Production Process for Manufactured Housing

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Abstract: A manufactured home is completely built in a controlled factory environment. Despite a large share of the market, the manufactured housing industry has a long way to go towards streamlining its production process. The objective of this paper is to map the production process of a manufactured housing factory and to demonstrate via simulation how the process can be improved. The production process including assembly, feeder, and storage stations were mapped using data from several manufactured housing plants and in-depth case studies at two plants in northern Indiana. The case study plants were also used for collecting cycle-time data for developing the simulation model for the roofing process. Subsequently, four "what if" scenarios were conducted to illustrate potential improvements to the production process. The efforts presented in this paper are part of on-going research sponsored by the National Science Foundation under the Partnership for Advancement of Technology in Housing (PATH) initiative.

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Introduction

The United States Census Bureau has estimated that Housing and Urban Development (HUD) code-based manufactured homes represented 22.7% of all new single-family housing in 1998 [MHI Quick facts 1999–2000 (MHI 2000)]. The HUD code manufactured housing has been evolving since 1976 and goes even further back in the early part of the 20th century when they were called trailers (HUD 1998). Over 19 million people across the country have decided to make a manufactured home their way of life (MMHA 2000). The trends, as summarized in Table 1, clearly show that manufactured housing has become a viable option to homebuyers in America.

A manufactured home is built in a controlled factory environment on a permanent chassis that is designed to be used with or without a permanent foundation when connected to the required utilities. Manufactured homes are built to the federal Manufactured Home Construction Safety Standards enforced by the Department of Housing and Urban Development (HUD 1995). Manufactured homes are single story and are delivered to the home site, which could be a private property or in a manufactured home community, in one, two, or occasionally, three sections.

Despite a growing market, the manufactured housing industry has not been able to emerge as a technologically advanced industry (Mehrotra et al. 2002). A typical manufactured housing plant fails to produce at maximum capacity and production rate because of several constraints in the production process such as:

1. Labor intensive rather than technology based production process;
2. The lack of extensive repetition in the manufactured housing production process. Each housing unit going through the assembly process is unique; and
3. Due to the difference between site-built and factory-built housing processes, innovations in site-built housing are not directly applicable to manufactured housing.

In order to develop an effective and efficient production system that would optimize the labor, technology, and material utilization, it is important to identify the deficiencies in the current production processes used by the manufactured housing industry and to suggest innovative methods for improving the production process.

The objective of this paper is to illustrate the production process of a manufactured housing factory and to demonstrate via simulation how the production process as well as the labor and material utilization could be improved and streamlined. The results presented in this paper are part of ongoing research sponsored by the National Science Foundation under the Partnership for Advancement of Technology in Housing (PATH) initiative.

Manufactured Housing Production Process

The construction process of a manufactured housing unit is similar in many ways to that of a site-built housing unit. While the materials used in both production processes are similar, the envi-

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Table 1. Manufactured Home Shipments (Source: MHI Quick Facts 1999–2000)

Year	1992	1993	1994	1995	1996	1997	1998
Total	210,787	254,276	303,932	339,601	363,411	353,377	372,843
Single-section	112,117	134,440	156,171	173,785	173,674	148,809	144,328
Multisection	98,670	119,836	147,761	165,816	189,737	204,568	228,515
Percent of single-family starts	17	18	20	24	24	24	23
Estimated retail sales (billions)	$5.99	$7.76	$10.18	$12.33	$13.96	$14.52	$16.33

ronment in which they are built is quite different (refer to Figs. 1 and 2). Two manufactured housing plants in northern Indiana were used as case studies to map the production process with respect to the sequence of activities at each station (including the feeder stations), duration of activities, as well as the material flow in the factory. Figs. 3 and 4 and Table 2 illustrate a sample activity relationship and process mapping at the selected set of stations (Senghore 2001).

A manufactured housing plant can generally be divided into five areas: (1) floors, (2) walls, (3) roofing, (4) exterior finishes, and (5) interior finishes. As shown in Fig. 2, floors are represented by stations 1 and 2, walls by stations 3 and 4, roofing by station 5 (Fig. 3), exteriors by stations 6 and 7, and finishes are represented by stations 8, 9, and 10. A plant can have up to 16 stations depending on the complexity of the homes built, the number of activities at various stations, and the size of the plant. Several stations in the production line are supported by feeder stations for activities such as cabinets, fixtures, and roofing support (Fig. 3).

Area 1: Floors

Manufactured houses are built on a steel base frame called a chassis. A single-wide house is built on one chassis whereas the floor plan for a double-wide house requires two chassis. The process starts with the floor frame being constructed on top of the chassis at station 1. The floor joists are put in place according to the plan and the specified spacing. The floor frame is followed by installation of all the mechanical work that needs to go underneath the house including HVAC and water lines. The floor is properly insulated before it is moved to station 2 for floor decking. All the activities described above are performed on each chassis entering the production line.

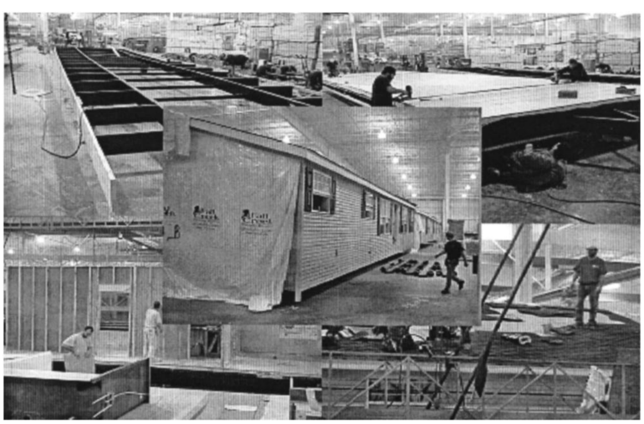

Fig. 1. Production environment in a manufactured housing factory

Area 2: Walls

The walls are generally built at a feeder station and then hoisted in place using an overhead crane that runs on tracks attached to the ceiling of the plant building. Fixtures such as kitchen cabinets, bathroom fixtures including tubs, water heater, and furnace are installed before the walls are put in place. After the partition walls are placed, the house moves to station 4 for the marriage walls (walls connecting two sections of a doublewide house) and exterior walls. All the walls are built complete with insulation at the feeder stations. At station 4 rough electrical and mechanical work is performed.

Area 3: Roofing Process

Roof assembly usually takes more than one station including feeder and main stations (Fig. 3). Fabrication of the individual roof trusses is generally contracted out to independent contractors. They are then stored in the plant and used as needed to assemble the whole roof and ceiling structure.

Roofing cluster starts when the whole roof structure built from the feeder station is transferred to the main line to be set on the section. From this point on two sets of activities are taking place in parallel: roof setting and exterior walls. Work is also being performed inside the house but the roof setting and exterior wall activities are considered the major activities. First, the sheets of gypsum ceiling boards are laid on a flat surface, and then the individual trusses are placed at the correct spacing. From there, the trusses are nailed together with 2×4's between them. A special type of glue is sprayed on the trusses at their point of contact with the ceiling board to hold them together. Insulation is placed on the down side of the roof slope and then it is moved to the adjacent feeder station for spray painting of the ceiling. Before the paint is sprayed, the joints between the boards are covered with tape and mud for a smooth connection. After the paint is applied, the roof is ready to be hoisted up for connection to the house. When the whole roof and ceiling structure is ready, it is sent to the main line for assembly.

On the main assembly line the two chassis of a double-wide house are temporarily aligned and joined together to assemble the roof. The two units are separated again when it gets to station 9. The main reason why the two units are attached at this point is to make sure the roof structure properly fits on the house. After the roof is set and secured to the walls of the house, insulation is sprayed on the roof. A worker standing on top of the house uses a powered hose to spray the insulation between the trusses and on top of the ceiling to insulate the roof. This activity can also happen when the roof structure is still at the feeder station. After insulating the roof a crew of workers deck the roof with sheets of plywood nailed to the trusses. The lower edge of the roof is then covered with paper for proper drainage measures before the shingles are placed.

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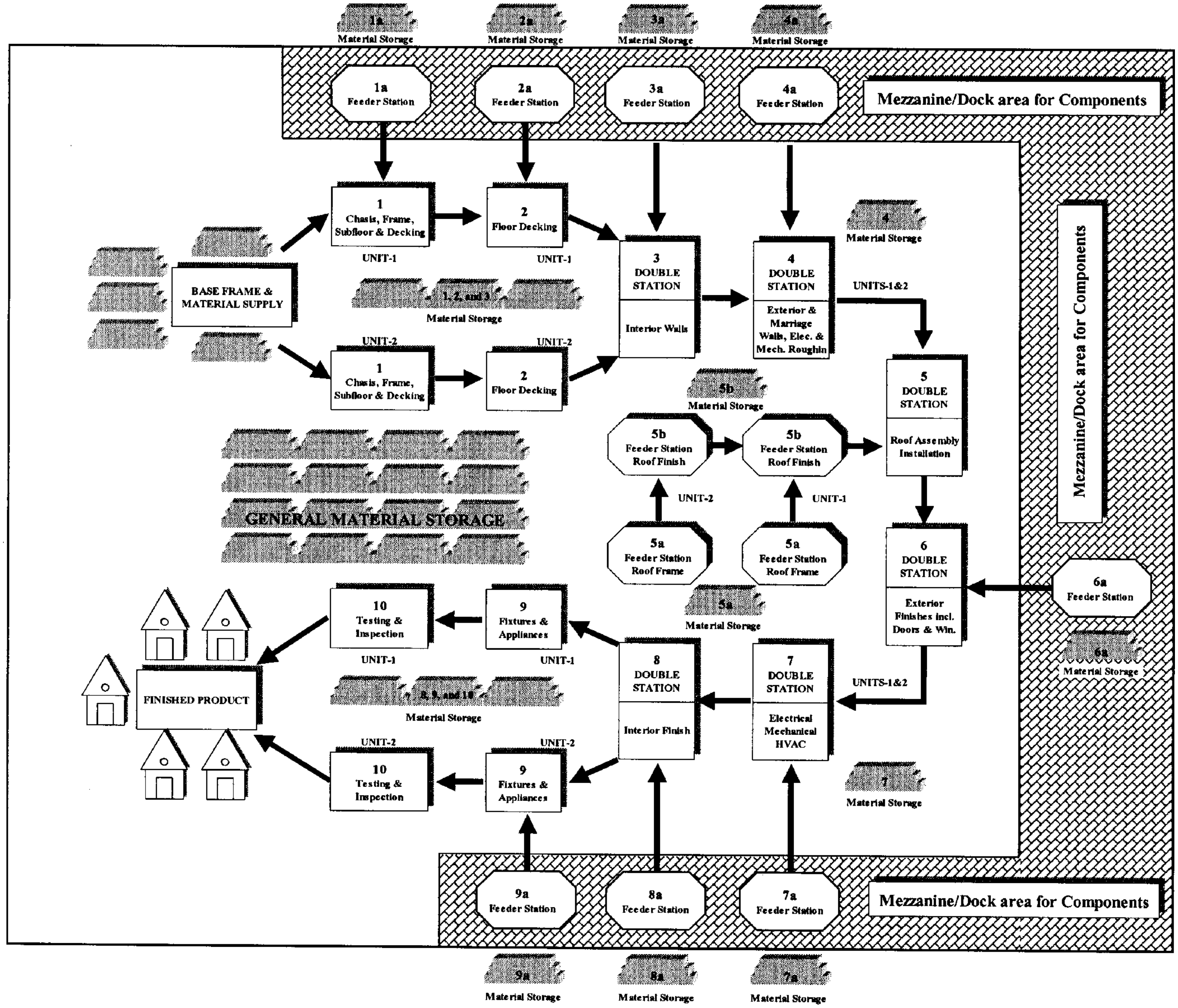

Fig. 2. Sample manufactured housing production process

Area 4: Exterior Finishes

While Fig. 2 shows stations 5 and 6 running in sequence, these two stations can essentially run in parallel. As work is progressing with the roof on top, workers are simultaneously installing doors and windows, exterior boards, siding, and so on.

Exterior and interior finishes start after the walls are installed. First, the walls are covered with exterior boards and door and window openings are cut. Once the doors and windows are installed, the house is covered with siding. These are the major activities happening in the above-described stations.

At station 7, electrical, mechanical, and HVAC work form the main activities at the station. Also at this station, the breaker box and certain appliances such as the fireplace are installed. A significant amount of testing and inspection is also performed at this stage including, gas test, plumbing tests, check for proper receptacle spacing, check for interior switches and their installation to manufacturer's specifications, and so on.

Fig. 3. Roof assembly

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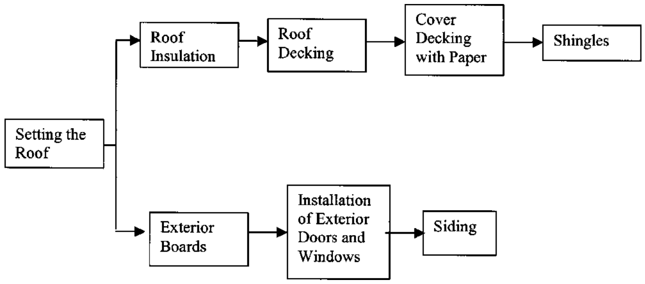

Fig. 4. Example activity relationship

Area 5: Interior Finishes

Activities for interior finishing starts after the roofing and exterior finishes have been performed. At station 8, the extent of the interior finishes depends on whether the house needs painting or whether it is going to have wallpaper. First, the axles and the wheels are installed for transportation. Installation of axles and wheels can also happen at station 1 depending on how the houses are moved between the stations at a particular plant. If the house requires wallpaper instead of painting, interior finishing continues at station 9. Window curtains are installed; appliances such as the dishwasher, toilets, washing machine, and dryer are fitted into place. In addition, any repair work that needs to be done also takes place at this station. If the house needs paint, then a whole day is spent on drywall finish. This is not because the activity takes too long, but because they have to wait overnight for the walls to dry.

One house takes approximately 1.5 days to go through the five areas described above. A finished house is typically stored in a yard for shipment to the dealers. Typical production of a factory would entail 5 to 6 sections/day. A subset of the production process described above was analyzed to determine process bottlenecks and to identify possible improvements in the production system.

Analysis of Production Process

The literature on production operations management provides a litany of techniques to analyze and improve production processes. Process mapping, time and motion studies (Oglesby et al. 1989), simulation modeling, kaizen (process improvement in Japanese) events, and six-sigma, are all examples of such techniques (Senghore 2001). The common element between these techniques lies in the end-goal of assessing the efficiency of production operations and identifying opportunities for improvement.

In this study, a hybrid approach was used to study the production processes in manufactured housing plants. The approach combines process mapping, time and motion studies, and simulation modeling. Process mapping was instrumental in understanding the production process steps and logistics. The time and motion studies provided a basis for comparing performance between assembly stations as well as data needed for running simulation models. Whereas simulation modeling was used to quantify and better understand the interactions between the different resources and work cells used in the manufacturing process while taking into account the inherent variability and nondeterministic nature of production operations. Simulation also allows the analysis of production and process improvement alternatives without having to implement these changes on the production floor.

Process Mapping

As mentioned earlier (refer to Fig. 2) the production process includes five main clusters: floors, walls, roofing, exterior finishing, and interior finishing. Process mapping was performed for each station within the five areas to determine the logical flow of the production unit and the interaction between the various stations within the system. Details for the roofing cluster are shown in Fig. 4.

Time Study

The primary reason for doing a time study is to measure job performance (Harrington 1991; Aft 1992). As the name implies, time is the main metric recorded in a time study. Typically, the main times recorded were cycle time and actual cycle time. According to Harrington (1991), "cycle time is the total length of time required to complete the entire process." This time includes the time it takes to perform the work and the time spent waiting for something, time spent chatting, or time spent waiting for resources to be available. The time that it takes to complete the process if there are no interruptions or stoppage is the actual cycle time; that is to say the time it will take to do the job under ideal circumstances. Total cycle time can be thought of as actual cycle time plus idle time. Both total cycle time and actual cycle time are collected for this research project. The difference between the total and actual cycle times provided the idle time for the activity. This applies to both individual activities and combination of ac-

Table 2. Process Mapping Data Sheet

Station No.	Activities	Crew size	Feeder name	Comment
8	Roof setting	3	Roof Feeder	
8	Finish ceiling wiring	1		Activities overlap into successive stations
9 and 10	Roof decking	3		
11	Cover roof deck with paper	3		
12	Install shingles	2	Shingles Feeder	
Feeder name	Activities	Crew size	Main station	Comment
Roof feeder	Trusses are assembled			
Shingles feeder	Shingles package is unwrapped and placed on moving bucket to installers	2	12	
Siding feeder	Cut siding material to specified lengths	1	11	

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Table 3. Manufactured Housing Project Data Sheet

Station #		Station Description:							
Chassis Number		Duration	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Comment
	Time								
	No. of labor								
	Time								
	No. of labor								
	Time								
	No. of labor								
	Time								
	No. of labor								
	Time								
	No. of labor								
Activity Description									
Activity related Material									
Activity Precedes/ Follows									

Supporting Stations Data							
Number	Activity Description	**Duratio n**	*Labor Force*	**Material**	*Sub Activity*	*Sub Activity*	*Sub Activity*

tivities at the station(s). The data sheet used for this process is shown in Table 3. This datasheet was used to collect data on the following parameters:

- Chassis number: Every section going through the line has a number written on the steel chassis that is the identification number for the product.
- Station number: This number is entered depending on the station that is being observed. Multiple station numbers can be used based on the activity relationship.
- Activity related material: Material that is being used to accomplish the task.
- Activity precedes/follows: This is the predecessor and successor of the activity being observed.
- Duration: The column under duration is used to enter the total cycle time for all the activities. This is from the start time of the first activity in the cycle and the finish time of the last activity.
- Supporting stations data: Supporting stations data is used for entering data on feeder stations.

A very important aspect of collecting data was to make sure idle time and actual work time are both captured in any duration of the activities. This further illustrates the point made above about the difference between total cycle time and actual cycle time. The problem was diffused by entering the actual start time and finish time of the activity cycle using a wrist watch, whereas a stopwatch was used to record durations for each activity.

For practical reasons, it was necessary to merge activities from certain consecutive stations while collecting time data. The reason for this was that activities would sometimes extend to successive stations if there was a delay of some sort.

Simulation Modeling

Computer simulation, regardless of the domain of application, is a way of mimicking reality. Simulation models facilitate examination of a production system with respect to the overall production of the system, interaction between flow units, location of bottlenecks, as well as effective utilization of resources (Halpin and Riggs 1992). For example, consider an existing crane that moves walls from the feeder stations to the main assembly line. When the crane is not moving walls, it is sitting idle. Similarly, a separate crane exists for moving roofs from the roof feeder station to

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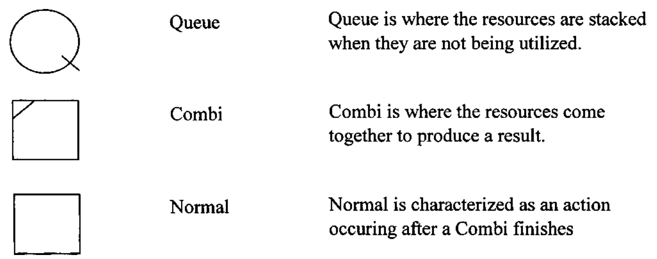

Fig. 5. Basic modeling elements [modified from Martinez (1998) and Halpin and Riggs (1992)]

the main production line. When the roof crane is not transporting roof structures, it is sitting idle. It is feasible that one of these cranes can be utilized for both activities. The effect this will have on production can be evaluated by simulation.

There are two different types of simulation: discrete-event simulation and continuous simulation. In discrete-event simulation the system is reproduced using activities, which start and end according to specified durations and number of attributes. The system is characterized by its state at any given point in time. In discrete-event simulation, the assumption is that the state of a system changes instantaneously at specific times marked by events (Martinez 1996). In the case of a continuous simulation model, the state of the system is represented by dependent variables that change continuously over time (Pritsker 1986). This research uses *EZSTROBE* software to conduct discrete-event simulation for the analysis.

Introduction to EZSTROBE

Construction simulation was initiated almost three decades ago and has seen considerable development since then (Halpin and Riggs 1992; Sawhney and AbouRizk 1993; Paulson 1995). Construction simulation was initially developed to address the demands of the industry especially in the transportation/highway sector. CYCLONE (Cyclic Operations Network) methodology, introduced in 1977, has become the basis from which most construction simulation software has been developed. *STROBOSCOPE* (State and Resource Based Simulation of Construction Processes) is the most recent simulation-modeling tool developed for construction applications (Martinez 1996). Unlike previous simulation tools, *STROBOSCOPE* requires the user to write a C-language based computer program to represent the process being simulated as well as specify the input characteristics and output formats. While capable of modeling simple to complex scenarios, the programming requirement in *STROBOSCOPE* makes it accessible only to advanced users of simulation.

To extend some of the powerful and versatile simulation capabilities of *STROBOSCOPE* to users with little background in computer programming, *EZSTROBE* was developed. *EZSTROBE* has the following features (Martinez 1998):

- It utilizes *CYCLONE*'s basic modeling elements (shown in Fig. 5) to construct activity cycle diagrams.
- A graphical user interface environment that uses MS VISIO to interact with the simulation system and construct an activity cycle diagram of the construction operations being modeled.
- It uses *STROBOSCOPE* simulation software as the simulation engine where the actual simulation is performed and results are generated.
- Allows the use of variables to parameterize the modeled construction operation.
- Allows generation of standard and customized results.

While not as powerful in modeling capacity as *STROBOSCOPE*, *EZSTROBE* could be used to model a host of moderately complex scenarios in construction and in applied research situations. Therefore *EZSTROBE* was used for this research.

Simulation Model for Manufactured Housing Processes

Manufactured housing utilizes assembly-line production with activities, processes, and associated resource requirements. Proper use and allocation of these resources is essential which requires a determination of operation durations, cost, and trade-off alternatives. A process model was developed based on the layout of two different factories. From that model, activities at four stations were transformed into a computer simulation model with an objective to determine ways to improve the production process.

Developing the process model included steps such as process mapping and the use of process flow diagram techniques like block diagrams and ANSI format. The process flow diagrams were further developed during the data collection stage when the understanding of the activity relationship was greatly improved.

Input data required for the simulation included time durations for various operations and production data. Figs. 6(a–c) show the simulation model that was developed from the production process model using the basic modeling elements shown in Fig. 5.

At this point, it should be noted that only four consecutive stations were transformed into a simulation model. The process being simulated starts from where the wall frames are installed to the station where axles and tires are installed. Detailed information is available regarding activity durations and other model characteristics in Senghore (2001). As depicted in Fig. 6(a), there are two paths in the model. Each section has to undergo activities shown on both paths.

Top Path

- As a framed house enters the first application station; the crew starts setting the truss from the feeder station as shown in the first combi. The activity needs resources from two queues to start. These are the setters and the roof from the feeder station.
- The activity that follows the roof setting is roof insulation. This activity takes place with one worker on top of the trusses spraying insulation on the roof using a hose. This activity is supported by two queues, one representing the worker spraying the insulation and the other representing the insulation material.
- After insulation, the roof decking activity follows. Roof decking consists of laying the sheets of roof boards on top of the roof structure. The roof decking combi shows three queues feeding into it. One is for the labor, the second one is for the roof boards, and the last queue represents the fusion queue from the previous page in the model.
- Roof covering follows roof decking. This is done for drainage purposes and to prevent freezing. Again, the activity needs labor and material. The dotted queues are *EZSTROBE*'s way of fusing two pages and facilitating continuity of one model.
- Installing shingles is the last roofing activity. From there, the tires are attached and the house is ready for interior finishes.

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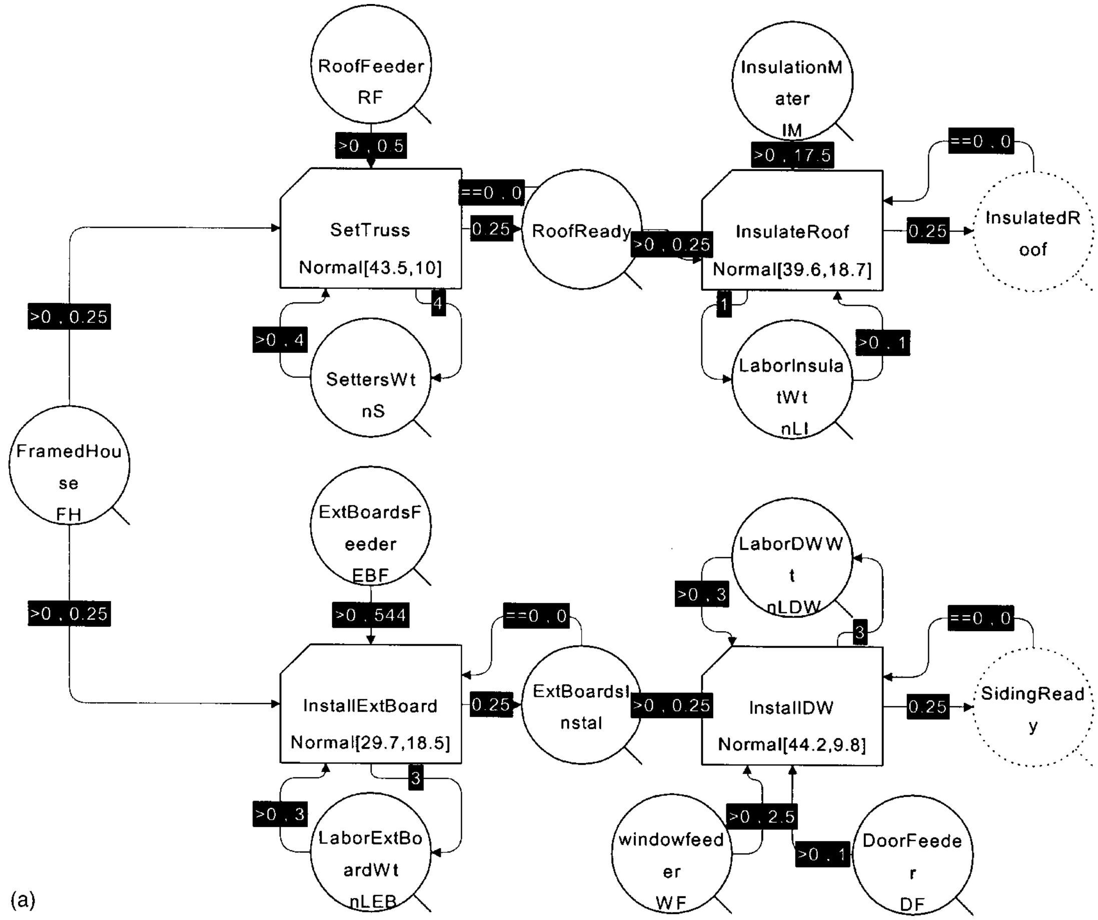

Fig. 6. (a–c) Simulation model of a section of manufactured housing production

Bottom Path

- The first activity on the bottom path is the installation of exterior boards. “InstallExtBoards” represents the material feeder needed for this activity and the other queue is for labor.
- Installation of doors and windows follows. This activity has two separate material feeder queues, one for doors and the other for windows. The top queue represents labor. The dotted queues are *EZSTROBE*’s way of fusing two pages and facilitating continuity of one model.
- After the doors and windows are installed, siding is placed on the walls.
- After this activity, interior finishing activities are represented on the bottom path such as molding the interior doors and windows and installing the padding for the carpet represented on the model as urethane foam. Carpet installation follows next. This represents the last process included in the simulation model.

As mentioned earlier, the activities on the top and bottom path of the model are being performed on the section simultaneously. To enable a separate analysis on each operation performed, the process had to be represented in the simulation model using the top and bottom path approach. A double-wide house includes two sections (chassis). According to the simulation logic of the model, one single section (0.5 house) is released into the model from the first queue “FramedHouse” in two parts. One part (0.25 house) is released to activity “SetTruss” and another part (0.25 house) is released to activity “InstallExtBoard.” This mode of representation ensures that each section undergoes activities on both paths (top and bottom) simultaneously.

The notation (==0,0) is introduced to (1) prevent the “SetTruss” and “InstallExtBoard” activities from stacking completed house sections before the assembly line advances to the next assembly stations and (2) to account for the limited physical space between successive stations. This notation is a (IF-THEN) condition which says if the content of the successor queue is not equal to zero (i.e., the space between the current assembly station and the next is not empty) then do not start the predecessor activity (combi). This condition has been used throughout the model.

The other feature, also used as a control mechanism, is that represented in the “dummy” combi and queue called “SectionControl” and “Control,” respectively. From field observations, it was noticed that activities on the lower half of the model progress faster than those on the upper half [refer to Fig. 6(a)]. This is caused by the large duration of the roof setting activity. Sometimes, the crews for installing exterior boards, doors and windows, and siding have to wait for the assembly line to move because of space restrictions. To control the “over-advancement” of activities, the combi “SectionControl” can only start if it gets a 1/2 section (0.25 house) from the queue “RoofDecked” and a 1/2 section from the queue “SidingInstalled.” Note that both of these queues can only be occupied by one house section at a time because of the (==0,0) condition explained earlier. The combi

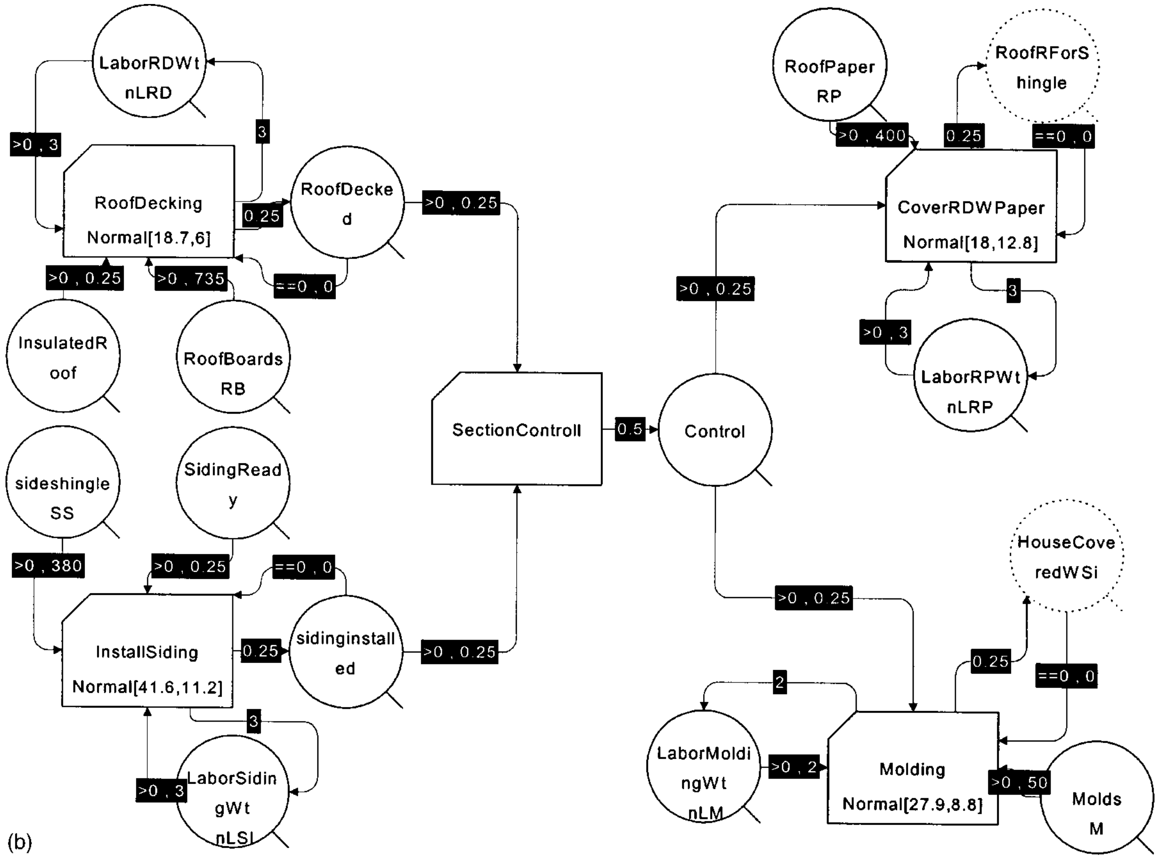

Fig. 6. (*Continued*).

"SectionControl" then releases the entire house section to the queue "Control," which in turn supplies the two remaining top and bottom paths of the model in a manner similar to that of the initial queue in the model "FramedHouse."

Model Implementation

Simulation models in *EZSTROBE* can be parameterized to give results in many formats. One is cost and another is resource utilization. In this research, resource utilization was analyzed with focus on labor resources. The mathematical formula used to calculate utilization, when a single resource is used by the activities and a single resource resides in the queue, is "1 – average content of the queue throughout the simulation." If multiple resources exist in the queue and are individually utilized by the activities, then the equation for utilization becomes "1 – average content of the queue/number of queue resources."

The simulation was executed using material and labor queues initialized with the quantities necessary to build 624 houses per year (based on an ideal production rate of 2.5 houses/day $\times$5 days/week$\times$50 weeks/year). Detailed information on material and labor quantities, and parametric formulation of model input and output can be found in Senghore (2001). After running the simulation model, it was possible to calculate the labor utilization for the different types of labor (Table 4).

Model Validation

Validation of the model requires that simulation model results come close or equal to those observed in the field (factory in this case). In this research, since the status quo from the factory was modeled, validation is done strictly by comparison. At the time of data collection from the first factory, the production rate of the factory, as stated by management, was 2.5 houses (5 sections) a day. This was also observed while collecting data at the factory.

When the model was run with the data collected from the factory (i.e., using data collected for 11 sections or 5.5 houses), it showed a production rate of 4.9 sections a day. This production rate was improved to 5.4 sections a day when the model was run with 624 houses, i.e., the simulation was performed for a year's worth of houses. This allowed the model to demonstrate the "long run" behavior of the production process.

The two figures are clearly close indicating the validity of the constructed simulation model and its suitability for making decisions. It is important to realize that although the simulation model does not represent the entire production process, it is still appropriate to make a comparison of model results to the overall production process rate. This statement can be reasoned by noting that because of the assembly line configuration and strictly under "long run" behavior conditions, the throughput of the system should not vary with measurement locations. To illustrate this argument further, consider the production rate of 2.5 "completed" houses (5 sections) a day reported by management. This figure indicates that a person standing at the end of the assembly line will observe 5 sections passing through the factory gate. If that same person stands at the end of the assembly station represented in the simulation model, that person will see, according to simulation results, 5 "incomplete" house sections pass through that observation post.

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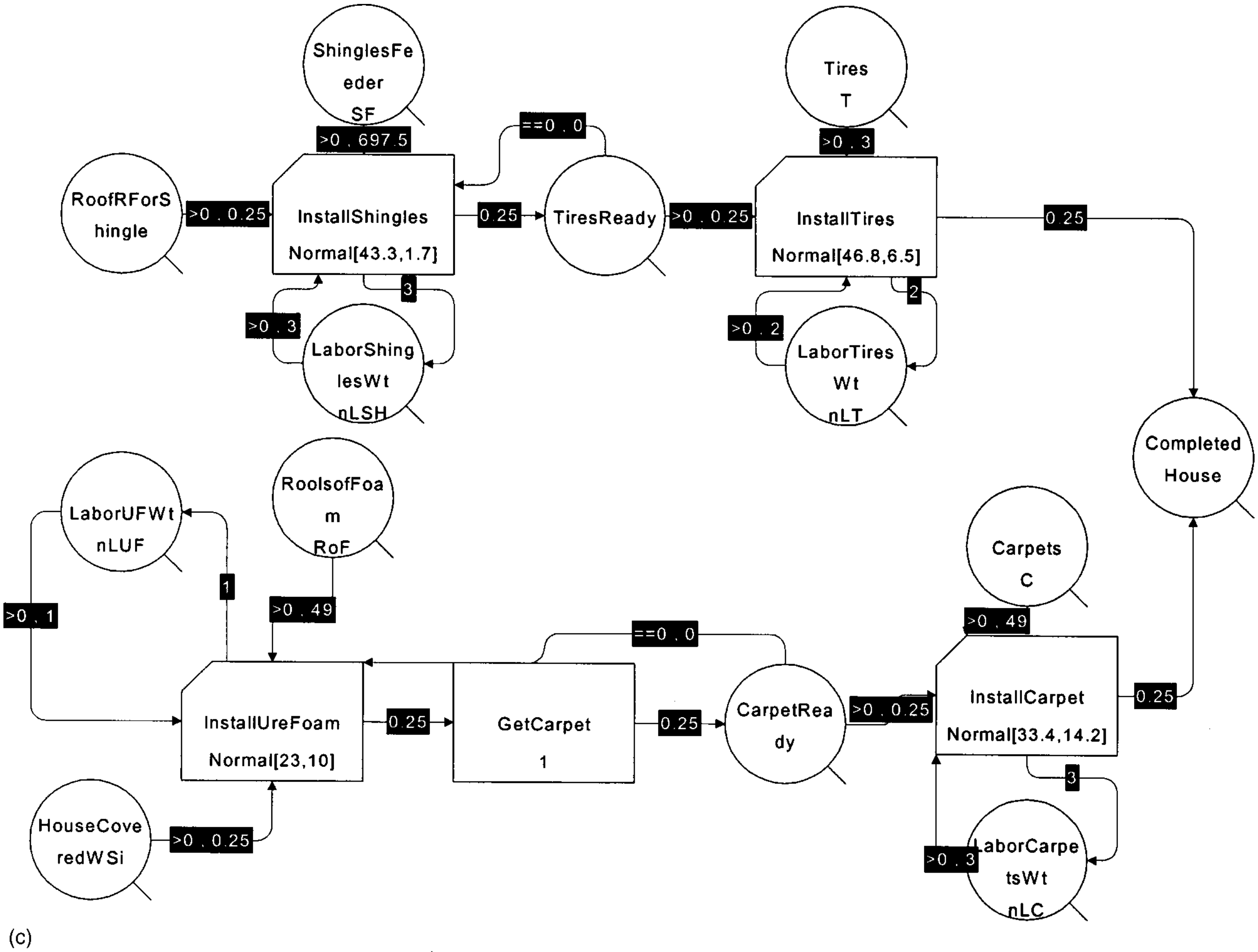

Fig. 6. (*Continued*).

Use of the Model for Decision Making / What if Scenarios

In this section, two possible production improvement scenarios are introduced. The two scenarios were analyzed using the simulation model. Other scenarios are discussed in detail in Senghore (2001). The scenarios are:

- Reducing roof setting activity durations, and
- Moving the activity "Insulate Roof "to the feeder station.

Roof Setting Scenario

Table 4 shows low utilization of all the labor except the setters. This is consistent with what was the observed on the factory floor. The roof setters utilization of 0.9808 corresponds to the observed production rate of 2.72 houses per day and the roof setting activity duration of 87 Min. The roof setting activity takes so long that the other activities were always severely delayed. The benefits of simulation can now be shown because what if scenarios can be

Table 4. Labor Utilization with Observed Production Rate of 2.72 Houses/Day (Roof Setters Activity Duration—87 Min.)

Labor	Utilization
Setters utilization—Roofing	0.9808
Labor utilization—Exterior boards	0.3462
Labor utilization—Doors and windows	0.5035
Labor utilization—Insulation	0.4503
Labor utilization—Roof decking	0.2130
Labor utilization—Siding	0.4689
Labor utilization—Roof paper	0.1997
Labor utilization—Molding	0.3195
Labor utilization—Shingles	0.4919
Labor utilization—Urethane foam	0.2609
Labor utilization—Tires	0.5299
Labor utilization—Carpets	0.3801

Table 5. Labor Utilization with Reduced Duration on Roof Setting Activity (Roof Setters Activity Duration—49 Min)

Labor	Utilization
Setters utilization—Roofing	0.8280
Labor utilization—Exterior boards	0.5905
Labor utilization—Doors and windows	0.8424
Labor utilization—Insulation	0.7449
Labor utilization—Roof decking	0.3572
Labor utilization—Siding	0.7878
Labor utilization—Roof paper	0.3552
Labor utilization—Molding	0.5380
Labor utilization—Shingles	0.8277
Labor utilization—Urethane foam	0.4369
Labor utilization—Tires	0.8987
Labor utilization—Carpets	0.6381

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Table 6. Sensitivity Analysis Data

Duration (min)	Utilization(%)	Production rate
10	34.32	4.59
20	47.1	4.51
30	59.61	4.44
40	73.53	4.26
50	83.96	3.97
60	88.91	3.6
70	94.95	3.21
80	96.57	2.93
87	98.08	2.72
90	98.63	2.59
100	99.31	2.35
110	99.6	2.17
120	99.65	2.02
130	99.79	1.84
140	99.87	1.71

suggested to find a way to remedy the situation. For example, the effect of reducing the duration for the roof setting on production and resource utilization was analyzed. This is possible by changing the quality of roof setters, by hiring more experienced workers, and/or increasing the crew size.

Reflecting this change in the model shows different numbers on labor utilization as shown in Table 5. The roof setters utilization of 0.8280 corresponds to activity duration of 49 Min. The labor utilization for the setters decreased by 16 percentage points but that of all the other labor crews increased. For example, the labor utilization for tires increased by 37%.

A sensitivity analysis was performed to study the impact of further reduction of roof setting activity duration on both labor utilization of the activity and overall production. After running the simulation model with different durations for the roof setting activity, the results of each scenario were tabulated as shown in Table 6. Figs. 7 and 8 show the plot of the results. Fig. 7 shows that an increase in roof setting activity duration causes an increase in resource utilization, but the rate of increase levels-off beyond 100 min. The opposite of this relation is shown in Fig. 8 where the production rate is inversely proportional to the activity duration. This relation is mainly caused by the "local" optimization of one process on the assembly in isolation of the rest of the assembly line. Overall, this "what-if" scenario demonstrates that by reducing the duration of the roof setting activity from 87 to

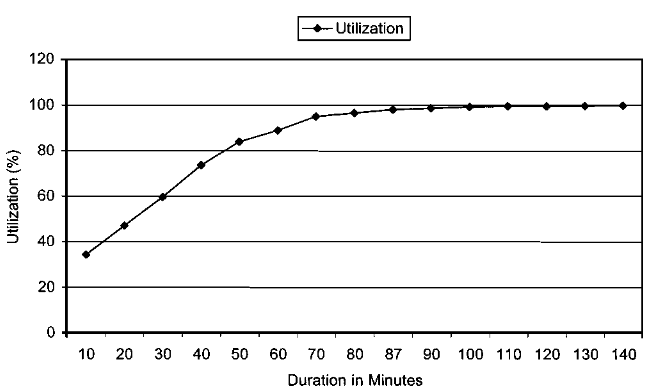

Fig. 7. Sensitivity analysis—duration versus utilization

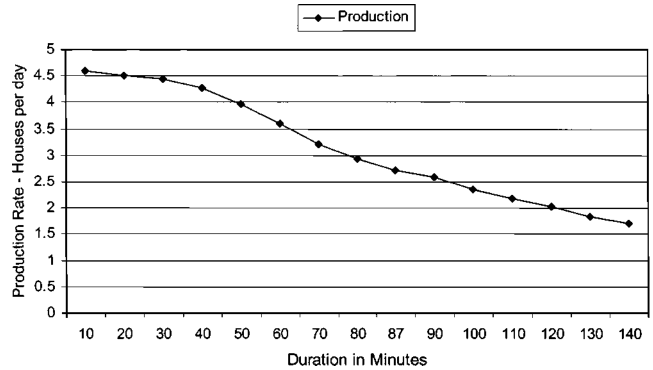

Fig. 8. Sensitivity analysis—duration versus productivity

47 min, thus reducing the utilization of roof setters from 0.9808 to 0.8280, the production rate can be improved from 2.72 houses per day to 3.99 houses per day.

The relations in Figs. 7 and 8 have profound implications that are counter to traditional management practices, especially those under mass production paradigms. To explain this somewhat cryptic statement, consider the current management practice that strives for 100% resources utilization, anything below 100% utilization is considered inefficient. However, the relation depicted in Figs. 7 and 8 clearly shows that striving for 100% resource utilization (of the roof setting crew) causes a decrease in overall productivity or system throughput. Therefore optimizing the performance of a production system is not focused on the production of individual workstations but on the reliability of workflow along the entire line.

Similarly other scenarios were implemented and discussed with the industry. These include roof insulation at the feeder station instead of the main assembly station, rearranging the feeder station between two parallel production lines, and providing a quality control/repair team at the end of the production line.

Conclusions

This paper presented the production process and material flow in a manufactured housing plant. It can be seen that despite the production line in a factory environment, the process is essentially labor intensive and technology deficient. It is based on a sequence of assembly stations along with a parallel line of feeder stations. Traditional simulation techniques can be successfully used to analyze the production process of manufactured housing and developing improvement strategies. Based on the "what if" scenarios, it was concluded that the manufactured housing industry can gain valuable insight by studying the process diligently. The various "what if" scenarios showed how using simulation, different options could be tested and studied for possible future implementation.

After analyzing the production process in two different manufacturing plants, the research team agreed with many other researchers that the manufactured housing industry is still primitive in terms of its equipment use and use of modern technology compared to other industries. The manufacturing process is very labor intensive and the industry as a whole can benefit from the use of more modern equipment such as faster cranes and a less labor intensive way of moving materials from feeder to main stations.

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References

Aft, L. S. (1992). *Productivity measurement and improvement*, Prentice-Hall, Englewood Cliffs, N.J.

Halpin, D. W., and Riggs, L. S. (1992). *Planning and analysis of construction operations*, Wiley, New York.

Harrington, H. J. (1991). *Business process improvement*, McGraw-Hill, New York.

Housing and Urban Development (HUD). (1995). *Manufactured home construction and safety standards, part 3280: Interpretative bulletins to the standards 1995*, HUD-U.S. Department of Housing and Urban Development, Washington, D.C.

Housing and Urban Development (HUD). (1998). *Factory and site-built housing: A comparison for the 21st century*, U.S. Department of Housing and Urban Development, Washington, D.C.

Manufactured Housing Institute (MHI). (2000). *Quick facts 1999–2000*, MHI, Arlington, Va.

Martinez, J. C. (1996). "*STROBOSCOPE*–State and resource based simulation of construction processes." Doctoral dissertation, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Mich.

Martinez, J. C. (1998). "*EZSTROBE*-Introductory general-purpose simulation system based on activity cycle diagrams." *EZSTROBE Software Tutorial*, Civil & Environmental Engineering Department, Virginia Tech, Blacksburg, Va.

Mehrotra, N., Syal, M., and Senghore, O. (2002). "Manufactured housing trends and regulations in michigan, vol. 1." *Project Rep.*, Michigan State University, Construction Management Program, East Lansing, Mich.

Michigan Manufactured Housing Association (MMHA). (2000). *Fact sheets*, Okemos, Mich.

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). *Productivity improvement in construction*, McGraw-Hill, New York.

Paulson, B. C., Jr. (1995). *Computer applications in construction*, McGraw-Hill, New York.

Pritsker, A. (1986). *Introduction to simulation and SLAMII*, A. Halsted Press Book, Wiley, New York.

Sawhney, A., and AbouRizk, S. M. (1993). "An overview of construction simulation and its applications." *J. Constr. Manage.* VIII, (II), 93–100.

Senghore, O. (2001). "Production and material flow process model for manufactured housing." Master thesis, Construction Management Program, Michigan State University, East Lansing, Mich.

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