Flow Production of Pipe Spool Fabrication: Simulation to Support Implementation of Lean Technique

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Abstract: Pipe spool fabrication is an important stage in industrial construction project delivery. It is a complex production system characterized by product uniqueness and high product mix, which pose challenges to the analysis and improvement of this system. This research applies lean production principles and flow production to shop fabrication, and uses a simulation-based approach as a tool to facilitate its implementation. The work described in the paper is based on a real case study undertaken with an Edmonton-based industrial construction contractor. The traditional batch-and-queue fabrication system and the new cell-based work flow fabrication systems were compared and analyzed. Simulation models were built to experiment with the old and new production systems and quantitatively test the effects of lean principles on the performance of the systems. The developed simulation-based approach proves a practical and more powerful tool than the value stream map for modeling and for quantitatively evaluating the performance of a complex and dynamic spool fabrication shop.

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Introduction

The variable characteristics of pipe spool fabrication, taken as a critical process of project delivery in industrial construction, make the application of new production management theory and techniques very challenging. However, the controllable shop environment marks it as a site for potential innovation in project management and improvement. Lean theory has been widely applied in the manufacturing industry in the last few decades, and it has proved to be very useful. The Lean Construction Institute has also begun work to disseminate the concepts of "lean delivery;" however, academically developed principles are not widely accepted by the construction industry. In industrial construction, lean techniques are rarely used by spool fabricators.

Compared to manufacturing, spool fabrication lacks a suitable tool for modeling and analyzing system changes and improvements. The value stream map (VSM) is a popular tool that can facilitate the application of lean production; however, it does not efficiently represent the dynamic nature and wide uncertainty of a spool fabrication shop. Simulation has been widely used and sometimes is the only appropriate tool for production system analysis; however, its use in a spool fabrication shop is challenging due to the above-mentioned characteristics.

This research is based on the production practices of an Edmonton-based pipe spool fabricator that has applied lean techniques in its shops. The paper initially introduces the background of industrial construction fabrication and its existing problems. Next, flow production, one of the lean principles, is explained and discussed. The two systems of a traditional fabrication shop and a flow fabrication shop are compared in the section "Traditional Fabrication Shop versus Flow Fabrication shop." The weakness of the VSM is discussed in the section "Limitations of Value Stream Map." The section "Simulation-Based Approach" presents two developed simulation models for the two systems. Historical cycle time is extracted and analyzed to compare the simulation results. The inner features and differences between the two systems are revealed by comparisons. In "Experimentation with the System Using Simulation," further experiments are conducted using the developed models to demonstrate other potential improvements for the new system. Conclusions are drawn in the last section, "Study Limitations."

Introduction to Spool Fabrication

Industrial construction includes a wide range of construction projects essential to our utilities and to basic industries, such as petroleum refineries, petrochemical plants, nuclear power plants, and off-shore oil/gas production facilities (Barrie and Paulson 1992). Industrial construction is one the most complex types of construction. The typical operations of pipe spool fabrication include cutting, fitting, welding, quality control (QC) checking, stress relief, hydro testing, painting, and other surface finishing. A spool is normally decomposed into pipes and fittings (elbow and flange). During the cutting stage, the raw pipes are cut to the required sizes. They are then fitted and welded. After QC checking, a welded spool may need to undergo any or all of the following operations: stress relief, hydro testing, painting, and other

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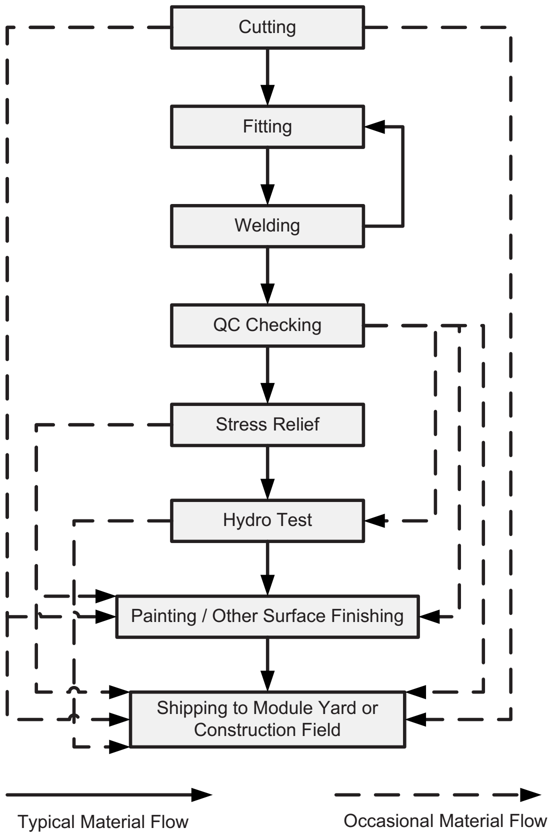

Fig. 1. Spool fabrication process

surface finishing. These typical processes are shown in Fig. 1. Spool fabrication has become a critical stage for the whole project delivery in industrial construction. Its performance directly influences the downstream stages: module assembly and site construction.

A spool fabrication shop appears to be much the same as a manufacturing shop, but for the fact that every product is unique and the product family is extremely varied. The process is also labor-intensive, less automated, and interrupted by frequent change orders from clients in the middle of the fabrication. These characteristics make daily shop management difficult and present a challenge to production scheduling. Existing project management systems such as Microsoft Project and P3 (Primavera Project Planner) cannot be applied effectively because this software is primarily activity-oriented, whereas fabrication shops process numerous unique products. This variation in production also makes the application of new production management approaches, such as lean techniques, very challenging.

Flow Production

Lean Thinking

Lean thinking has proven very useful for improving production processes and product quality in the last few decades, and lean production techniques have been widely applied in the manufacturing industry. Lean thinking is concerned with the elimination of waste: "waste" is defined as over or under production, wait-time, transportation, inappropriate processing, unnecessary materials inventory, unnecessary motion, and product defects. Under the lean thinking umbrella, there are principles, methods, techniques, and tools that can be applied to eliminate one or more of the aforementioned wastes. Lean thinking has five basic principles: (1) know the real value; (2) map the value stream; (3) flow; (4) pull; and (5) perfection (Womack and Jones 1996). In this research, we focus on the investigation and implementation of one of the lean principles: flow production.

Batch-and-Queue System

The common practice of almost all manufacturing systems a few decades ago was the batch-and-queue system. Womack and Jones (1996) investigated and analyzed the bicycle industry, which was a highly disintegrated traditional batch-and-queue system that differentiated production activities by type. Many industries even designed and built departments for each type of activity such as cutting, bending, fitting, welding, or painting. Materials or parts were processed batch-by-batch for each activity and were then sent to inventory to await the next activity. When the products are highly mixed, the changeover of tools is frequent and wastes time. In order to reduce the frequency of changeover, larger batches are processed, which leads to the problem of tracking inventory and sending parts to the next correct process at the right time. Such a system causes several types of waste, as defined by lean thinking: overproduction, wait-time, transportation, inventory, and motion. Furthermore, the total lead time of the batch-and-queue system is lengthy due mainly to the above wastes.

Flow Production System

Flow, one of the five basic principles of lean thinking, was described by Womack and Jones (1996) as lining up "all of the essential steps needed to get a job done into a steady, continuous flow, with no wasted motions, no interruptions, no batches, and no queues" and as "the end objective of flow thinking is to totally eliminate all stoppages in an entire production process." In a flow system, the operation's activities are ordered in a sequence, often arranged in a "U"-shaped cell. If only one product moves at one time, it is called "one-piece-flow."

Flow systems greatly reduce the waste, delays, and wait-times created by a batch-and-queue system. They reduce inventory and transportation, which subsequently results in less labor motion and space occupation. However, implementing a flow system, especially a one-piece-flow method, has certain requirements. The changeover time of a machine should be short, or even instantaneous, from one product specification to the next. The size of a product should be suitable: too small a product leads to an inefficient use of set-up time. Laborers need to be crosstrained in order to perform more tasks.

Traditional Fabrication Shop versus Flow Fabrication Shop

Fabricating pipe spools involves a number of processes, all of which have to be completed for each spool regardless of the production system followed. The amount of waiting time for each spool in between these processes and the amount of material handling and transportation time spent for moving spools between these processes characterize the type of production system followed in the shop. Figs. 3 and 5 show the sequence of processes (rectangular shapes) and inventory and queuing (triangles) in both the batch-and-queue system and the continuous flow system. In

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

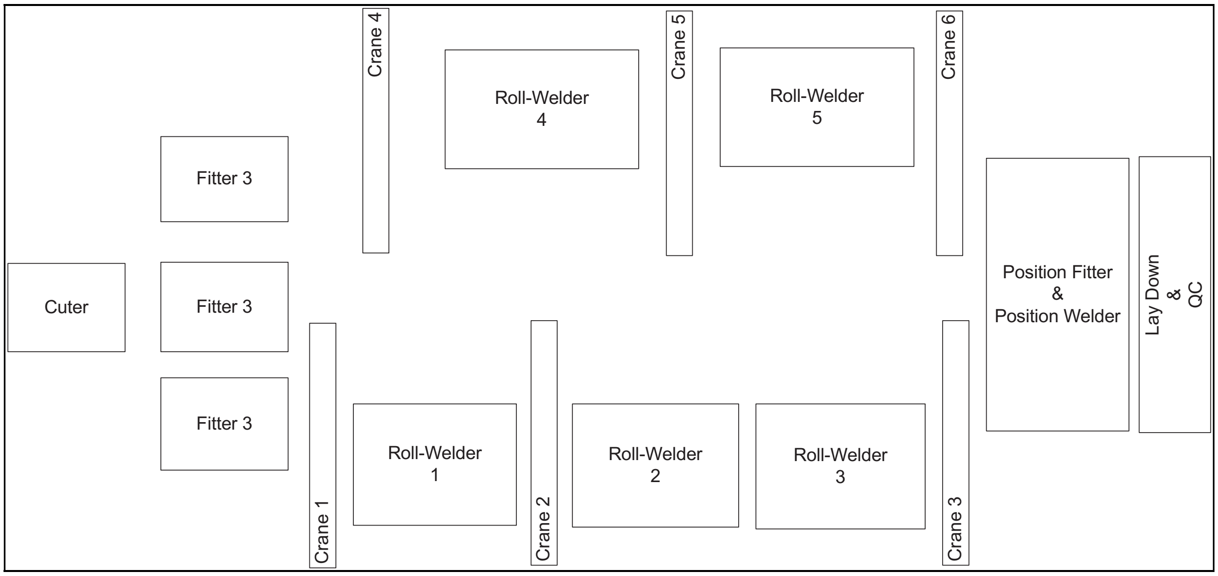

Fig. 2. Layout of the old shop

the first case, spools (and/or their parts) complete one process and move to waiting areas where they are queued for the next processing station. When the next station is free to process new spools, they are moved again to that station. In the second case, a number of processes are lumped together in one processing cell where spools are moved once to that cell, and as many processes as practically possible are completed in the cell. The following two sections describe the operations under each system in more detail as they pertain to the fabrication shop used in this study.

Batch-and-Queue Spool Fabrication Shop

The Edmonton-based industrial construction contractor in this research had used the batch-and-queue fabrication system for many years. They have five shops. The five shops employ the same process with comparable facilities, equipment, and laborers. They fabricate spools of different sizes and materials. By designing five similar production shops to fabricate different product families, instead of assigning one shop for each activity, the company un-

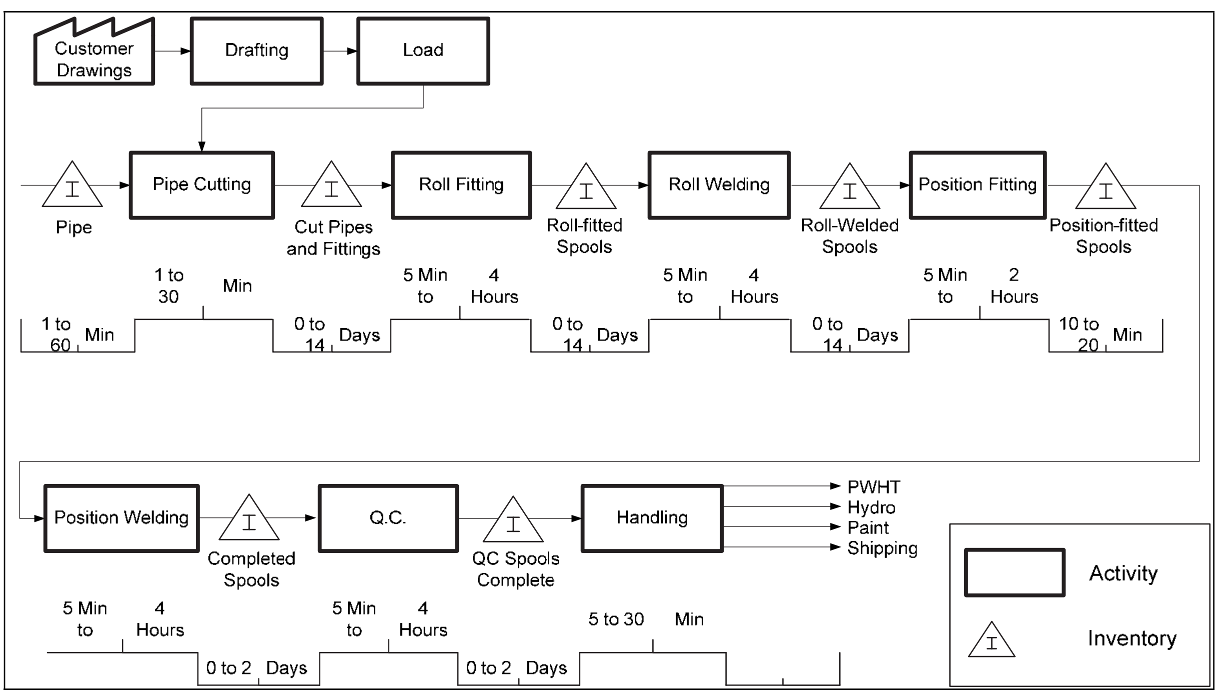

Fig. 3. Value stream map of the old system

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

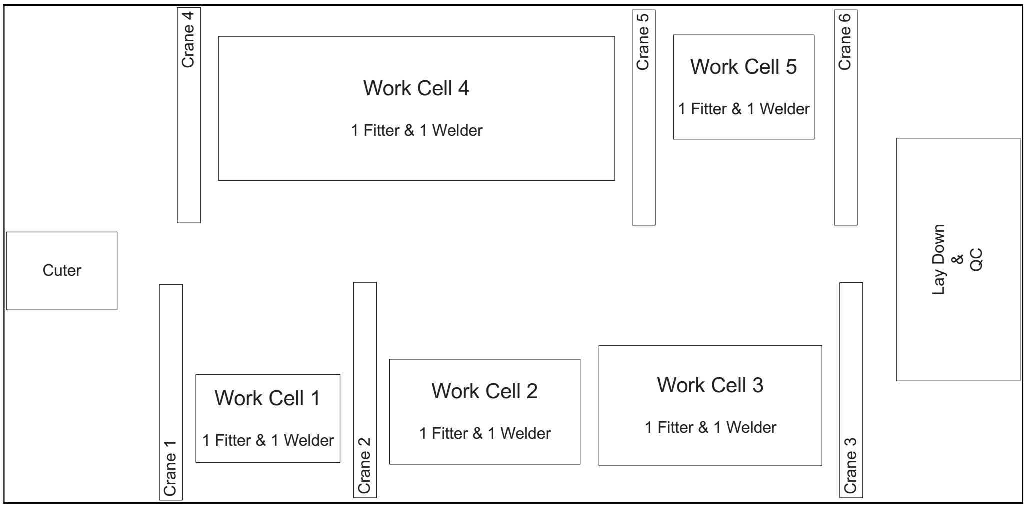

Fig. 4. Layout of the new shop

intentionally involved lean thinking. However, each shop was still a batch-and-queue system. Fig. 2 shows the layout of one of the five shops, which include such personnel as one cutter, three roll-fitters, five roll-welders, one position-fitter, one position-welder, and six cranes.

In order to analyze the old system and identify the nonvalue-added activities, the production management staff drew a VSM for the old system (Fig. 3). Because of the unique nature of pipe spool and the resulting wide range of uncertainty, the staff can only estimate loosely for each activity and inventory. The estimated minimum cycle time is 1 h and the maximum cycle time is 42 days based on the VSM.

The old fabrication system was based on the activity-oriented layout. The machines and those laborers having the same function were grouped and sequenced from the entrance to the exit of the shop. Several wastes were identified in this configuration, including high inventory levels. It was observed that the old floor was always cluttered. Cut pipes, fitted parts, and welded parts were piled on the floor. The waiting time of parts is long, especially the roll-welded parts waiting for position-fitting. Therefore, much of the space in the shop was occupied. Roll fitters and roll welders were scattered throughout the shop, and materials were moved between working stations and the central floor repeatedly. In the old system, fitters and welders had to walk back and forth with transportation between the working stations and the central floor. The position-fitter also spent time looking for the required parts of a spool on the central floor and sometimes returned without finding the required parts. A scheduling problem was also associ-

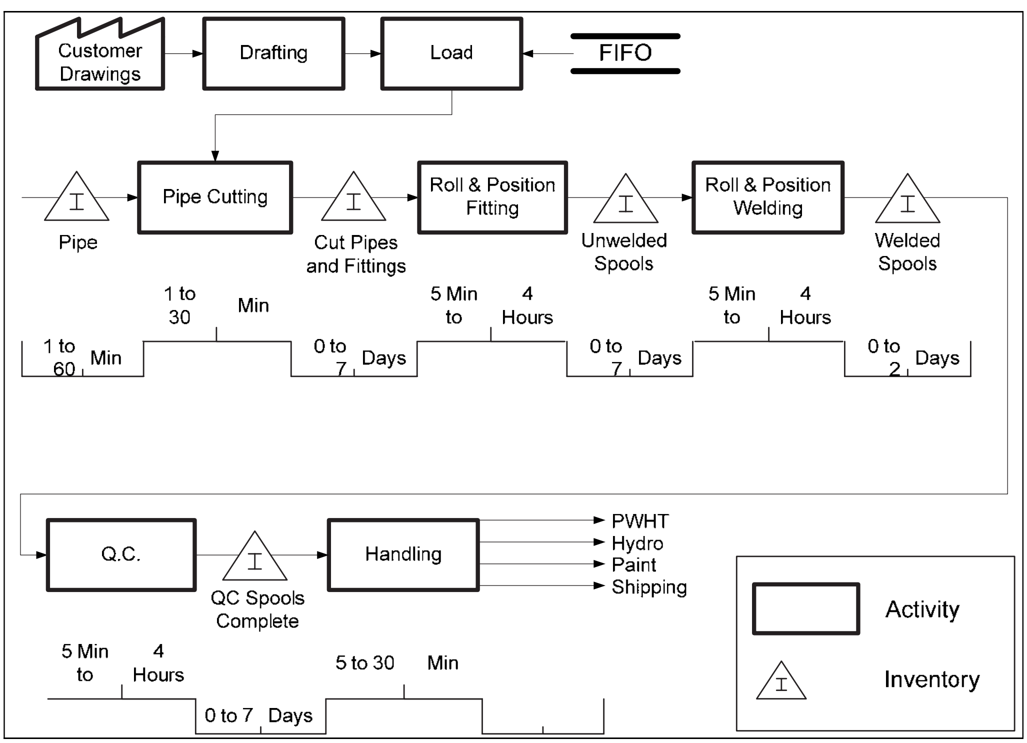

Fig. 5. Value stream map of the new system

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

ated with the old system in that there was no consistent queuing rule to follow. This resulted in some materials and parts staying on the floor for a long time. The final result of the above waste and the queuing problem was a long cycle time of spool fabrication.

Flow Spool Fabrication Shop

Because of the high uncertainty and complexity of spool fabrication, the fabricator decided to reduce risk by testing lean production in one of the five shops. The fabricator changed its traditional fabrication shop layout to a flow fabrication system. In order to facilitate a flow system, other techniques such as 5S (Hirano 1996) and the virtual factory were also applied. Fig. 4 shows the new layout, where one cutter is at the front of the shop and five work cells are arranged along the two sides. There is one fitter and one welder in every work cell. Laborers were crosstrained so that each fitter can do roll-fitting and position-fitting, and each welder can do roll-welding and position-welding.

Shop drawings are loaded into the shop batch-by-batch. Cutters cut pipes and send them to the central floor. Drawings are assigned to the five work cells according to the length of the spool. The maximum quantity that each work cell can hold is 200 welding diameter inches. The fitter of each work cell moves all the pipes and fittings composing one spool from the central floor to the work cell using cranes if necessary. A spool is completely fabricated in one work cell. The queuing rule, first-in-first-out (FIFO), is strictly followed if there is more than one spool being fabricated in the work cell. The fitter sends the finished spools to the lay-down area, where they are checked by the QC crew and then moved out of the shop by the mobile crane.

The VSM for the newly reconfigured system was drawn as well (Fig. 5). The minimum cycle time is 22 min, and the maximum cycle time is 25 days, based on the VSM.

In the new system, a flow is formed in each work cell. All roll-fitting, roll-welding, position-fitting, and position-welding are sequenced and finished in one work cell. After being evaluated using lean thinking again, the above identified wastes are reduced or eliminated. Inventory is greatly reduced in the new system. Fitted or welded parts are no longer piled on the central floor. The wait is thereby reduced, as is the inventory. The wait-time of roll-welded parts for position-fitting is greatly reduced owing to the elimination of the bottleneck for position-fitting. As a result, the space used for inventory is reduced. The floor becomes clearer and more orderly. In the new system, most of the material handling happens inside the work cell. The repetitive movement of materials between working stations and the central floor is eliminated. The transportation distance between fitting and welding is reduced to almost zero. Associated with the reduction of transport, the extra motion of fitters and welders between the working station and the central floor is also eliminated. The FIFO queuing rule is consistently followed if there is more than one spool being fabricated in each work cell, which guarantees that no spool stays in the work cell for very long. Finally, a shorter fabrication cycle time is achieved by the reduction or elimination of the wastes and by following the queuing rule.

Limitations of Value Stream Map

As discussed above, some improvements in shop performance have been observed. The VSM was used as a tool to describe and compare the two systems in order to facilitate the implementation. As a paper and pen tool, the VSM is easy to learn and may be used to identify wastes in a system. However, the VSM is a static snapshot constructed by following the flow of the system; it cannot represent the variability, dynamic nature, and high uncertainty of such a complex system with product uniqueness and high mix. The comparison of the VSM and simulation was discussed by Lian and Van (2002), and similar findings were obtained. In the system studied for this paper, every spool is unique and vastly different in terms of size and configuration. The activity duration and the inventory delay of individual spools vary widely. Fitting and welding activities may be repeated a number of times, as determined by the configuration of the spool. The system is frequently interrupted by rework or by the client's immediate needs. The cycle time of a spool may range from several minutes to a few weeks. It is very difficult for production staff to utilize a VSM to model and represent such a system when evaluating the improvements from a new system. This is demonstrated by a historical data analysis and in the simulation results outlined in a later section of this paper.

We need a more powerful tool to model such a system, to evaluate the performance changes, and to test more scenarios. In this research, the simulation-based approach is chosen as the tool to evaluate the application of lean techniques in industrial construction fabrication.

Simulation-Based Approach

Simulation is widely used in the manufacturing industry. Over the past 20 years, there have been numerous studies on repetitive construction processes using simulation. Simulation has been proven to be a powerful tool to model and analyze processes. Lean thinking focuses on studying production processes in order to eliminate waste and to improve quality. Thus, as Halpin in Halpin and Kueckmann (2002) remarks, "lean thinking and simulation are very closely linked and even synonymous." Simulation can be used as a quantitative means to test and validate lean concepts and applications prior to implementation. For example, Tommelein (1998) successfully used simulation to model a matching problem in order to compare push-driven and pull-driven processes. The simulation results showed that the pull-technique in material delivery is a useful tool for improving performance. This paper uses simulation to facilitate the application of flow production to improve the performance of pipe spool fabrication.

Choosing the Tool and Preparation Work

In order to describe and compare the two systems and to experiment with alternative scenarios for the new system, the pipe spool fabrication shop is modeled using the enhanced Common Template in the Simphony simulation development environment (Hajjar and AbouRizk 2002). Simphony is a simulation platform for developing special purpose simulation (SPS) templates for the construction industry and for building models. It allows developers to implement highly flexible simulation methods supporting graphical, hierarchical, modular, and integrated modeling.

In spool fabrication, every spool is unique and needs to be recognizable during the entire process. Also, each spool does not travel through the system as one entity most of the time. Rather, it flows in the form of raw materials or a few parts. The original set of modeling elements in Simphony's Common Template does not directly support the modeling of assembly processes in which a

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

Table 1. Newly Developed Elements to Enhance Common Template of Simphony

Name	Notation	Description
Assembly		Entities with the same product ID can locate each other in a queue in this element and transfer out as one entity. The number of entities to be assembled can be dynamic and defined by the attribute of the entities.
Batch		Specified number of entities can become a bundle in this element and can transfer out as one entity; each of them, however, is still distinguishable, and all the features of each entity are retained in the original.
Unbatch		Always paired with "Batch". Batched entities are released here to their original state without any change to each of them.

final product is built out of individual parts flowing in the simulation network. Although original elements could be customized through Visual Basic scripts to accommodate the required modeling functionality, three new simulation elements, "Assembly," "Batch," and "Unbatch," were designed and developed by the writers in order to facilitate more efficient and flexible experimentation with the models. Table 1 summarizes the functions of the newly developed elements.

The models for both the old and new systems each describe 100 spools being fabricated in the fabrication shop. Each shop is different from the other in terms of facility, capacity, and fabricated spools. In order to compare simulation results with real production performance and to model the process as realistically as possible, the configuration of the spools fabricated in this specific shop and their shop-specific production processes were studied.

The productivity of spool cutting, fitting, and welding is affected by several factors such as welding diameter inch, pipe size, weight, configuration, material, and welding procedure. Welding diameter inch is usually the main factor used by fabricators for scheduling and cost estimating purposes. It significantly affects the duration of cutting, fitting, and welding activities and is, therefore, used as a critical configuration parameter for describing spools in the simulation model. The data for the spools fabricated in this shop within the past two years were extracted from a database, and a statistical distribution was fitted to model the variation in spool welding diameter inch. An exponential distribution with a mean of 10.66 diameter inches was selected based on *K-S* and χ-Square goodness of fit test results. Distribution fitting was performed using commercial software (EasyFit). Fig. 6 shows a comparison of the actual data and the fitted distribution in addition to goodness of fit test results for other distributions. The fitted distribution was used to generate the welding diameter inch of the 100 sample spools.

In addition to welding diameter inch, a spool has two other important parameters that are used to capture the features of its production process. The first is "Roll-welding Parts Number," which is the number of individual spool parts that can be assembled using roll-fitting and roll-welding processes. The second is "Roll-welding Repeating Times of Each Part," which is the number of times the roll-welding process has to be repeated for each part of the spool. The combination of these two parameters gives an indication of the overall complexity of any particular spool, reflecting weight, dimension, configuration, and fitting/welding procedure of the spool. This information was deduced from the production crew's experience and generated as uniform and triangular distributions in the model. A time study of cutting, fitting, welding, and materials handling was conducted by time recording in shop and by interviews with superintendents and foremen.

It is common practice to allocate separate fabrication bays for spools with special materials or very heavy weights. In addition, the purpose of the model was mainly to compare between two alternative production systems if applied within the same fabrication bay. Therefore, it was assumed that spools simulated in the model have insignificant material and weight variation.

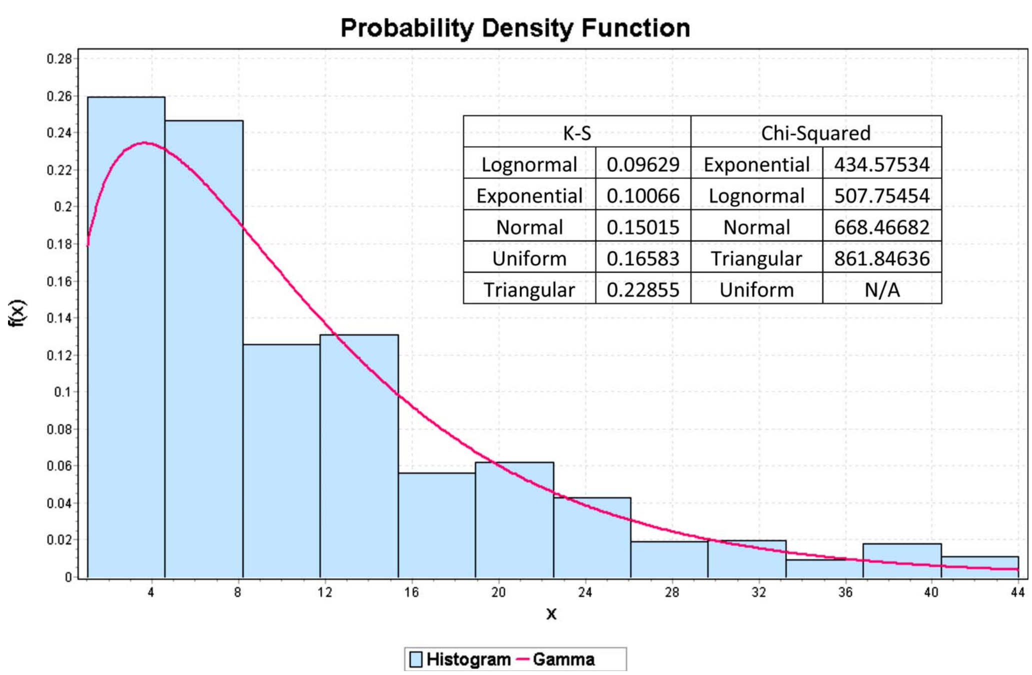

Fig. 6. Modeling spool welding diameter inch variations using an exponential distribution

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

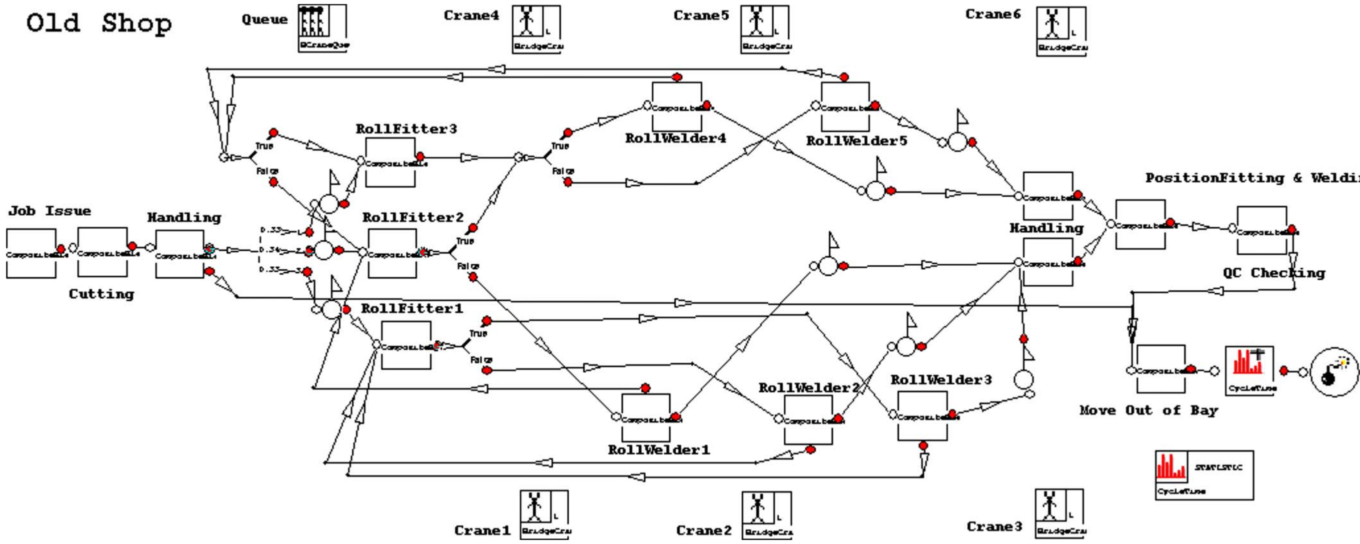

Fig. 7. Batch-and-Queue fabrication system

Simulation Model for Batch-and-Queue Fabrication Shop

Fig. 7 shows the model of the old fabrication system represented at the top of the hierarchy. This level of the hierarchy models both the shop layout and the process flow. Each working station shown at this level is detailed by a process model simulating the activities and interactions with resources within this working station. Detailed process models for a roll fitting station and roll welding station are illustrated by Fig. 8 at the second level of the hierarchy. This two-level hierarchical graphic model maps the whole production system virtually, as described in the section "Batch-and-Queue Spool Fabrication Shop."

A sample job consisting of 100 spools was loaded into the bay. The model is run and the time taken to produce each of the 100 spools was recorded in the simulation. The recorded data were extracted from simulation database and analyzed. The average simulation fabrication cycle time of a spool is 10.8 working days. The maximum cycle is 55.42 days. The cycle time distribution is given in Fig. 9.

Simulation Model for Flow Fabrication Shop

Fig. 10 shows the model of the new fabrication system represented at the top of the hierarchy. This level of the hierarchy models both the shop layout and the process flow. Each working station shown at this level is detailed by a process model simulating the activities and the interactions with resources that occur within it. A detailed process model for a work cell is illustrated in Fig. 11 at the second level of the hierarchy. This two-level hierarchical graphic model maps the whole production system described in the section "Flow Spool Fabrication Shop" virtually.

The same sample job, consisting of 100 spools, was loaded into the shop model. The model was run and the time required to produce each of the 100 spools was recorded in the simulation. The recorded data were extracted from the simulation database and analyzed using BestFit. The average simulation fabrication cycle time of a spool is 6.7 working days. The maximum is 38.87 working days. The cycle time distribution is given by Fig. 12.

Historical Cycle Time Analysis

Historical data were extracted from the fabricator's information system, where spool start and finish times are recorded. Statistical analysis of fabrication cycle time was then done based on 1,146 and 1,161 spools, respectively, for the old and new systems.

The average spool fabrication cycle time in the old system is 11.5 working days. The maximum is 75 working days. The histogram of the actual working cycle time is shown in Fig. 13.

The average spool fabrication cycle time of the new system is 7.0 working days. The maximum is 81 working days. The histogram of the actual working cycle time is shown in Fig. 14. Table 2 summarizes the output statistics of the simulation model for the old and new shop layouts in comparison to the historical statistics of actual shop data.

Validation and Discussion

Comparison of Historical Cycle Time between Old System and New System

The historical cycle time analysis revealed the different features of the two systems. There is a difference in the average fabrication cycle time of up to 4.5 days between the two systems. The cycle time distribution of the old system is more scattered, with a small percentage of spools having an abnormally long cycle time. The cycle time distribution of the new system is more convergent. The mode of the two distributions contributes to the difference as well. The likelihood of a cycle time of two days in the old system is higher than with the new system. The likelihood, however, of a cycle time of 3, 4, and 5 days with the new system is higher than with the old system. It is concluded that the old system has higher variability and requires higher inventory on the shop floor, whereas the new system is more controllable and carries fewer inventories on the shop floor.

Validation of New System Simulation Model and Discussion

The average simulation cycle time, 6.7 working days, is a little shorter than the average historical cycle time of 7.0 working days.

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

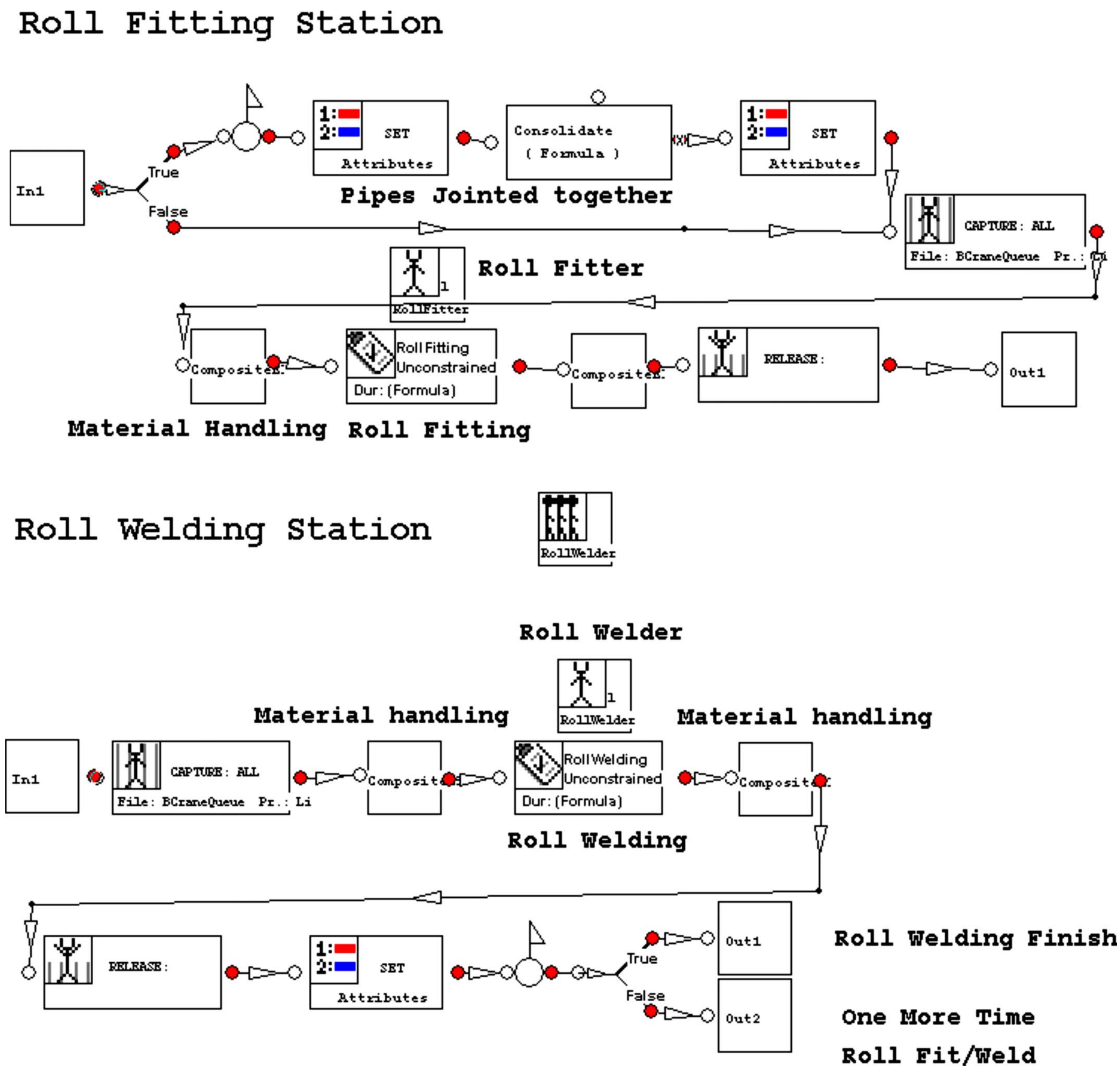

Fig. 8. Detailed process modeling of roll fitting and roll welding

The simulation cycle time distribution (Fig. 12) and the historical cycle time distribution (Fig. 14) are very similar with only a slight difference in the mode. This difference is considered acceptable, and it is reasonable to assume that the average and mode values of the simulation results are smaller than that of the real result. There are a few possible explanations for this: the model did not include certain trivial activities such as breakdowns. Although rework was simulated, what and where it happened, and how much time was spent on each rework activity, were not traceable. The cycle time in the simulation model was calculated by deducting the cutting start time from the moving out time. In historical data, the time of issuing shop drawings, which is considered the start time, was normally earlier than the cutting start time.

Validation of Old System Simulation Model and Discussion

The average simulation cycle time, 10.8 working days, is also shorter than the average historical cycle time of 11.5 working days. This difference is considered acceptable, but the similarity between the simulation cycle time distribution (Fig. 9) and the historical cycle time distribution (Fig. 13) of the old system is not as accurate as that of the new system. This is because the old system cannot be described clearly: it basically followed the FIFO queuing rule for a long-term run, but there were no clear shop control rules. During production, the queuing rule and control logic are inconsistent. Laborers might drop all current work and change tasks to fabricate a different spool on a rush order. They could also hold some spools, or forget them on the floor for a very

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

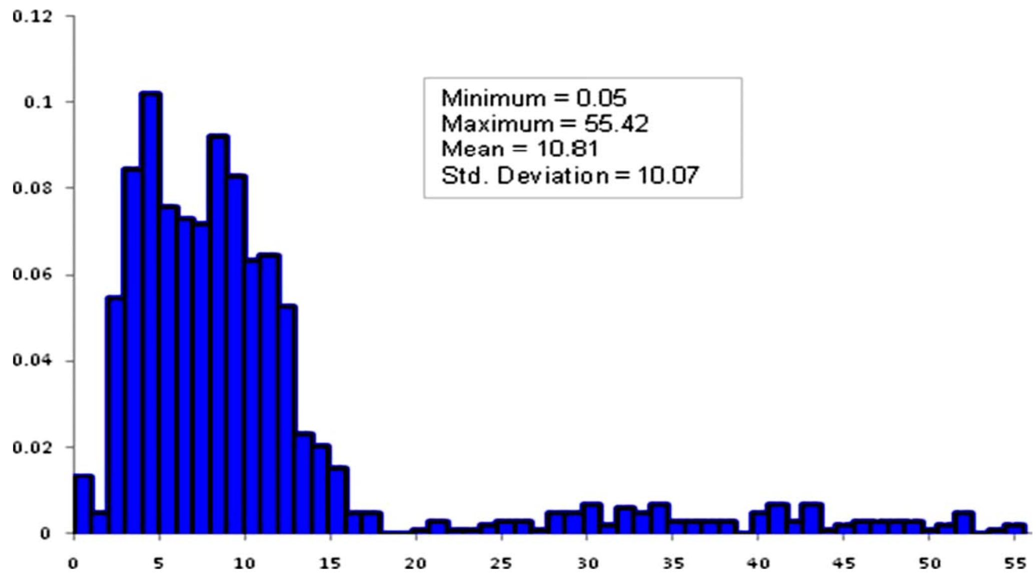

Fig. 9. Cycle time distribution of simulation output of batch-and-queue fabrication shop

long time. As such, the above model that uses the FIFO queuing rule cannot reflect the features of old system as accurately as it does for the new system.

Experimentation with the System Using Simulation

There are other potential improvements that could be made to the studied shop; the above experience can be introduced to the other shops as well. The simulation-based approach is an effective quantitative tool for testing more scenarios.

Analysis of Rework Reduction

The rework percentage is set at 10% in the above base model. If rework is reduced, the average cycle time will be reduced. The sensitivity analysis is done based on the developed model of the new shop. The result is shown in Fig. 15. It indicates that the fabrication cycle time is very sensitive to rework. Strategies should be implemented to reduce rework.

Analysis of Fitting Time Reduction

Cleaning and grinding are part of a fitting activity, but these are nonvalue-added activities. Improving the cutting process may re-

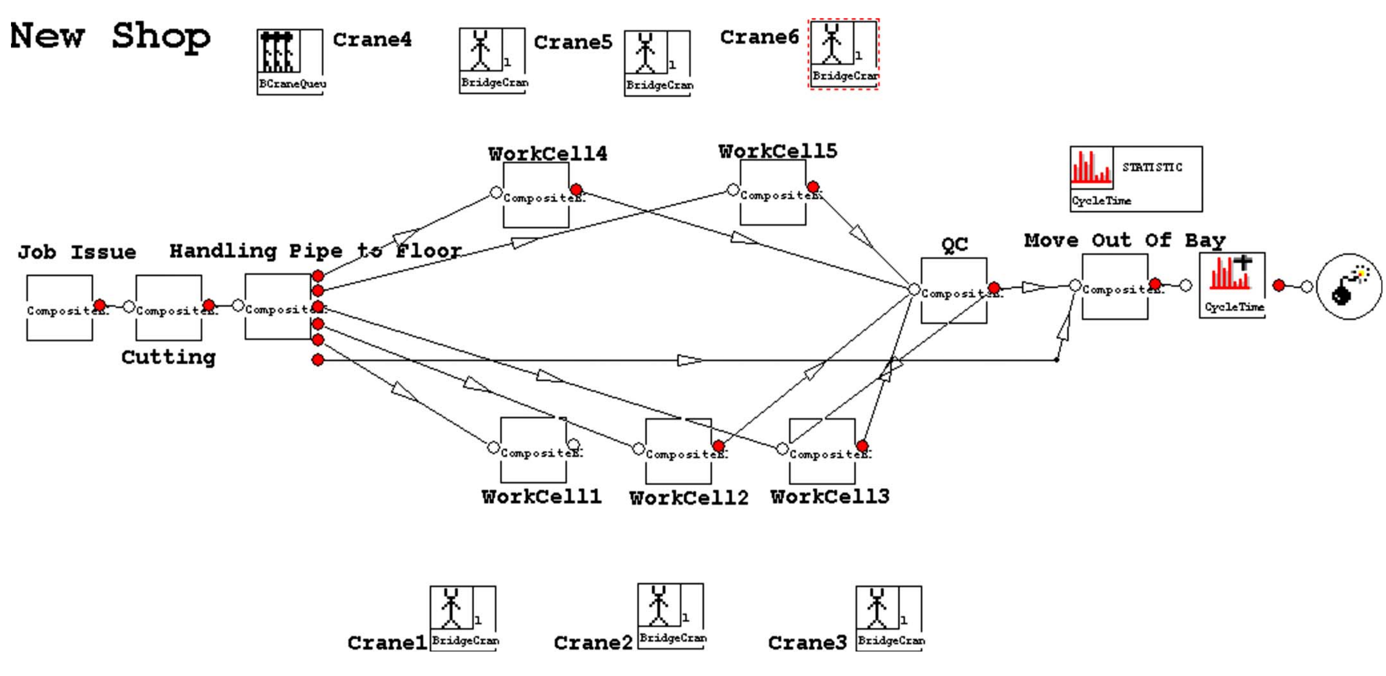

Fig. 10. Flow fabrication system

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

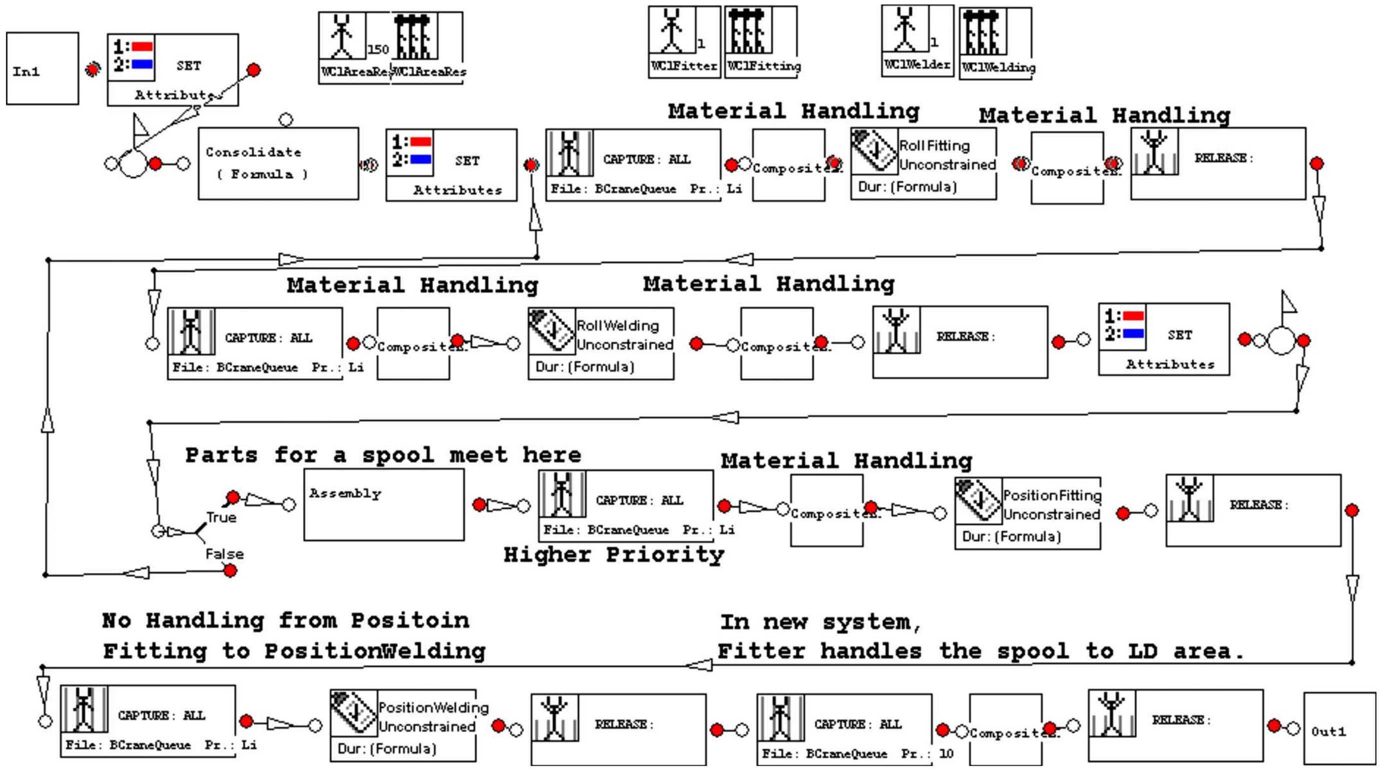

Fig. 11. Detailed process modeling of a work cell

duce or remove cleaning and grinding activities, which may in turn result in a reduction of the fitting time. A sensitivity analysis was conducted, and the result is shown in Fig. 16.

One-Piece-Flow Fabrication

The flow fabrication system described is not yet a one-piece-flow production. A spool is normally decomposed into a few parts, which can be roll welded, and each part often needs to repeat its fitting and welding processes several times before it is completed. Additionally, fitting productivity is different than welding productivity. The fitter should not be idle when the spool is being processed by the welder. Since each work cell processes several spools at one time, the system is not an ideal one-piece-flow production.

As described in the section "Introduction to Pipe Spool Fabrication," fitters and welders had been crosstrained in the shop

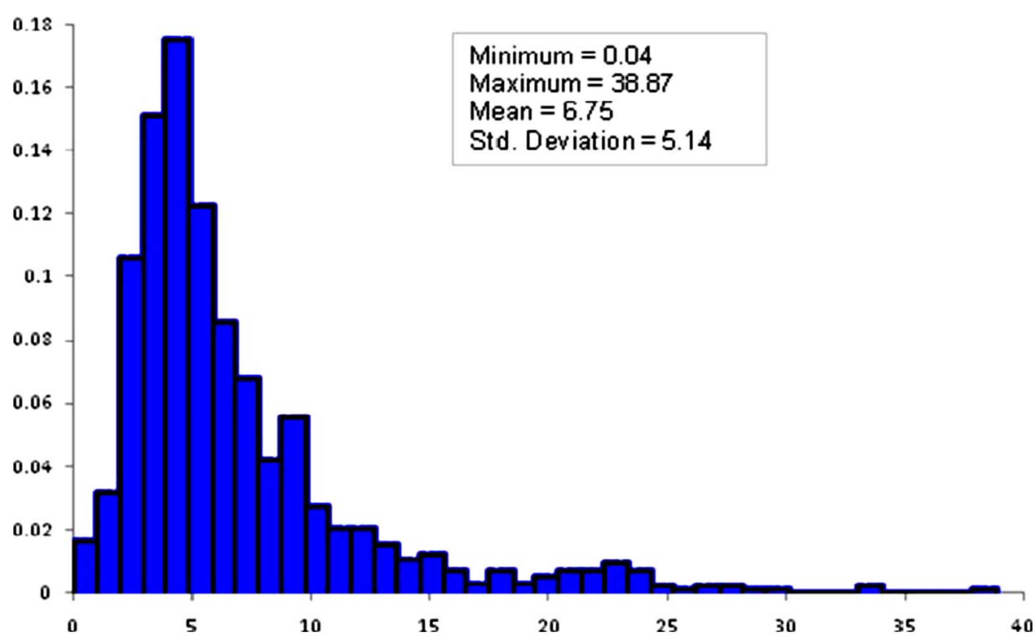

Fig. 12. Cycle time distribution of simulation output of flow fabrication system

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

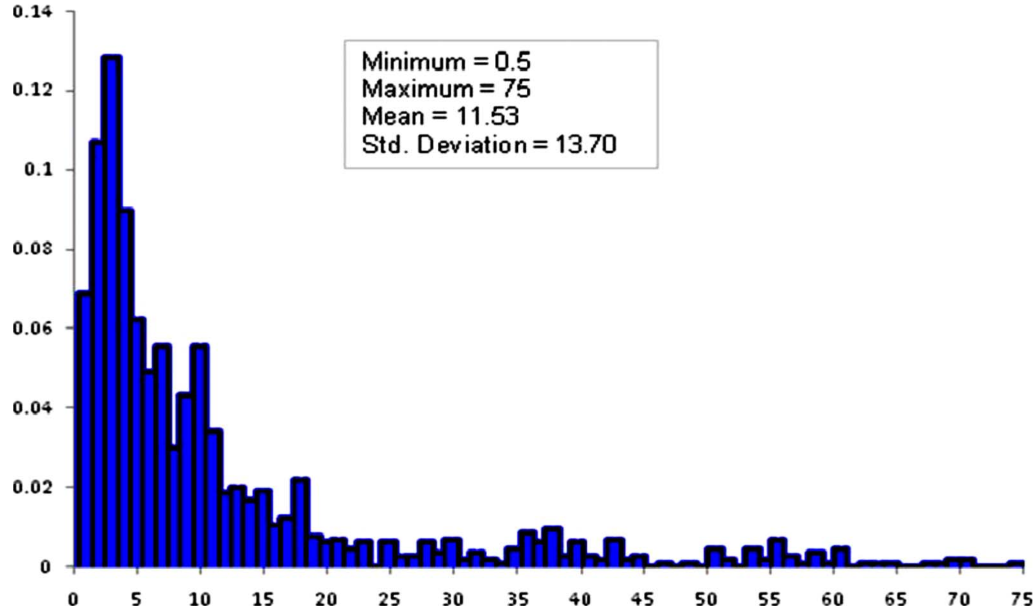

Fig. 13. Cycle time distribution of batch-and-queue fabrication system from historical data

under review. If each laborer can be trained to do both fitting and welding, the work cell can be designed as a one-piece-flow production system. It also removes the nonvalue-added activity of material handling between the fitter and the welder. The model of the new shop was modified based on the assumptions that each laborer can do both fitting and welding and that there are two laborers in each work cell. All process models of the five work cells were rebuilt at the second level of the hierarchical model. The new model was run, and the simulation results were extracted and analyzed. The average simulation fabrication cycle time is 4.9 working days, and the maximum is 26.9 working days. The cycle time distribution is given in Fig. 17.

Transfer Successful Experience to Other Shops

The five shops operated by the fabricator in this research are different from each other in terms of space, capacity, machine type, and material handling facilities. Each of the five shops is unique. The experience gained from the experimental shop cannot be naturally and easily transferred to other shops, especially in terms of the design and number of work cells. The developed model was modified to simulate other shops' systems without much excessive effort. Different scenario experiments on a computer can reduce risks in the reconfiguration of these shops.

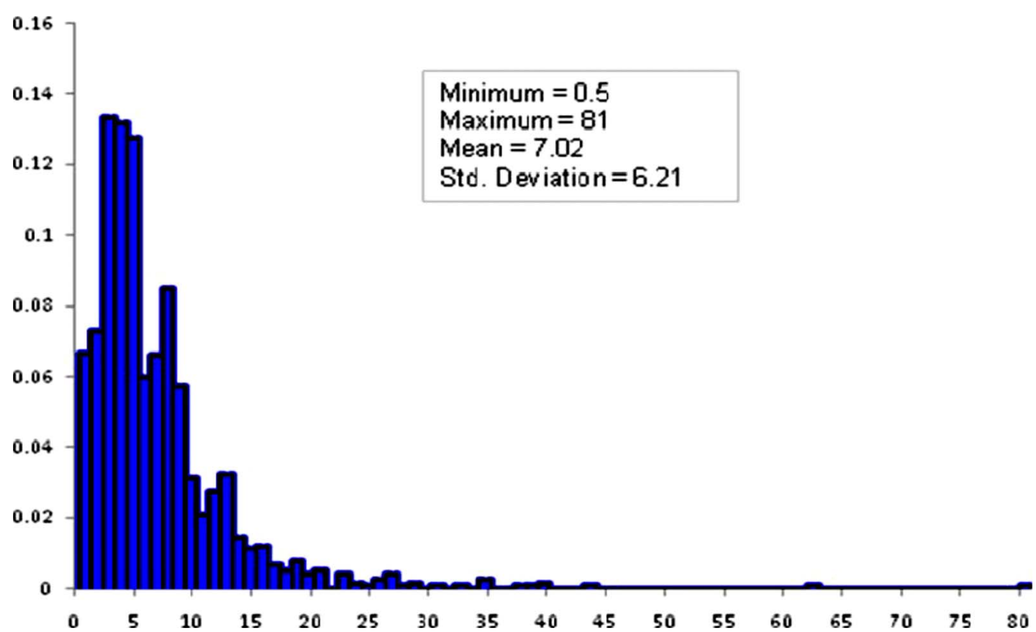

Fig. 14. Cycle time distribution of flow fabrication system from historical data

J. Constr. Eng. Manage., 2009, 135(10): 1027-1038

Table 2. Simulated and Actual Cycle Time Statistics under Old and New Shop Layouts

	Simulation output		Actual data	
Statistic	Old layout	New layout	Old layout	New layout
Mean	10.8	6.75	11.5	7.02
Std. dev.	10.07	5.14	13.7	6.21
Min.	0.05	0.04	0.5	0.5
Max.	55.4	38.87	75	81

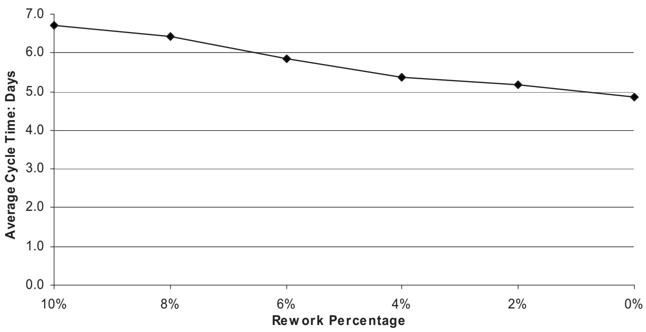

Fig. 15. Sensitivity analysis of average cycle time to rework reduction

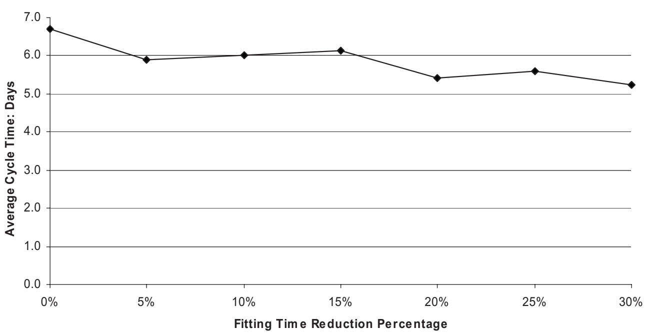

Fig. 16. Sensitivity analysis of average cycle time to fitting time reduction

Study Limitations

The methodology and the tool presented in this paper can be used to study any spool fabrication shop. However, statistical results only represent a local sector of the industry and cannot be generalized to other locations unless similar studies are repeated and documented to draw general conclusions.

Conclusion

A pipe spool fabrication shop is characterized by product uniqueness and by a high product mix. These characteristics make the analysis and improvement of the production system very challenging. This research is the first study of its kind in applying lean production techniques to shop fabrication, and the first to use a simulation-based approach as a tool to facilitate its implementation. It was shown that one of the lean principles, 'flow,' can improve the production performance of pipe spool fabrication shops. The simulation results and real-world data analysis concur with the benefits of implementing flow production in industrial construction fabrication. The simulation-based approach used in this study also indicates other potential improvements for a spool fabrication system. The research proves that the developed simulation-based approach is a practical and more powerful tool than the VSM for modeling and quantitatively evaluating the performance of a complex and dynamic spool fabrication shop. It provides an in-depth understanding of fabrication system performance and the improvements achieved by applying lean techniques. The understanding and improvements may be extended to other areas in construction.

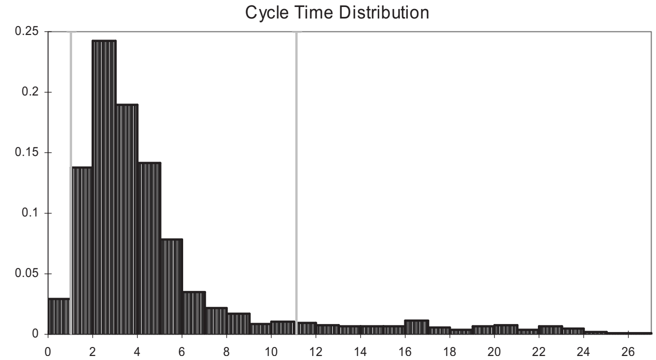

Fig. 17. Cycle time distribution of simulation output of one-piece-flow fabrication system

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J. Constr. Eng. Manage., 2009, 135(10): 1027-1038