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BUILDING A VIRTUAL SHOP MODEL FOR STEEL FABRICATION

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ABSTRACT

Steel fabrication is a complex process, which encompasses product uniqueness, a high product mix, and a number of activities involving a variety of equipment and labor disciplines. The steel fabrication industry needs advanced tools and techniques in order to estimate, plan, and control fabrication shops. This paper proposes a system for building virtual fabrication shop models capable of estimating, scheduling, and analyze production. The system defines conceptual models for product, process, and the fabrication facility itself. It offers tools, such as product modeling, process modeling and planning, and a special purpose facility modeling tool, which allow users to implement these conceptual models. Modeling enhancements have enabled a more accurate modeling of machine and labor productivity, as well as better management of shop production rules. The modeling capability of the developed system is demonstrated through a case study.

1 INTRODUCTION

Steel has been an important component in buildings, bridges, and other structures for more than a century. It allows designers and contractors to construct both simple and complex structures in efficient, time-saving, orderly, and economical ways (AISC 1998). These benefits are ensured through a well-planned and controlled steel fabrication process.

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 differentiates the steel fabrication process from most other manufacturing processes in which identical products are produced in mass quantities . A steel fabrication shop is intended as a production system, possessing many resources with different processing capabilities, in order to respond to the variety of steel product types. Steel fabrication activities require a variety of machines and labor disciplines in order to produce unique steel pieces. Generally, estimating and scheduling of a fabrication project is based primarily on personal experience, information from drawings, and a knowledge of the current status of the shop. However, given the complexity of steel products; the large number of potential recourses, activities, and interactions; and the possible combinations of all these variables, an accurate analysis of such a production system can be extremely difficult. Some analysis methods, such as spreadsheet or linear programming models, may not be able to capture all the intricacies of product, process, queuing, and other phenomena observed in the actual system. 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 to estimate, schedule, and control the steel fabrication process.

Simulation models can be used to represent almost any level of detail in order to provide an accurate representation of a real-world system. This paper proposes a virtual shop modeling approach for analyzing 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 estimating, scheduling, and analyzing production in a steel fabrication shop.

2 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 1.

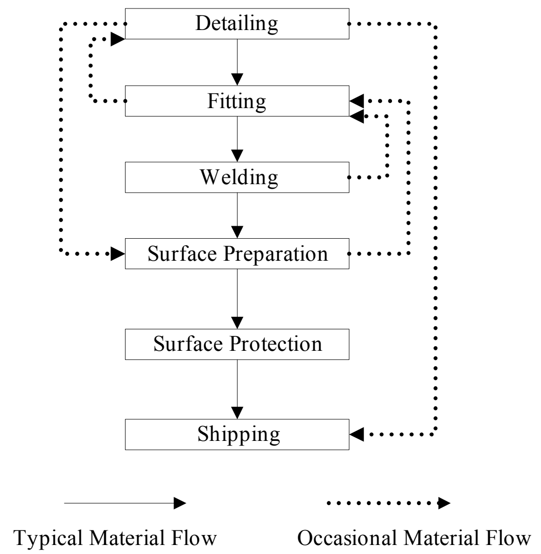

Figure 1: Steel Fabrication Process

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, which join 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 1.

3 VIRTUAL SHOP MODELING SYSTEM

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

3.1 System Architecture

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 comprises both the Product/Process Modeling System (PPMS) and the fabrication Facility Modeling System (FMS). The system architecture is illustrated in Figure 2.

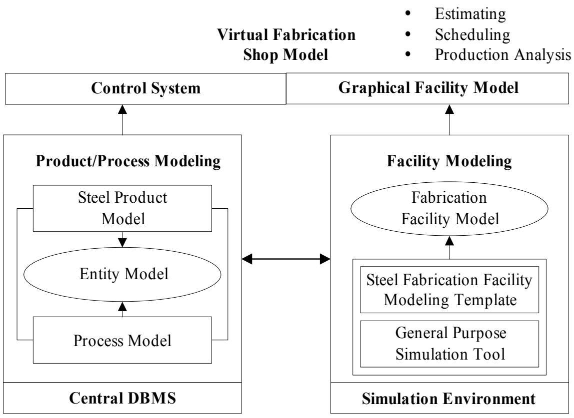

Figure 2: Virtual Shop Modeling System Architecture

PPMS creates a mechanism to define steel products, model the fabrication process, and set up relationships between product model, 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. PPMS is implemented in the central database, which is a relational Data Base Management System (DBMS). It can interface with CAD systems and planning systems to facilitate the definition of steel products and job order dispatching 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, labor, 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 FMS are synchronized at different modeling stages.

3.2 Product/Process 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. The steel component is the most basic element of the steel fabrication process, and is modeled as a product in the virtual shop model. A steel component is defined by the product model and the process model. It carries product definitions and processing plan information.

3.2.1 Product Model

The product model carries all product definition data, including physical attributes and Work Breakdown Structure (WBS) information. Examples of physical attributes include the steel component's material type, size, weight, connection method, and the quantity and size of the 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 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 the WBS and load list schedules are inputted by users into the virtual shop model.

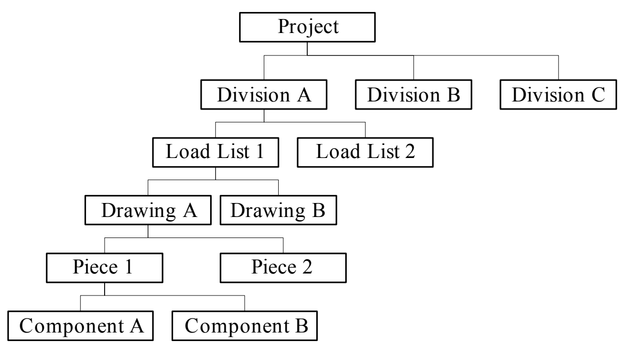

Figure 3: Work Breakdown Structure

3.2.2 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. It specifies the operations and their sequence. The process model also defines resources required for these operations. It specifies a list of working stations for each fabrication operation, where steel components can be processed. Stations are defined in the facility model, which is described in Section 3.3. 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.

3.2.3 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 is illustrated in Figure 4.

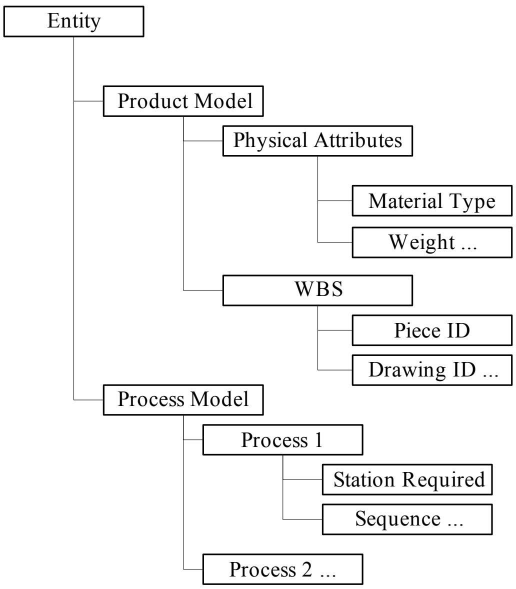

Figure 4: Entity Model

The concepts of product model, process model and entity model were implemented in the central database. At present, steel structures are designed and detailed using CAD tools. A CAD model captures a vast amount of product definition data in an electronic format. The CAD Integration Service was designed and implemented to automate the process of extracting and mapping data from a CAD model to the product model. The database 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.

3.3 Fabrication Facility Modeling

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

3.3.1 Steel Fabrication Modeling Template

The design of this customized modeling tool follows the Special Purpose Simulation (SPS) approach (AbouRizk and Hajjar 1999). SPS enables a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to easily 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* (AbouRizk and Hajjar 1998). *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 equipment, labor 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 5. A brief description of these elements is available in Table 1.

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 the 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 behavior 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,

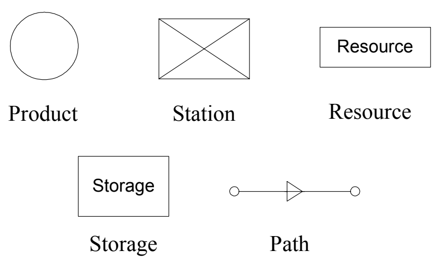

Figure 5: Graphic Representations of Modeling Elements

Table 1: Elements of Steel Fabrication Modeling Template

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

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 by *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.

3.3.2 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 equipment 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.

3.4 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 output. Data is 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 6.

The database and control systems create an open structure for the virtual shop model to interface with other existing applications, such as in estimating, scheduling, the inventory control system, and CNC control programs. For example, in the case study, which will be discussed later, an existing scheduling system was linked to the virtual shop model. Users can create load lists and develop 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

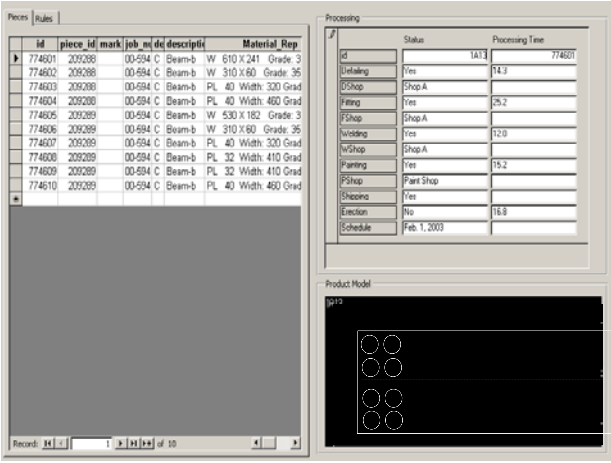

Figure 6: Sample User Interface for Product Modeling

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.

4 ENHANCEMENTS FOR ADVANCED VIRTUAL SHOP MODELING

Modeling the steel fabrication shop for estimation and shop scheduling functions comes with a high expectation for the accuracy of output. Therefore, ensuring the modeling accuracy is very important. Several techniques were developed by the authors to increase the accuracy and simplify the virtual shop modeling process. These techniques are virtual machining station modeling, labor productivity modeling, and shop knowledge management (Song and AbouRizk 2003).

4.1 Virtual Machining Station Modeling

Many steel detailing operations are performed using automated CNC machines in contemporary fabrication shops. A virtual machining station modeling technique was proposed to study the uncertainties related to the CNC machining station, and to accurately estimate the processing time based on product complexities and other context variables. Product definition data is used to generate CNC part-processing programs, which calculate machining time based on machine specifications, such as travel speed and drilling speed. A library of reusable station models was built to facilitate the construction of the virtual shop model.

4.2 Labor Productivity Modeling

Fitting, welding, and painting of steel pieces are labor-intensive operations. As well, steel pieces are unique within a project and vary considerably from one project to the next. This means that each piece will represent different degrees of complexity for each fabrication operation and will generally require different amounts of labor resources. This amount depends on many factors, including the geometry of the piece, its nature, the quantity of utilized steel components making up the overall piece, and processing specifications. Labor productivity is also affected by factors, such as design quality, operator experience, and shift arrangement, and are subject to a wide range of fluctuation. A non-statistical simulation input modeling method, the neural network approach, was used to model labor productivity and estimate processing time. Many of the uncertainties associated with processing time can be reduced with additional information about the influencing factors and by utilizing this advanced predictive model.

4.3 Shop Knowledge Management

There are numerous production rules on the shop floor for decision making during day-to-day operations, such as the order of product processing, which station should be selected to perform an operation, and the method by which a product can be processed and routed in the shop. They correspond to dispatching rules, station selection rules, station processing rules, and product routing rules. This shop knowledge is extremely important for simplifying and automating the virtual shop modeling process. A knowledge structure was defined to help users organize and manage these production rules. An example application of shop knowledge management is the Computer Aided Process Planning (CAPP) system for steel fabrication. CAPP is process planning done partially or entirely by a computer (Banks 1998). CAPP systems represent production knowledge as internal data structures and procedures so that planning decisions can be made by the computer. The structured utilization of prior knowledge in the fabrication process was found to greatly reduce the complexity and time required to build and run a virtual shop model.

5 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, twelve fitting stations, and twelve welding stations. Figure 7 shows a schematic layout drawing of Shop C. Materials are handled by three 10-ton bridge cranes and a number of fixed jibs.

The CAD system used by the drafting department of the company is StruCAD (StruCAD 2003). Entity model data is gathered from the material reports and CNC data files exported from the CAD system. An existing schedul-

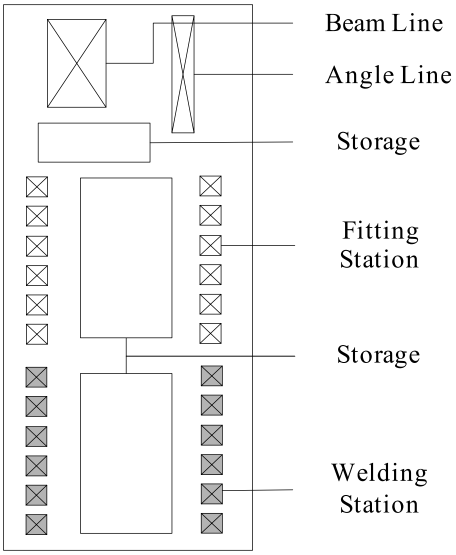

Figure 7: Schematic Layout Drawing of Shop C

ing software allowed the user to create load lists and production schedules. 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*. Labor productivity influencing factors were identified for the fitting and welding operations. Data was collected through time studies, and used to build the fitting and welding productivity models. These predictive models were embedded into station models using a Dynamic Link Library (DLL). Production rules were implemented using Structural Query Language (SQL) in the central database. Figure 8 shows some screenshots illustrating the virtual shop model built in a hierarchy structure. These screenshots are plant, shop, and station models (from left to right). The fabrication of 200 steel pieces, containing 1010 steel components, were simulated using the virtual shop model. The simulation results showed that the average total time for fabrication was 126.2 hours. The actual fabrication hours collected from the company's shop timesheet system was 132.0 hours. This indicates that the developed shop model is accurate, and can be used as an estimating tool.

6 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 various uncertainties in an industrial shop environment. Besides normal uses of simulation modeling in new system design and bottlenecking analysis, users can also perform estimating and scheduling tasks with this model.

The "as built" shop model can serve as an estimating system to accurately estimate labor hours for new projects. 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 quantity of work and the required duration, and appropriately load each resource.

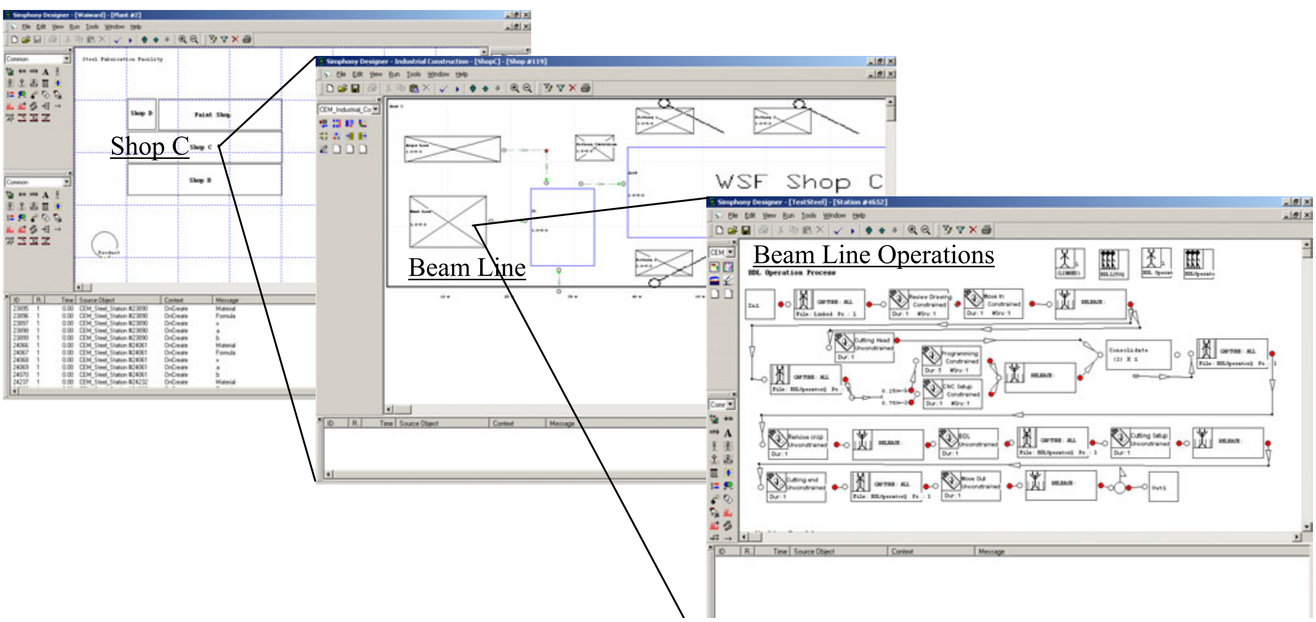

Figure 8: Virtual Shop Model Hierarchy

Future work is required to further integrate the virtual shop model to other fabrication management systems for modeling inputs and output analysis. This integration would make the model more beneficial to ordinary users. An animation system will also be incorporated into the modeling system in order to visualize the steel fabrication process.

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