes	Yes	5+	4	4
39	Plate work	Supply only	Unit price	Yes	Yes	Yes	3-5	3	3
40	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
41	Both	Supply & erect	Unit price	Yes	Yes	Yes	5+	3	3
42	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
43	Both	Supply only	Unit price	Yes	Yes	Yes	5+	2	3
44	Structural	Supply only	Unit price	No	Yes	Yes	1-2	4	4
45	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
46	Both	Supply only	Unit price	Yes	No	No	5+	3	3
47	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
48	Both	Supply only	Unit price	Yes	No	No	5+	3	3

ID	Project type	Work scope	Contract type	Dynamic structure	Fire proof	Fall arrest	Crew size	Crew quality	Overall complexity
49	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3
50	Both	Supply only	Unit price	Yes	No	No	5+	3	3
51	Both	Supply only	Unit price	Yes	Yes	No	5+	3	3
52	Both	Supply & erect	Unit price	Yes	Yes	Yes	5+	4	3
53	Both	Supply only	Lump sum	Yes	Yes	Yes	5+	3	3
54	Both	Supply only	Unit price	Yes	Yes	No	5+	3	3
55	Both	Supply only	Unit price	Yes	Yes	Yes	5+	2	3
56	Plate work	Supply & erect	Unit price	No	Yes	Yes	3-5	4	4
57	Both	Supply & erect	Unit price	Yes	Yes	Yes	5+	3	3
58	Both	Supply & erect	Unit price	Yes	Yes	Yes	5+	4	3
59	Both	Supply only	Unit price	Yes	Yes	Yes	5+	3	3

Table B-2. Steel Drafting Productivity Data (2)

ID	Eng. Standard	Piece cloning %	Total quantity (unit)	Client index	Engineer index	Admin. %	Overtime %	Sub-Contract	Productivity (hr/unit)
1	3	0.34	14482.79	0.13	0.19	0.00	0.11	0.40	0.11
2	3	0.12	6877.06	0.13	0.19	0.00	0.12	0.44	0.20
3	5	0.27	13262.96	0.10	0.10	0.01	0.06	0.06	0.12
4	3	0.39	4941.95	0.13	0.19	0.00	0.18	0.43	0.11
5	3	0.21	23514.76	0.12	0.13	0.08	0.25	0.00	0.17
6	3	0.22	5466.15	0.13	0.19	0.00	0.13	0.40	0.25
7	3	0.33	599.79	0.13	0.14	0.02	0.11	0.12	0.17
8	2	0.34	15779.64	0.23	0.13	0.08	0.17	0.32	0.14
9	5	0.44	13258.42	0.23	0.28	0.03	0.13	0.36	0.15
10	5	0.25	1067.07	0.23	0.28	0.13	0.14	0.95	0.39
11	2	0.34	1003.40	0.23	0.10	0.04	0.21	0.00	0.22
12	2	0.72	4439.94	0.23	0.28	0.02	0.12	0.16	0.06

ID	Eng. Standard	Piece cloning %	Total quantity (unit)	Client index	Engineer index	Admin. %	Overtime %	Sub-Contract	Productivity (hr/unit)
13	2	0.13	467.87	0.13	0.19	0.00	0.20	0.27	0.36
14	3	0.40	6274.06	0.23	0.10	0.03	0.18	0.28	0.14
15	3	0.61	903.03	0.23	0.10	0.01	0.13	0.28	0.41
16	3	0.59	11696.31	0.23	0.10	0.06	0.23	0.60	0.10
17	4	0.19	24229.52	0.07	0.07	0.11	0.16	0.20	0.10
19	4	0.66	1084.33	0.23	0.10	0.00	0.05	0.95	0.16
20	4	0.22	1172.33	0.13	0.14	0.01	0.05	0.00	0.21
21	5	0.53	5512.72	0.15	0.28	0.05	0.12	0.07	0.12
22	3	0.40	8443.64	0.17	0.15	0.34	0.15	0.24	0.14
23	3	0.32	18181.78	0.15	0.10	0.36	0.03	0.38	0.02
24	3	0.15	390.30	0.17	0.15	0.29	0.02	0.90	0.32
25	3	0.42	2464.60	0.26	0.28	0.06	0.10	0.89	0.16
26	4	0.28	3908.40	0.26	0.28	0.22	0.02	0.77	0.10
27	4	0.21	1680.60	0.26	0.28	0.18	0.06	0.85	0.21
28	4	0.22	685.73	0.26	0.28	0.00	0.07	0.93	0.20
29	4	0.22	707.00	0.26	0.28	0.01	0.03	0.89	0.15
30	4	0.32	691.27	0.26	0.28	0.02	0.06	0.89	0.20
31	3	0.37	8978.52	0.13	0.05	0.04	0.19	0.00	0.07
32	2	0.23	799.84	0.23	0.10	0.08	0.02	0.00	0.17
33	3	0.05	6685.22	0.15	0.10	0.07	0.00	0.64	0.06
34	5	0.72	22226.99	0.10	0.10	0.07	0.08	0.05	0.25
35	5	0.09	11992.49	0.10	0.10	0.14	0.04	0.08	0.04
36	2	0.71	8182.00	0.26	0.28	0.32	0.05	0.57	0.10
37	3	0.08	1539.59	0.23	0.13	0.11	0.08	0.00	0.42
38	3	0.23	934.13	0.47	0.19	0.16	0.14	0.00	0.14
39	3	0.06	1082.55	0.13	0.13	0.10	0.06	0.33	0.27
40	3	0.57	1679.75	0.26	0.28	0.31	0.03	0.80	0.30
41	3	0.27	835.02	0.21	0.19	0.09	0.02	0.00	0.30
42	3	0.61	464.93	0.26	0.28	0.28	0.01	0.89	0.47
43	3	0.24	1089.57	0.26	0.28	0.21	0.04	0.78	0.43
44	3	0.01	2205.42	0.15	0.18	0.12	0.06	0.38	0.41
45	3	0.17	6286.17	0.26	0.28	0.09	0.04	0.64	0.32
46	3	0.14	13881.40	0.15	0.13	0.06	0.08	0.00	0.15
47	3	0.12	139.73	0.26	0.28	0.15	0.02	0.93	0.63
48	3	0.16	4106.95	0.15	0.18	0.10	0.09	0.00	0.15
49	3	0.29	681.07	0.31	0.28	0.20	0.03	0.79	0.42
50	3	0.18	17181.25	0.15	0.13	0.02	0.04	0.00	0.10
51	3	0.43	12093.47	0.15	0.18	0.19	0.06	0.12	0.25
52	4	0.35	1508.54	0.16	0.28	0.15	0.15	0.00	0.22
53	3	0.48	299.00	0.27	0.15	0.20	0.03	0.00	0.36
54	3	0.07	4675.87	0.26	0.28	0.12	0.06	0.63	0.27

ID	Eng. Standard	Piece cloning %	Total quantity (unit)	Client index	Engineer index	Admin. %	Overtime %	Sub-Contract	Productivity (hr/unit)
55	3	0.11	670.60	0.26	0.28	0.05	0.02	0.74	0.41
56	3	0.53	2526.22	0.06	0.10	0.27	0.17	0.00	0.07
57	3	0.14	278.49	0.27	0.19	0.05	0.02	0.00	0.39
58	1	0.44	2116.44	0.21	0.18	0.00	0.09	0.00	0.28
59	3	0.40	3382.52	0.15	0.28	0.14	0.09	0.00	0.32

APPENDIX C: VIRTUAL SHOP MODELING SYSTEM DOCUMENTATION

SYSTEM OVERVIEW

The virtual shop modeling system is a special-purpose simulation tool that allows users to develop virtual shop models for steel fabrication. This document provides technical information on the development of this modeling system.

The virtual shop modeling system consists of the Product/Process Modeling System (PPMS) and the fabrication Facility Modeling System (FMS), which are described in Chapter 4. Product definition data and simulation outputs are modeled and stored in the central DBMS. A variety of DBMS, such as Microsoft Access 97 and Microsoft SQL Server, can be used to implement the central database. Microsoft Access 97 is used in this document to illustrate the database design and implementation.

INSTALLATION AND SET-UP PROCEDURE

The following is a step-by-step procedure to set up the virtual shop modeling system:

1. Set up the facility modeling template.
    - Copy and place the file "CEM_Industrial_Construction.st" into *Simphony*'s template folder.
    - Enable the template in *Simphony*.
2. Set up the central database system.

    - Set up a model directory, such as a directory in the root directory of C drive (C:\Shop).
    - Copy and place the database file "Simulation97.mdb" in the model directory.
  - Note: The current version of the modeling system only supports Microsoft Access 97 databases, not Microsoft Access 2000 databases. The aforementioned database file is a Microsoft Access 97 database. This database should *NOT* be converted to a Microsoft Access 2000 database.

3. Set up the ANN models. Please skip this step if no neural network model is used in the virtual shop model.
  - Copy and place the file "NS2-32.DLL" in the system directory (C:\Windows\System32\).
  - Register NS2-32.DLL file by running "Regsvr32 NS2-32.DLL".
  - Copy and place any ANN model definition files (*.def) in the model directory.
4. Create new virtual shop models.
  - New virtual shop models should be saved in the model directory.

PRODUCT DATA MODEL

Products are the driving force of a virtual shop model as they are the elements that move through it. Within the context of the modeling system, steel components are represented by a flow entity. The entity model combines the product model and the process model. The structure of the entity model is described in the section titled "Entity Model" in

Chapter 4. Table C-1 shows a description of tables related to the steel product data model in the central DBMS. The relationship diagram of these tables is shown in Figure C-1.

Table C-1. Product Related Tables

Table	Description
Piece	Lists of steel pieces or assemblies and their physical properties and WBS information.
Component	Lists of steel components and their physical properties.
Process	Lists of general fabrication processes. This is the master table of the Sub-Process table.
Sub_Process	Lists of steel fabrication operations for each fabrication process.
WSGroup	Lists of station controllers and the stations that they control.
Process_Plan	Lists of the process plan for each steel component.

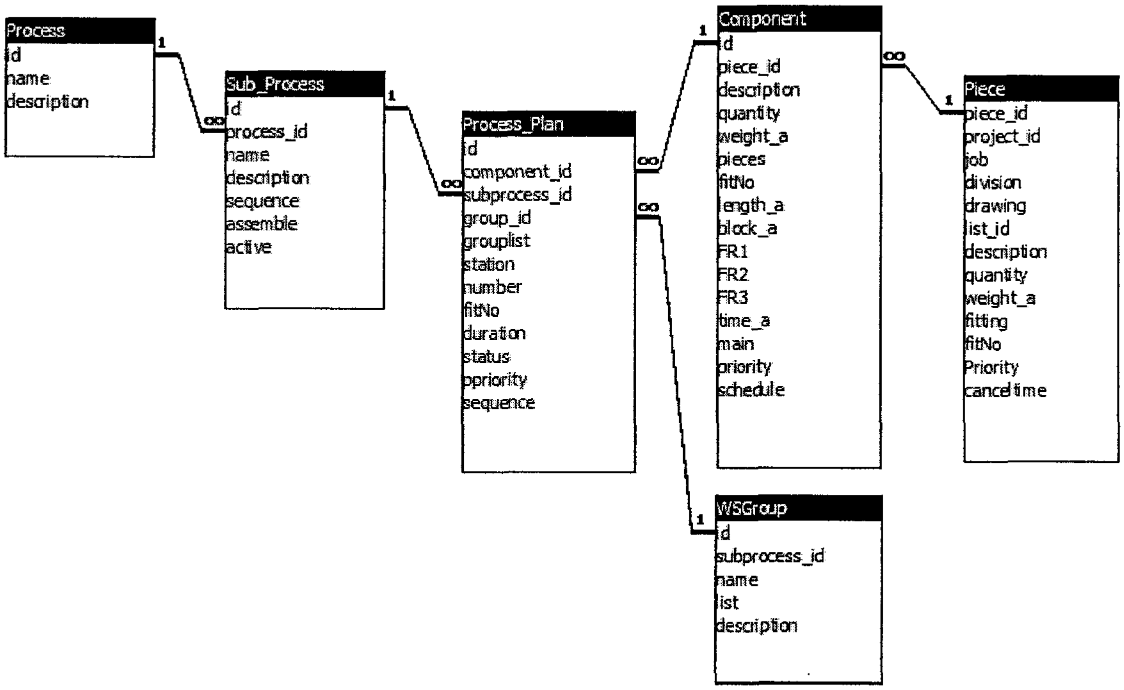


Figure C-1. Relationship Diagram of Product-Related Tables

An SQL query in the central database, titled "Product", collects information from these product-related tables to populate the entity model described in the previous section.

Figure C-1 also shows examples database table attributes. Attributes may be added or deleted as necessary. However, besides the primary keys and foreign keys for each table, some attributes are mandatory and are reserved by the modeling system. They must appear in the "Product" query. Table C-2 describes these system attributes.

Table C-2. System Attributes of the Product Data Model

Table	Attribute	Description
Piece	priority	The dispatching priority of a steel piece.
	canceltime	The time a steel piece is cancelled, if any.
Component	main	If a component is the main material, set the value to 1, otherwise 0.
	priority	The dispatching priority of a steel component.
	schedule	The time a steel component is issued for fabrication.
Sub_Process	assemble	If an operation is an assembly operation, set the value to the name of the identifier that identifies an assembly, such as piece_id.
WSGroup	name	The name of a station controller.
Process_Plan	station	The list of stations that are capable of performing a fabrication operation.
	number	The number of stations required for an operation.
	duration	The duration of an operation, or the name of a duration estimation model.
	status	The status of an operation.
	ppriority	The dispatching priority of a steel component at an operation.
	fitNo	The number of steel components making up a steel piece.

Extracting data captured in CAD models can simplify the process of collecting product definition data, such as physical attributes of steel components. The data exchange interface between the central DBMS to a CAD system is dependant upon the characteristics of the CAD system. The interface must be designed for a specific CAD system. The design of the interfaces will not be further discussed.

FACILITY MODELLING SYSTEM

The facility modeling system consists of a special-purpose template for steel fabrication, a general-purpose simulation tool, and an animation tool. The general-purpose simulation tool used in this system is the Common Template in *Simphony*. The current version of the virtual shop modeling system allows users to build animation model using the Animation Template in *Simphony*. More information regarding the Common Template and Animation Template can be found in the *Simphony* user manual.

Basic Concepts

This section defines briefly the basic concepts underlying the facility modeling system.

Facility Hierarchy

A steel fabrication facility can be decomposed into a hierarchy that represents its various components. A steel fabrication facility consists of a number of fabrication shops that vary in terms of layout, resource configurations, and production polices. Each fabrication shop has a number of stations, storage areas, and moving paths.

Product

Products are entities that move through a virtual shop model. Depending on the context, a product can be a steel component, an assembly, or a batch of steel components or assemblies. At the beginning of a simulation experiment, products are steel components with attributes. During the experiment, steel components may be batched or assembled, and become one product. This product may later be un-batched or disassembled into a number of products.

Location

Locations are places where a product may stay or move through. A location can be a station controller, a station, a storage area, or a moving path. The capacity of a location is the quantity of products it can process at one time. The capacity can be measured by the number of products, or any numeric product attributes, such as weight, area, or length. The status of a location can be available, full, or breakdown/maintenance, and changes dynamically during a simulation experiment. A product cannot move into a location until the location becomes available.

A Capacity Control Location (CCL) is a special type of location that determines if a product can enter into subsequent moving paths. A CCL is either a station, a station controller, or a storage area. When a product enters a CCL, it probes the moving paths that lead the product to the next CCL. If the next CCL is not available, the product cannot enter into the moving paths, and will queue in the current CCL.

Processing Mode

The processing mode of a station can be single, batch, or assembly. The processing mode of a storage area or a path can be single or batch. For batching and un-batching, the size of a batch can be measured by the number of products, or any numeric product attributes. If a station performs an assembly operation, the station will use the identifier specified by the assembly operation to identify the components of an assembly.

Dispatching Rule

A product is issued for fabrication according to its scheduled time. During the fabrication operations, products may compete for the same location. As a default, products are served on a first-come-first-serve basis. However, when a priority is specified, the product with the highest priority will be dispatched and served first. Each product has two types of priority: a general product priority and an operation priority. The operation priority specifies a product's dispatching priority for a specific operation. If this priority is not specified, then the general product priority will be used.

Routing

The process plan specifies the required operations and their sequences. The product routing predicts and determines the traveling pattern of products among these required operations. A routing procedure is conducted to probe the subsequent moving routes for a product whenever it leaves a location. The procedure conducted depends on the location, the product's process plan, and the dynamic context.

Modeling Elements

The implemented special-purpose template for steel fabrication includes ten modeling elements: product, plant, shop, station, resource, storage, path, in port, out port, and a drawing tool. The following section describes these modeling elements. A number of flow charts illustrate the computational logic of the product, station, storage, path, in port, and out port elements shown at the end of this section.

Product Element

The product element imports products defined in the central database to the facility model. It then releases products to the virtual shop model according to the production schedule. The product element also offers basic simulation services, such as searching process plans, probing travel paths, and routing for products. At the end of a simulation experiment, the product element exports the outputs to the central database.

Plant Element

This element represents a fabrication facility. It is the parent of all shop elements. Shop models are built as sub-models of the plant element.

Shop Element

The shop element represents a fabrication shop. The components of the shop, such as stations, storages, and paths, are built as sub-models of the shop element. A plan element may contain multiple shop elements.

Station Element

The station is a location where a fabrication operation can be performed on products. The duration of the operation may be specified in a product's process plan, sampled from a statistical duration, or determined by a predictive model, such as an ANN model.

The station controller, a dummy station, models the foreman's basic decision-making capabilities in job dispatching and station selection. A station controller controls a group of stations performing the same operation. A station controller determines which station should be selected to process a product according to station selection rules. A number of station selection rules are embedded in the current version of the modeling system. These selection rules can be random, alternative, shortest queue length, or shortest waiting time.

Resource Element

The resource element represents equipment or labour in working stations and material handling systems. It can model interruptions and track resource utilization.

Storage Element

The storage element models buffer areas in the shop where steel products can stay and wait for stations, paths, or other storage areas and resources.

Path Element

The path element, along with the storage element, defines the shop material handling system. Paths are the routes that products travel through from a source location to a destination.

In Port Element

The in port element redirects simulation entities to a lower level sub-model of a product, station, storage, or path element. Users can use the Common Template to develop the sub-model. The in port element supports batching and assembling functions.

Out Port Element

The out port element sends simulation entities from a lower level sub-model to the parent element. Users can use the Common Template to develop the sub-model. The out port element supports the un-batching function.

Drawing Tool Element

The drawing tool element can create layout gridlines and import plant and shop layout drawings from a CAD system.

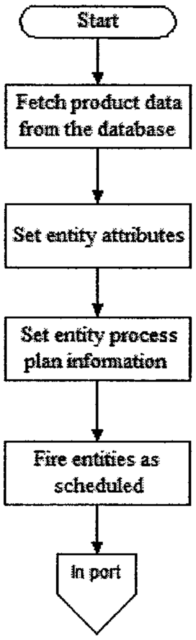
Product

Legend

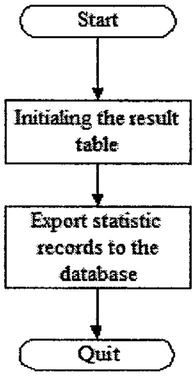
▭ Action ◇ Decision ⬭ Terminator ⬠ Process Link

Element: Product
Page: 1 of 6
Revision: 1
Date:

Simulation Process



Post Simulation Process



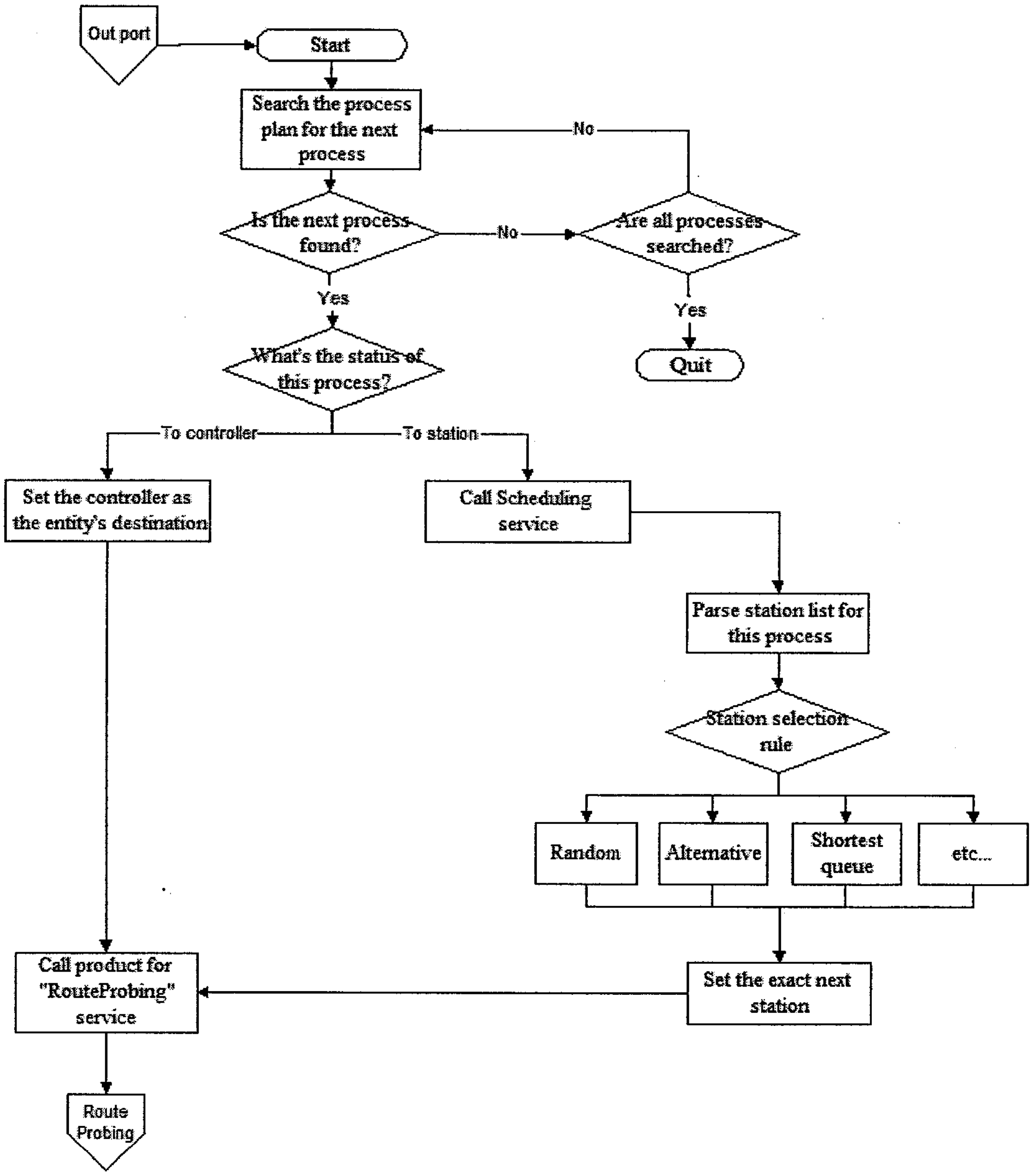
Product

Legend
▭ Action ◇ Decision ⬭ Terminator ⬠ Process Link

Element: Product
Page: 2 of 6
Revision: 1
Date:

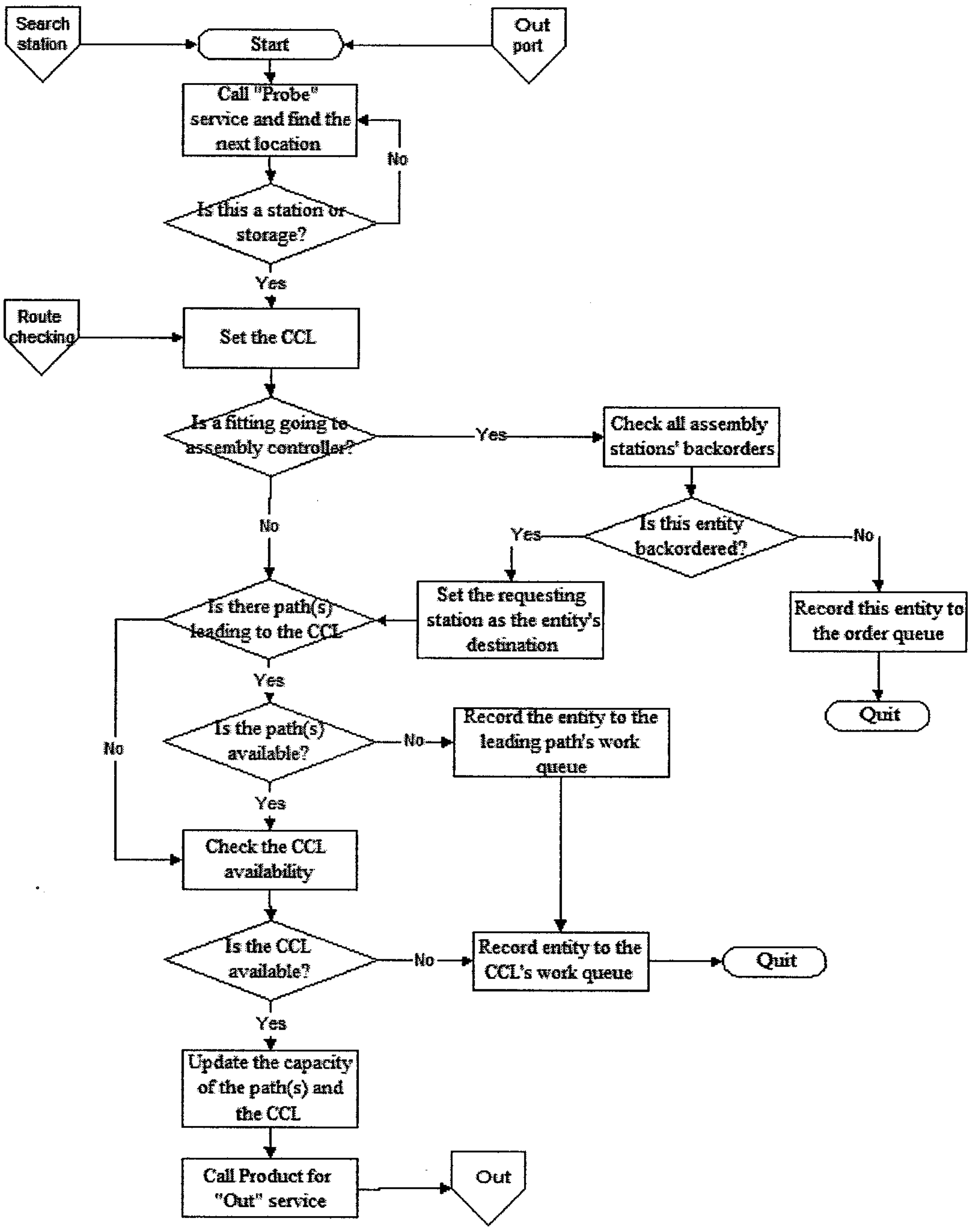
Simulation Services: SearchStation

SearchStation: Search in an entity's process plan and schedule the next operation



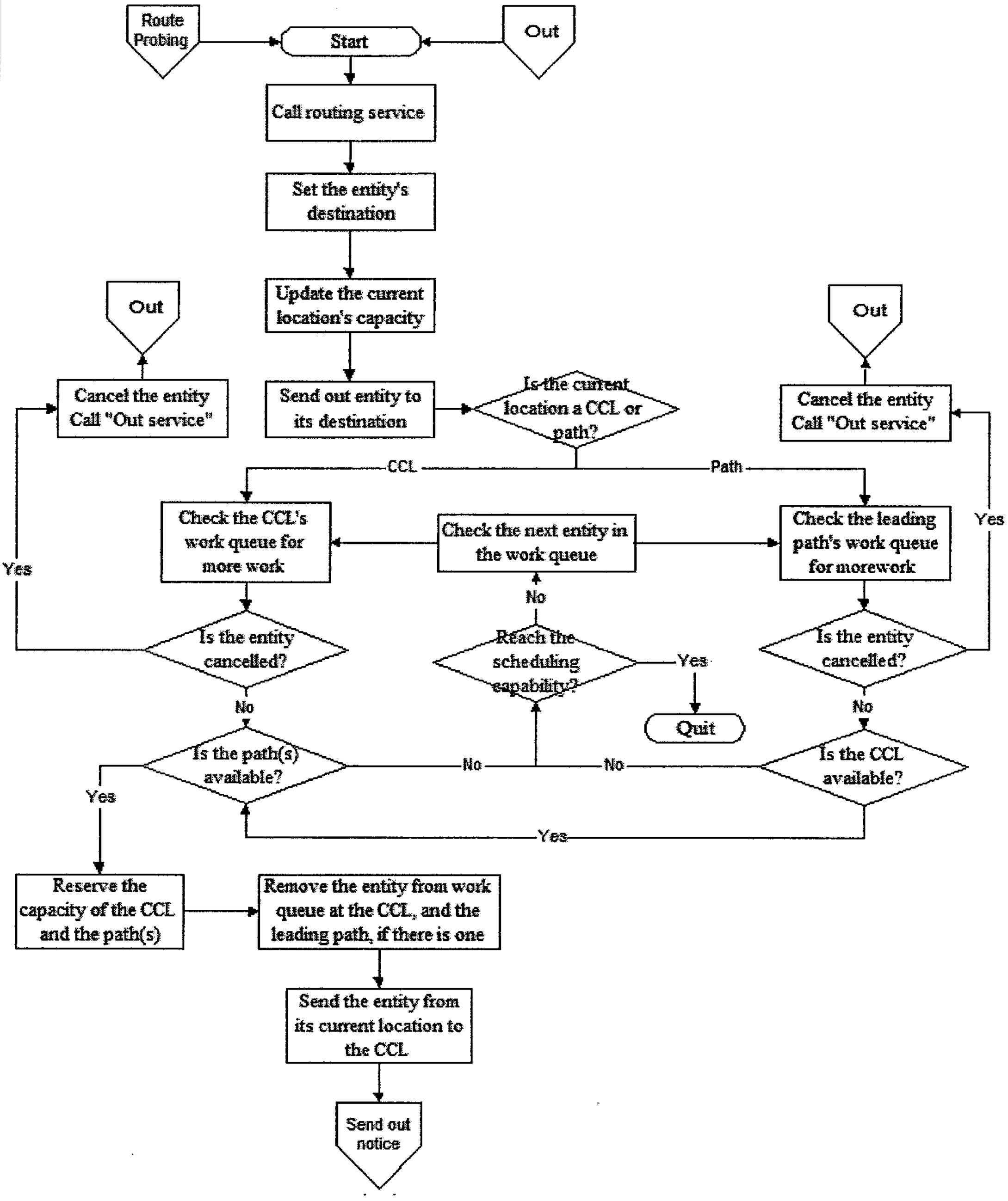
Simulation Services: RouteProbing

RouteProbing: Probe from the current location for the next Capacity Control Location(CCL)



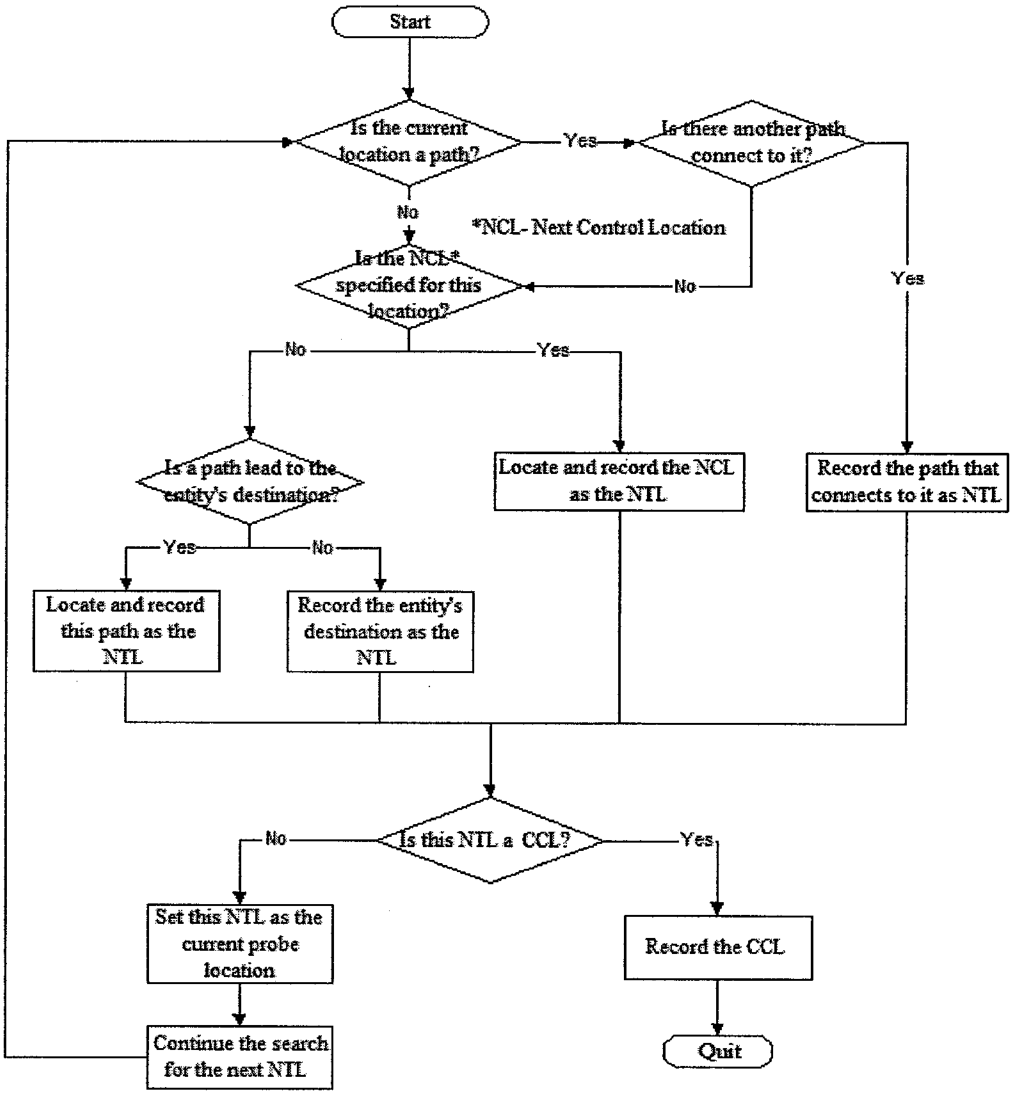
Simulation Services: Out

Out: Send out an entity to the destination, and search for the current location for more work.



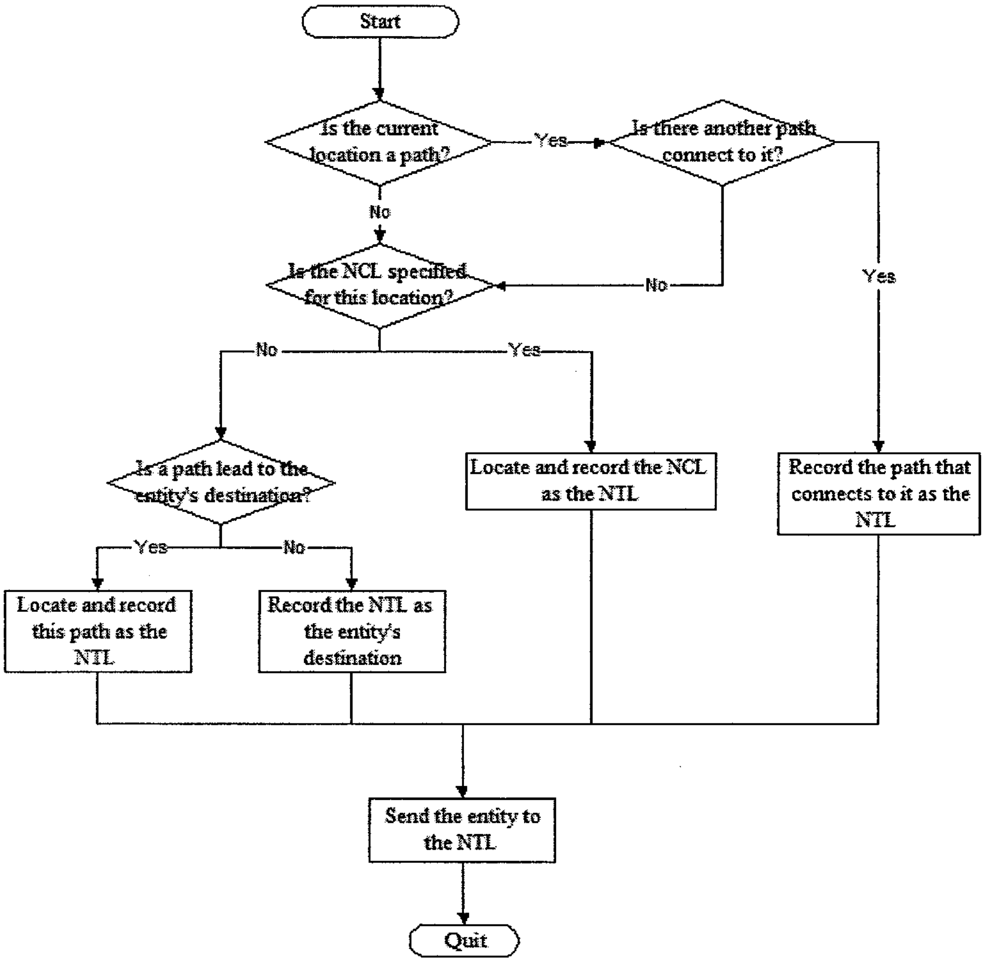
Simulation Services: Probe

Probe: Search and record an entity's destination, or Next Travel Location (NTL).



Simulation Services: Routing

Routing: Send out an entity from its current location to its Next Travel Location (NTL).

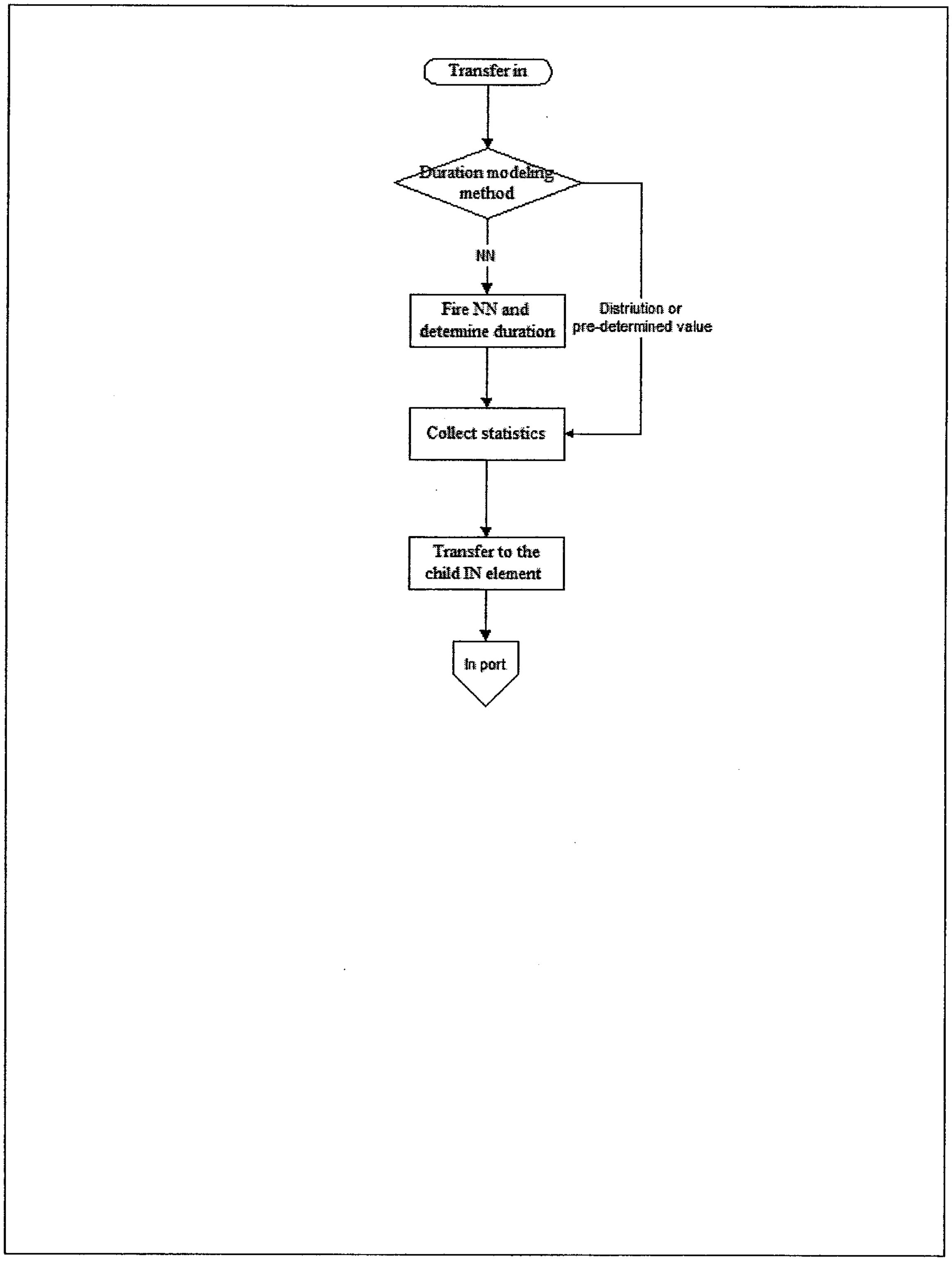


Station

Legend

▭ Action ◇ Decision ⬭ Terminator ⬠ Process Link

Element: Station
Page: 1 of 1
Revision: 0
Date:



Storage

Legend
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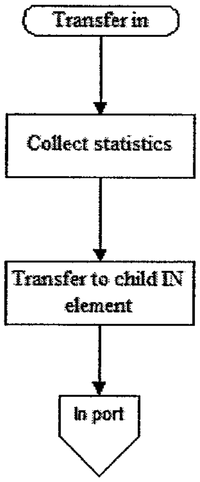
Element: Storage
Page: 1 of 1
Revision: 0
Date: Oct. 12, 2003

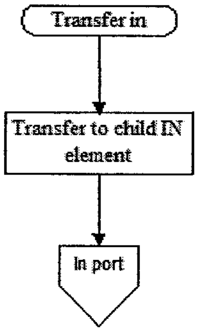


Path

Legend

□ Action ◇ Decision ▭ Terminator ⬠ Process Link

Element: Path
Page: 1 of 1
Revision: 0
Date:



In Port

Legend
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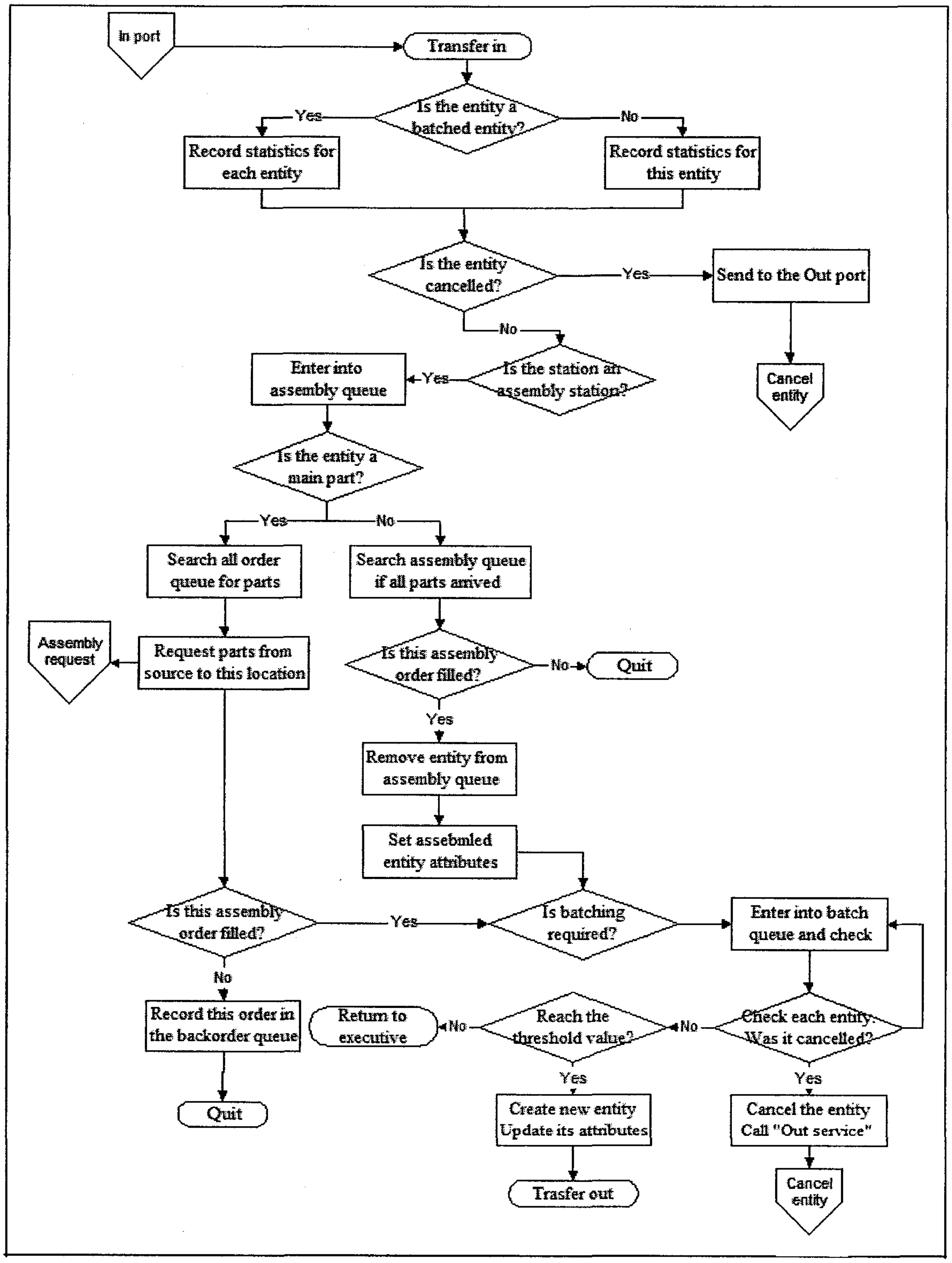
Element: In Port
Page: 1 of 1
Revision: 0
Date:



Out Port

Legend
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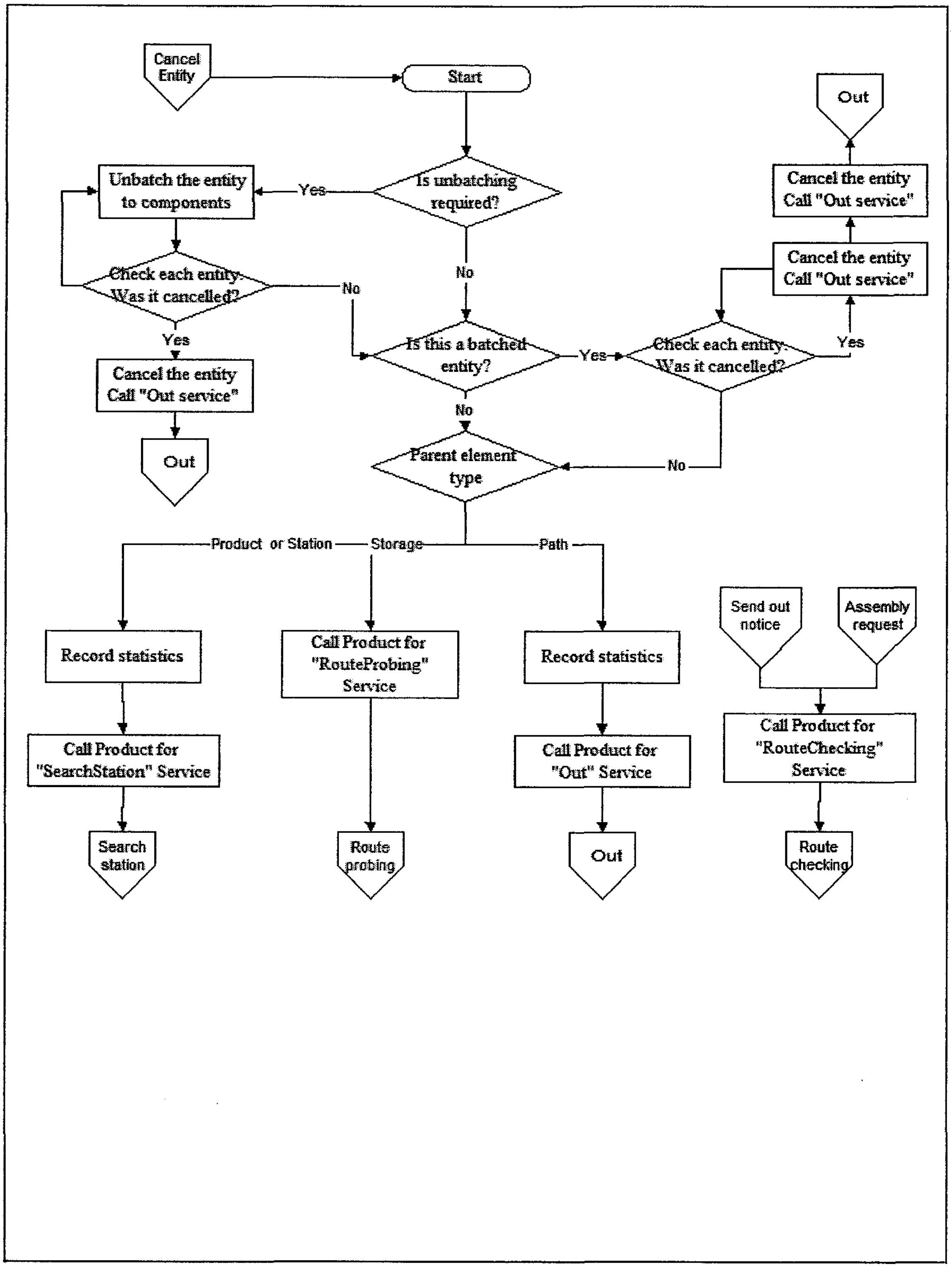
Element: Out Port
Page: 1 of 1
Revision: 0
Date:



SYSTEM OUTPUTS

Statistics are collected by modeling elements during a simulation experiment, and are accessible through the elements' interfaces. Besides these statistics, upon the completion of a simulation experiment, statistics collected for steel components are also exported to the "Output" table of the central database. Table C-3 summaries the structure of the output table.

Table C-3. Output Data Structure

Attribute	Description
product_id	The identifier of a steel component.
sub_process	The identifier of an operation.
name	The name of a location.
type	The type of a location, such as station, path, storage etc.
et	The time when a product enters a location.
lt	The time when a product leaves a location.
ps	The processing duration.
run	The identifier of a simulation experiment.

Based on the raw data stored in the output table, users can query the simulation output or analyze the output using external applications. The modeling system can present the simulation output in the form of statistics report or graph, project schedule, and animation. Users can customize statistics reports to meet their specific needs. In this version of the modeling system, project schedules are generated by Microsoft Project. Integration with Microsoft Project was developed based on the Microsoft Project object model. The animation is achieved using the Animation Template in *Simphony.*

APPENDIX D: PRODUCTION RULES FOR THE VIRTUAL SHOP MODEL

Production rules represent the knowledge of process planning. Production rules are mostly unique to a specific production environment, which is characterized by its layout, resource capacity and allocation, and production policies etc. The production rules defined for Waiward Steel Fabricators Ltd. (WSF) Shops B and C are presented here to demonstrate the structure of production rules. WSF Shops B and C are configured to handle structural steel, such as columns, beams, and bracings. The steel fabrication operations in these two shops are detailing, fitting, and welding. Detailing stations at Shops B and C are equipped with Computer Numerical Control (CNC) machines, including beam drill lines, plate punch and plasma cutting system, plate drill and plasma cutting system, structural burning system, and angle line. All CNC machining stations are controlled by the detailing supervisor, which is represented as a controller named "WSG-BC-Detailing" in the WSF virtual shop model. Table D-1 shows a description of these detailing stations. Each fabrication shop has six fitting stations and six welding stations with similar layout and processing capacity. Fitting stations at Shops B and C are controlled by the controllers titled "WSG-B-Fitting" and "WSG-C-Fitting" respectively in the WSF virtual shop model. Similarly, the controllers "WSG-B-Welding" and "WSG-C-Welding" control the welding stations in Shops B and C.

Table D-1. Steel Detailing Stations

Name	Station Code	Description
Beam drill line	BDL600	Cut and drill structural steel; the maximum width of steel members which can be handled is 600 mm.
Beam drill line	BDL750	Cut and drill structural steel; the maximum width of steel members which can be handled is 750 mm.
Beam drill line	BDL1250	Cut and drill structural steel; the maximum width of steel members which can be handled is 1250 mm.
Angle line	AngleMaster	Shear, punch, and mark various structural angle
Plate drill & plasma cutting system	FPB1500	Cut and drill steel plate; the maximum width of steel plate which can be handled is 1546 mm.
Plate punch & plasma cutting system	FPB1800	Cut and punch steel plate; the maximum width of steel plate which can be handled is 1851 mm.
Structural burning system	Burningtable	Cut larger steel sheets to appropriate size for FPB1500 and FPB1800.

The process plan of a steel piece at the detailing stage is affected by a steel piece's physical properties, processing requirement, and workstations' functions and their capacity. Specifically, for WSF Shops B and C detailing, these influencing factors include material category, width of steel members, holing method, workstations' functions, and their capacity measured by the maximum material width they can handle. Steel materials are classified into three categories, which are steel plate, structural steel, and structural angle. Steel plate refers to steel sheet with a variety of thickness and sizes. Like plate, structural steel shapes are available in a variety of sizes and weights, such as I beam, wide-flange beam, channel, rounds, squares, and tubing. Angle-shaped structural steel members are classified into the structural angle category. Width of steel pieces refers to the width of the steel piece's cross section. For a particular steel piece, holing methods can be punching (P), drilling (D), or unspecified (U), which means either punching or drilling is suitable for holing. Workstations' function and capacity is listed in Table D-1. Table D-2 shows the static production rules defined for WSF Shops B and C detailing. The "Station list/Note" column shows a list of eligible workstation names or comments. During simulation experiments, dynamic rules, such as dispatching rules and station selection rules defined in station controllers, will be applied to determine the exact workstation for a steel piece. Records with "Beyond shop capacity" showing in the "Station list/Note" column will be highlighted for users to verify.

Table D-2: Production Rules for Steel Detailing

ID	Material category	Width	Holing	Station list/Note
1	Structural steel	<=600 mm	D/P/U	BDL600/BDL750/BDL1250
2	Structural steel	>600 mm & <=750 mm	D/P/U	BDL750/BDL1250
3	Structural steel	>750 mm & <=1250 mm	D/P/U	BDL1250
4	Structural steel	>1250 mm	D/P/U	Beyond shop capacity
5	Structural angle	All	D	Refer to Rules 1, 2, and 3
6	Structural angle	All	P	AngleMaster
6	Structural angle	All	U	AngleMaster
7	Steel Plate	All	D/P/U	Burningtable for material preparation, followed by Rules 8 to 14.
8	Steel Plate	<=1546 mm	D	FPB1500
9	Steel Plate	<=1546 mm	P	FPB1500/FPB1800
10	Steel Plate	<=1546 mm	U	FPB1500/FPB1800
11	Steel Plate	>1546 mm & <=1851 mm	D	Beyond shop capacity
12	Steel Plate	>1546 mm & <=1851 mm	P	FPB1800
13	Steel Plate	>1546 mm & <=1851 mm	U	FPB1800
14	Steel Plate	>1851 mm	D/P/U	Beyond shop capacity

The process plan of a steel piece at the fitting and welding stages are primarily determined by its connection type. For a particular steel piece, the connection type can be welded connection (W), bolted connection (B), or a mix of welded and bolted connections (M), depending on the steel engineer's design decision. Table D-3 shows the static production rules defined for steel fitting and welding.

Table D-3: Production Rules for Steel Fitting and Welding

ID	Connection type	Station list/Note
1	W	All fitting stations for fitting, followed by Rule 4 for welding.
2	B	All fitting stations for assembling and inspection.
3	M	All fitting stations for fitting, followed by Rule 4 for welding.
4	W/M	All welding stations for welding.

APPENDIX E: STEEL FITTING PRODUCTIVITY DATA

A time study was conducted in WSF Shops C for three months. It resulted in the collection of 131 observations on the steel fitting operation. Each observation record contains information about the activity duration, product-related influencing factors, which include piece weight, piece length, the number of fittings, and the number of cutouts, and work environment-related factors, which include fitter rank and working shift. Table E-1 shows these records. For confidentiality reasons, fitting duration data were scaled.

Table E-1. Steel Fitting Productivity Data

ID	Weight (kg)	Length (m)	No. of fittings	No. of cutouts	Rank	Shift	Duration (Min.)
1	888	7.0	13	0	1	Day	88
2	125	4.4	5	2	2	Night	18
3	125	4.4	5	4	3	Night	29
4	168	4.5	5	2	2	Day	24
5	216	5.6	5	0	3	Day	22
6	168	4.5	5	2	2	Day	24
7	168	4.5	5	2	2	Day	24
8	26	1.0	5	3	3	Day	12
9	31	1.2	5	3	3	Day	12
10	168	4.5	5	2	3	Day	19
11	26	1.0	5	3	3	Day	12
12	168	4.5	5	2	3	Day	17
13	165	4.5	5	1	3	Day	12
14	386	9.0	5	1	1	Day	47
15	346	8.4	3	0	1	Day	21
16	218	5.7	5	0	3	Day	20
17	168	4.5	5	2	2	Night	24
18	216	5.6	5	0	2	Night	16
19	36	1.5	5	3	3	Night	13
20	168	4.5	5	2	3	Night	22

ID	Weight (kg)	Length (m)	No. of fittings	No. of cutouts	Rank	Shift	Duration (Min.)
21	146	4.5	5	2	2	Day	16
22	168	4.5	5	2	3	Day	17
23	418	4.5	8	1	1	Night	32
24	388	1.4	21	0	1	Day	103
25	1359	8.7	6	6	1	Day	59
26	1720	10.3	7	0	1	Day	47
27	1650	10.4	5	0	2	Night	47
28	1658	10.5	5	0	1	Day	47
29	1650	10.4	5	0	2	Night	51
30	538	4.4	7	1	1	Day	50
31	52	4.0	1	0	2	Day	8
32	1839	10.4	5	0	1	Day	59
33	58	4.3	4	1	2	Day	10
34	538	4.4	7	1	1	Day	51
35	2550	11.0	7	1	2	Day	55
36	2914	11.0	5	3	1	Day	83
37	2915	11.0	5	2	2	Night	83
38	484	4.4	5	1	2	Night	26
39	1569	14.1	8	1	1	Day	114
40	78	4.0	2	0	2	Night	20
41	5	0.3	3	0	1	Day	4
42	110	3.1	3	0	1	Day	36
43	53	1.5	5	3	3	Day	20
44	141	3.4	7	0	3	Day	24
45	277	5.8	5	1	1	Day	20
46	8	0.2	2	0	3	Day	8
47	886	10.3	8	0	1	Day	47
48	52	1.3	3	0	3	Day	32
49	260	2.3	8	0	2	Day	55
50	15	0.6	3	2	3	Day	12
51	15	0.6	3	2	3	Day	12
52	7	0.5	1	1	3	Day	8
53	83	2.8	5	0	2	Day	16
54	47	1.5	3	3	3	Day	18
55	19	1.2	3	2	2	Day	12
56	65	2.5	3	0	2	Day	47
57	101	2.3	5	3	3	Day	41
58	77	1.7	5	3	3	Day	43
59	85	3.2	1	2	2	Day	24
60	28	0.8	5	3	2	Day	12
61	329	3.5	5	4	1	Day	36
62	76	0.9	3	4	3	Day	36

ID	Weight (kg)	Length (m)	No. of fittings	No. of cutouts	Rank	Shift	Duration (Min.)
63	65	1.4	7	4	3	Day	50
64	6	0.3	2	1	2	Day	8
65	54	2.1	6	0	2	Day	36
66	135	4.7	4	0	1	Day	16
67	33	1.0	7	0	3	Day	12
68	52	2.4	5	0	3	Day	55
69	111	3.3	6	3	3	Day	58
70	52	2.4	5	4	3	Day	39
71	67	1.5	5	2	3	Night	24
72	66	1.4	5	0	2	Night	21
73	221	3.5	5	2	3	Night	47
74	221	2.6	5	2	3	Night	47
75	23	0.7	3	0	3	Day	12
76	10	0.6	1	2	2	Day	8
77	59	3.2	3	0	3	Day	24
78	44	2.3	4	2	3	Day	39
79	13	0.6	2	2	3	Day	9
80	788	9.1	32	4	1	Night	189
81	420	3.5	21	0	2	Night	95
82	92	3.9	2	0	3	Night	24
83	829	10.9	8	0	2	Night	71
84	39	3.0	2	0	2	Night	16
85	61	4.6	3	0	2	Night	24
86	39	2.9	2	0	2	Night	16
87	49	3.7	2	0	2	Night	24
88	1747	10.4	5	4	1	Day	47
89	1739	10.3	5	0	1	Day	47
90	803	10.6	6	0	2	Night	55
91	803	10.6	6	0	2	Night	47
92	43	3.1	4	0	2	Day	16
93	314	6.8	5	2	1	Day	59
94	386	5.5	5	1	2	Day	24
95	462	6.7	5	3	2	Day	24
96	780	9.0	5	3	1	Day	24
97	478	8.4	10	0	2	Night	71
98	42	3.1	4	0	2	Night	24
99	92	2.9	4	0	3	Day	24
100	25	1.0	4	2	2	Night	12
101	156	4.0	3	0	2	Day	12
102	112	4.0	6	1	2	Day	16
103	98	2.4	8	2	2	Day	36
104	986	9.5	6	4	2	Day	63

ID	Weight (kg)	Length (m)	No. of fittings	No. of cutouts	Rank	Shift	Duration (Min.)
105	482	7.0	5	3	2	Day	24
106	26	1.0	5	4	1	Night	12
107	213	2.9	3	2	2	Day	24
108	140	3.9	7	0	2	Day	20
109	350	7.2	5	0	2	Night	16
110	644	6.9	19	0	1	Day	71
111	727	6.9	33	0	1	Day	122
112	85	2.5	5	0	2	Day	28
113	373	6.3	5	0	2	Day	24
114	15	0.5	4	0	3	Day	12
115	1805	11.0	7	1	1	Day	87
116	125	3.4	9	4	2	Night	36
117	168	4.5	5	2	3	Day	22
118	305	5.4	5	0	2	Day	24
119	14	0.9	3	0	2	Day	9
120	392	7.7	2	2	1	Day	51
121	82	4.3	2	0	2	Night	16
122	484	4.4	5	1	1	Day	28
123	1840	10.4	14	0	1	Day	71
124	334	7.3	3	3	1	Day	20
125	168	4.5	5	2	2	Night	24
126	1617	10.4	8	0	1	Day	63
127	40	1.9	2	0	1	Night	16
128	805	10.7	7	0	2	Night	47
129	288	5.2	10	0	3	Day	51
130	53	3.9	3	0	2	Day	10
131	174	6.0	5	0	1	Day	51