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Analysis of a Modular Housing Production System Using Simulation

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Abstract

This paper presents the development of a simulation model for an existing modular housing factory. The activities of the system under study were mapped out, and the process time and total cycle time data of approximately 20 cycles were collected for all activities at the assembly and subassembly stations. Modeling assumptions were determined based on the real system constraints that were observed during the data collection process. The observed constraints included types and sizes of housing units produced and the ways these various types were processed through the system. The model was verified by observing the animation of the entities at a low speed run after each development committed on the model to check that entities are directed through the correct logic. The model was validated by comparing the production output of the model performance measures with the real system outputs. The run results showed a bottleneck free system with average queue time at stations one to station three of 60, 5, and 3.6 minutes respectively over a one week of operation, which is considered to be insignificant. The simulation model provides an efficient tool for production managers to evaluate and analyze the MH production system i) decide the appropriate product mix batch sizes and ii) locate potential bottlenecks hindering the productivity.

Keywords: Modular Housing; Simulation; Productivity; Construction Operations; Factory Layout; Production Line.

1. Introduction

Modular Housing (MH) is a major type of Factory-Built Housing that is fully constructed in a factory. MH units are produced in the form of a single section or multiple sections (usually two sections). Recently, the manufactured housing industry has started to construct two story housing units. MH is emerging to satisfy new trends of customer demand. The housing units can be assembled on rented or owned lots, within MH communities or private land lots, respectively. Since the implementation of the Housing and Community Development Act in 1976, the manufactured homes (termed mobile homes before the issuance of the 1976 HCDA) had become the first form of permanent housing built to meet the national standard of construction and safety.

MH dominates a respectable market share in the United States; and has started to appear as a valid competitor against the on-site constructed house. Their lower initial cost (approximately 1/2 of the site built house cost) makes them economically attractive to low income households, young families, elderly and retired persons [1]. The increasing demand for modular houses has urged production managers to (i) improve the productivity of the modular housing construction processes by reducing production cycle time and (ii) enhance the quality of both materials and workmanship.

Cost and Quality play an important role in favor of modular housing compared to other conventional types of housing; Table 1 shows cost and size comparison of modular housing or manufactured homes to site built homes. Maintaining these criteria would qualify MH to be a major provider of housing units to satisfy the increasing housing demand in the United States.

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Table 1. Cost and size comparisons for new modular homes and new single-family site-built homes (2001-2007) [2].

Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
New Manufactured Homes (Including typical installation cost)							
(All Homes)							
Average Sales Price	$48,900	$51,300	$54,900	$58,200	$62,600	$64,300	$65,100
Average Square Footage	1,545	1,590	1,620	1,625	1,595	1,605	1,595
Cost Per Square Foot	$31.65	$32.26	$33.89	$35.82	$39.25	$40.06	$40.82
Single-Section							
Average Sales Price	$30,400	$30,900	$31,900	$32,900	$34,100	$36,100	$37,200
Average Square Footage	1,115	1,125	1,100	1,090	1,085	1,105	1,095
Cost Per Square Foot	$27.26	$27.47	$29.00	$30.18	$31.43	$32.67	$33.97
Multisection							
Average Sales Price	$55,200	$56,100	$59,700	$63,400	$68,700	$71,300	$74,100
Average Square Footage	1,695	1,710	1,735	1,745	1,720	1,745	1,775
Cost Per Square Foot	$32.57	$32.81	$34.41	$36,33	$39.94	$40.86	$41.75
New Single Family Site-Built Homes sold (house and the land sold as a package)							
Average Sales Price	$213,200	$228,700	$246,300	$274,500	$297,000	$305,900	$313,600
Less Land Price	-49,056	-54,560	-62,929	-73,082	-78,219	-79,973	-84,268
Price of Structure	$164,144	$174,140	$183,371	$201,418	$218,781	$225,927	$229,332
Average Square Footage	**2,282**	**2,301**	**2,315**	**2,366**	**2,414**	**2,456**	**2,479**
Cost Per Square Foot	**$71.93**	**$75.68**	**$79.21**	**$85.13**	**$90.63**	**$91.99**	**$92.51**
Manufactured Home Shipments							
Year	2001	2002	2003	2004	2005	2006	2007
Total	193,120	168,489	130,815	130,748	146,881	117,373	95,769
Single	48,924	37,156	26,202	33,995	52,027	33,033	30,729
Multi	144,196	131,333	104,613	96,783	94,854	84,340	65,040
Estimated Retail Sales (billions)	$9.5	$8.6	$7.2	$7.7	$9.2	$7.5	$6.2

In 2000, 22 million Americans (about 8.0 percent of the U.S. population) lived full-time in 10.0 million modular homes. In the same year multi section homes represented 70.1 percent of all industry shipments. In 2001, the average cost of modular home was $48,800. Although, in 2000, 1/6th of new single-family housing starts were modular homes, when the industry shipped 250,550 homes from 280 manufacturing facilities [2].

The increased demand on multisection units and on MH units in general suggests that production managers should improve the productivity of their factories in order to fill the existing gap between supply and demand.

2. Research Background

MH production problems stem from the fact that a typical modular housing plant is unable to meet the high production demand due to the lack of a streamlined assembly process [3-8]. Moreover, the MH industry has not been able to emerge as a technologically advanced industry due to the adoption of labor driven processes, coupled with the lack of applied technology and computerization [9]. A streamlined assembly line for MH can be achieved through balancing the assembly line activities and their respective workloads. MH production lines are constrained by the mixed model manufacturing that involves the production of different housing unit sizes at the same production line. In order to streamline the production, it is important to equalize the workload variations in the mixed-model manufacturing systems [10]. Modularization and mass production of MH facilities are undermined by the unique nature of the house product. Therefore, production managers should apply new innovative techniques to identify system bottlenecks and to maintain a balance between efficiency and the implications of product design variations. Two strategies had been suggested for productivity improvement in MH; namely: extensive automation and lean production: extensive automation was concluded as a risky strategy that is subject to wild market swings while lean production may provide many of the same benefits [11-12].

This paper covers the development process of a simulation model for analyzing the production process of an existing MH facility in Indiana/ United States. The factory name is not revealed for confidentiality reasons. Simulation models offer a flexible tool for conducting a what-if-scenario analysis that targets the overall system improvement. Furthermore, simulation models can be extremely useful in (i) predicting the performance of virtual system designs, (ii) understanding how the real system functions, and (iii) evaluating the real system performance accurately. The overall goal of the research is to improve the productivity of the MH production systems, by identifying and removing process bottlenecks. Improved productivity would consequently improve the affordability of MH in order to serve the crucial demand of the middle and low-income households in the United States.

3. Simulation Model

The sequential steps that were adopted for developing the simulation model are depicted in Figure 1: i) Understand how the existing system operates; by observing the system components then capturing the logic of the product flow through the system, ii) Define the system constraints that result in specific assumptions which are applied to the simulation model development, iii) Collect cycle time data for the stations and for the sub activities running within the stations, iv) Define the probability distributions of the cycle time data for each station using the Input Analyzer tool provided by the simulation software, v) Develop the simulation model according to the existing system assumptions and constraints, vi) Verify the model during the development phase by checking the animation display in order to insure compatibility with the modeling assumptions, and vii) Validate the model by comparing the model results with the real system outputs.

The model assumptions are determined by the real system operating conditions, the station sequencing (i.e., organization of the factory layout), and the product sequencing (i.e., the flow logic of the housing sections through the system.

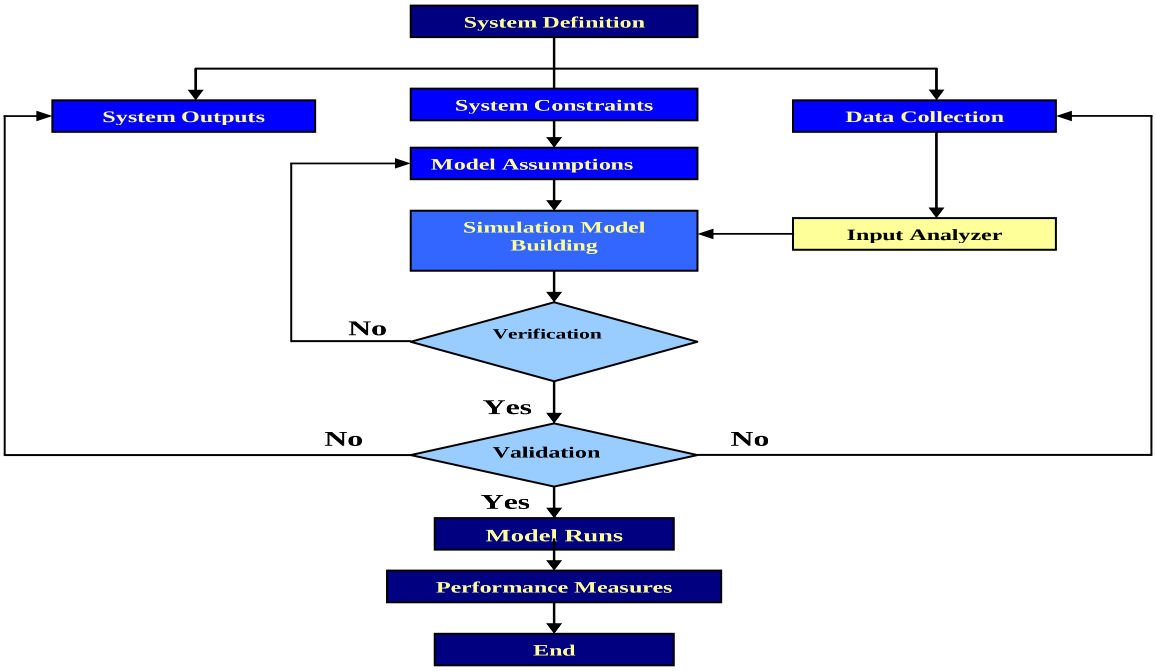


Figure 1. Methodology of developing the simulation model.

3.1. Production Process Description

The list of assembly and subassembly stations of the production line are depicted in Table 2. The U-Shape flow pattern was observed as a dominant physical shape of MH assembly lines. Additionally, the facility employs *double section processing*, which enables the processing of one full house (two sections) simultaneously at some stations. The floor subassembly (i.e., floor jig) provides assembled floor sections to the floor decking assembly station shown in Figure 2. The ready floor components are placed in a *hopper* or overhead storage that enables continuous processing of the next component while the ready component is attached to the chassis at the floor Decking station. Roofing activities were observed to be independent from the activities of the exterior and interior finishes, where the three operations occupy three successively independent stations.

Table 2. Description of stations activities and sub activities.

No.	Station Name	Description of Stations Sub activities
I-Main assembly stations		
1	Chassis Entries	Chassis on wheel and axle pulled into the factory, main wood frame is fixed.
2	Floor Decking	Place assembled floor frame with insulation, ductwork and wiring over the chassis, fastening, floor decking.
3	Interior Walls	Placement of Vinyl tile.
		Placement of interior walls (one sided studs panels).
		Placement of cabinets, toilet compartment, bathtub, and kitchen sink.
4	Exterior Wall Station	Placement of exterior walls.
5	Electromechanical Equipment	Rough electrical and mechanical, and final exterior walls installation. Installation of all electrical and mechanical equipment.
6	Roofing	Roof installation.
		Installation of shingles on the roof and cut outs for doors and windows.
7	Exterior Finish	Exterior wall finishes and installation of siding. Trim and installation of Exterior door and windows.
8	Interior Finish	Begin interior finishes, install carpet foam, complete interior drywall finish. Install carpet, final electrical and plumbing finishes, install marriage walls.
9	Cleanup and testing	Interior Finishing and cleanup, placement of material to be installed at site.
II-Feeder Stations or Sub-assembly stations		
10	Heat duct and Networks	Fabrication and storage of ductwork and plumbing, and placement of tires.
11	Floor Building feeder	Assemble floor frame, place water insulation, place heat insulation (rockwool), place floor joist, place wire and duct work, stapling.
12	Interior wall feeder	Sub-assembly of interior walls.
13	Assembly of cabinets, kitchen, and toilet sinks.	
14	Sub-assembly station for roofing main activity stations.	
15	Fabrication of roof truss, installation of ceiling board, painting, and drying.	
16	Installation of loose and rigid insulation.	
III-Storages		
17	Storage of ductwork and plumbing pipes.	
18	Storage of cabinets.	
19	Storage of drywall panels.	
20	Storage of drywall, doors and windows, and sheathing.	
21	Storage of roof shingles.	
22	Storage of foam and carpet and drywall (marriage).	
23	Storage of wall boards and tools.	
24	Storage of mirror and appliances.	
25	Storage of drapes and appliances.	
26	Storage of toilets and materials to be shipped to the site for onsite installation.	
27	Storage of drywall panels and wooden members for roof frame fabrication.	

The material handling system (the mobility system for the housing sections) permits the movement of the sections in the lateral direction of the layout by using bearing-wheeled U-sections attached beneath the wheels of the housing sections.

Although the product types and sizes are similar to other case study factories with approximately similar labor force size, the production of this factory was observed to have higher productivity output of 10 sections/ day, instead of 7 sections/ day observed at other comparable factories [7].

Figure 2 shows the stations located at the beginning and end of the assembly line. These stations consist of floor decking, interior and exterior wall, roof insulation and roof set. The factory layout, the exact distribution of operations, their respective activities throughout the different assembly, and subassembly stations are depicted in Figure 3.

The building blocks of the existing factory layout are shown in Figure 4. The building blocks are the basic stations of the assembly line associated with defined work component and time durations (i.e., station processing time) that have direct impact on the total product (i.e., housing unit) cycle time. Additionally, the building units diagram shows the exact sequence of stations and dependencies between the different operations running within the factory shop floor. The station processing times were collected from the real system; and will be discussed in the following section. The simulation model simulates the building units as processors and utilizes specified real time data for every processor of the system.

Figure 2. Different stations of the production line.

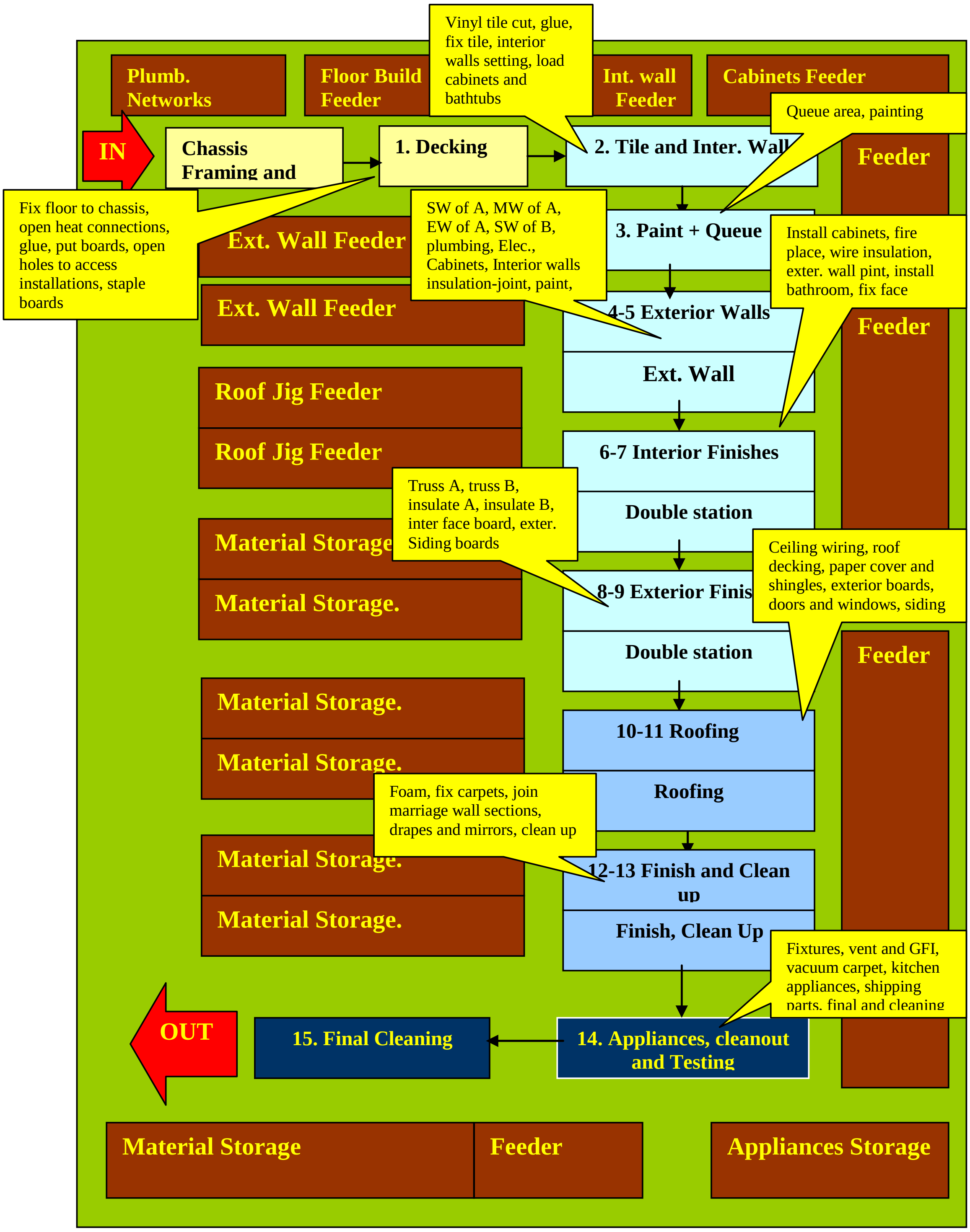


Figure 3. Factory layout, material flow pattern, and activity breakdown.

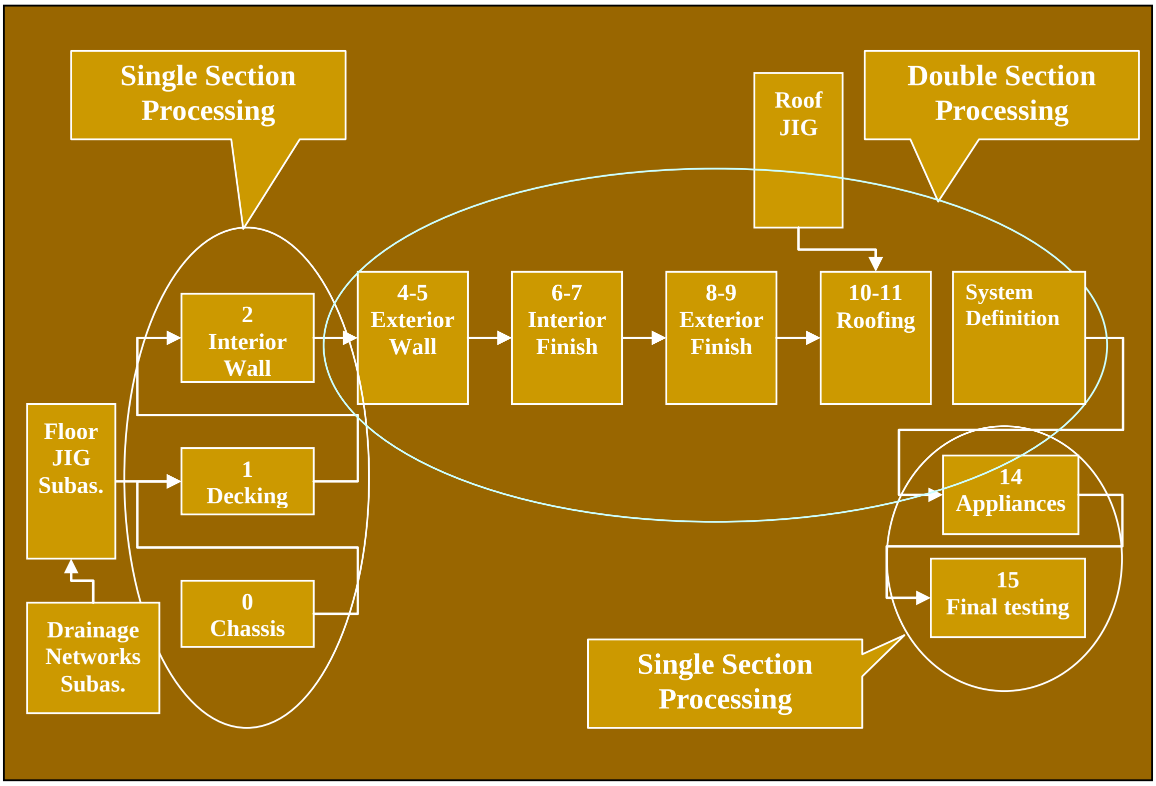


Figure 4. The building units of the real system.

3.2. Data Collection

The production process was mapped out at all assembly and subassembly stations. Table 2 shows the activity distribution on the assembly and subassembly stations of the factory. Furthermore, the factory production line, the actual flow of materials, and products through the system were observed as shown in Figure 3, in order to understand the system behavior and to determine the system constraints, which are used in developing the simulation model.

Two types of process time data were collected from the factory: i) the total station cycle time, and ii) the process time of all activities running in the station. 30 cycle data were collected for the total cycle time for each station and for every activity running at each station. The total cycle time for each housing floor (one section) is approximately two days. Data were collected over several field trips by a data collection team. The factory maps were prepared at the first visit and were used to prepare data collection sheets on Excel. The data collection tables were filled with time data relevant to each floor number copied from the tag on each chassis. During each visit, 10 data sets relevant to 10 sections were collected in the data collection sheet. As depicted by the steps described in Figure 1, the real time data (i.e., station cycle times) were transformed into stochastic time distributions using the Input Data Analyzer tool accompanying the simulation software (Arena), the distributions are described in Table 3.

Table 3. Data distributions obtained via the Input Analyzer tool in the simulation software.

No. of Server	Distribution	Expression	Square Error	Average	Standard Deviation
Server 1	Normal	NORM(38.1, 10.8)	0.035242	38.1	10.9
Server 2	Triangular	TRIA(19.5, 42.3, 54.5)	0.039624	38.8	8.28
Server 3	Normal	NORM(34.8, 7.29)	0.029086	34.8	7.41
Servers 4-5	Weibull	80.5 + 71 * BETA(0.722, 1.55)	0.052994	103	18.3
Servers 6-7	Weibull	80.5 + WEIB(28, 1.24)	0.049658	107	20.1
Servers 8-9	Beta	33.5 + 31 * BETA(0.692, 0.794)	0.050311	47.9	9.8
Servers 10-11	Normal	NORM(99.5, 12.6)	0.048788	99.5	13
Servers 12-13	Normal	NORM(192, 26.8)	0.055613	192	27.5
Server 14	Poisson	POIS(77.9)	0.181286	77.9	8.38
Server 15	Beta	39.5 + 21 * BETA(0.94, 1.16)	0.062861	48.5	6.12
Time between arrivals: 15.5 + 66 * BETA(0.967, 1.44), Square error= 0.058028.					

3.3. Model Assumptions

The model was built based on the following assumptions to match the nature of the real manufacturing system and reflect the logic i.e., sequence, and constraints i.e., space, layout shape, and distances among stations which are captured via the time data of travel and transport of material from station to station:

1. Section (b) always follows section (a) at all stations.
2. When section (a) is processed at a station, section (b) is simultaneously being processed at the previous station;
3. Section (a) should enter station 4. But section (b) should not. It rather wait in queue behind (a) then follow it to station 5;
4. The two housing sections for double-bay units are matched at the exterior wall and roofing stations and are processed simultaneously. The two sections are then split before passing through the finishing stations.
5. Housing unit of 80 ft length, for example, spends a certain processing time at each station that is different from the 55 ft length. Therefore, processing times for each section size was modeled via a statistics data distribution that includes all processing times.

3.4. Model Verification

Verification is the process to check that the model is running according to the modeling assumptions [13]. Model verification involves testing whether the model incorporates all the real system operations, such as: i) station sequencing (*i.e.,* organization of the factory shop-floor layout); ii) floor sequencing (*i.e.,* the flow logic of the floor units between the stations); and iii) inspection and rework that are included in the simulation model as approximate data; and were estimated by the production manager of the factory [16-17].

The model was verified by observing the animation of the entities at a low speed run after each development committed on the model to check that entities are directed through the correct logic as stated in the above assumptions. The batch size, processing times, and inter arrival time were controlled to observe different effects on the model outputs. The simulation model was developed, checked, modified to match SIMAN code, the model assumptions, and the actual plant conditions and specific sequence and nature of the activities.

Arena simulation software was used because it is specific to industrial and manufacturing applications. Furthermore, Arena has an efficient interface capability (animation display) that enables the modeler to follow the model logic and to verify it. Arena simulation package includes two statistical interfaces: the Input Data Analyzer and the Output Data Analyzer. The two statistical tools were used to convert the real time data into stochastic distributions and to obtain the 95% confidence intervals of the model performance measures respectively [13]. The model provides a run report that includes statistical data for many performance measures of interest such as: i) the mean product cycle time, and ii) the mean queue time at every station of the assembly line. The performance measures provide a clear idea about how the system operates and the system-specific characteristics. A stochastic simulation model has one or more random variables as inputs. The output can only be treated as a statistical estimate (confidence interval estimate) of the true characteristics of the real system [13-15]. Moreover, the model outputs identify the problems (i.e., process bottlenecks) of the simulated system.

3.5. Model Validation

Validation is the process to ensure that the behavior of the model matches the behavior of the real system [13]. Major limitation of the model is the work incentive nature of the operations. Whenever a group finishes 6-7 sections, they stop work and leave. The other lagging groups stay longer time to finish their quota before they leave. This limitation hinders the two conditions we need to satisfy in order to validate the model:

1. The cycle time of the housing section is approximately two days.
2. The production for one working day is approximately equal to 10 sections.

The model validation process involves a comparison of the real system outputs and the simulation model outputs for the 95% confidence interval on the mean production rate value, which was obtained and found to be conforming to the above two validation items [15].

3.6. The Simulation Model Components

MH processes include inter-activity relationships, interactions, and mutual impacts, which can be modeled by Arena. For the purpose of developing the simulation model, the manufacturing plant was divided into different modules. Every module represents a conceptual abstraction of activities which can be functionally classified together as a group. Different modules of the simulation model are depicted in Figure 5, based on the actual sequence of stations observed in Figure 3.

The Arrive Module is the first module of the system in which all housing section sizes (45ft, 55ft, 65ft, 75ft, 85ft) are generated.

The entities are generated according to an assigned accumulative probability [DISC(.2,1,.4,2,.6,3,.8,4,1,5)]. The time between the entity arrivals is a Beta distribution [15.5 + 66 * BETA (0.967, 1.44)] with a computed Square error = 0.058028], with a maximum batch size of 50 entities.

The two sections, (a) and (b), of the double bay house move together through the system. Therefore, the two entities are joined together at the Choose Module. Thus, the Choose Module is included in the model logic to accumulate two similar entities together, based on their assigned attribute. The if-statement of the Choose Module joins the two entities together according to similar assigned attribute numbers 1-5. The attribute numbers refer to different entity sizes. When two similar entities are accumulated in the Choose Module, they are directed immediately to the Pick Queue Module. The Pick Queue Module keeps the two entities in a storage state until they are sent directly to the Match Module. The function of the Match Module is to match the two entities together, so that they move together through the rest of the system's modules.

All house entities exit the five match modules corresponding to each house size, and enter the first Server Module (station 1: the floor decking assembly station). Then it is sent to stations 2 and 3: the interior wall assembly station and the queue paint station, respectively.

The entities are processed inside each server according to an assigned process time that is referenced in the Sequences Module. The function of the Sequences Module is to specify, in a list format, the time distribution associated with every entity size at every Server Module.

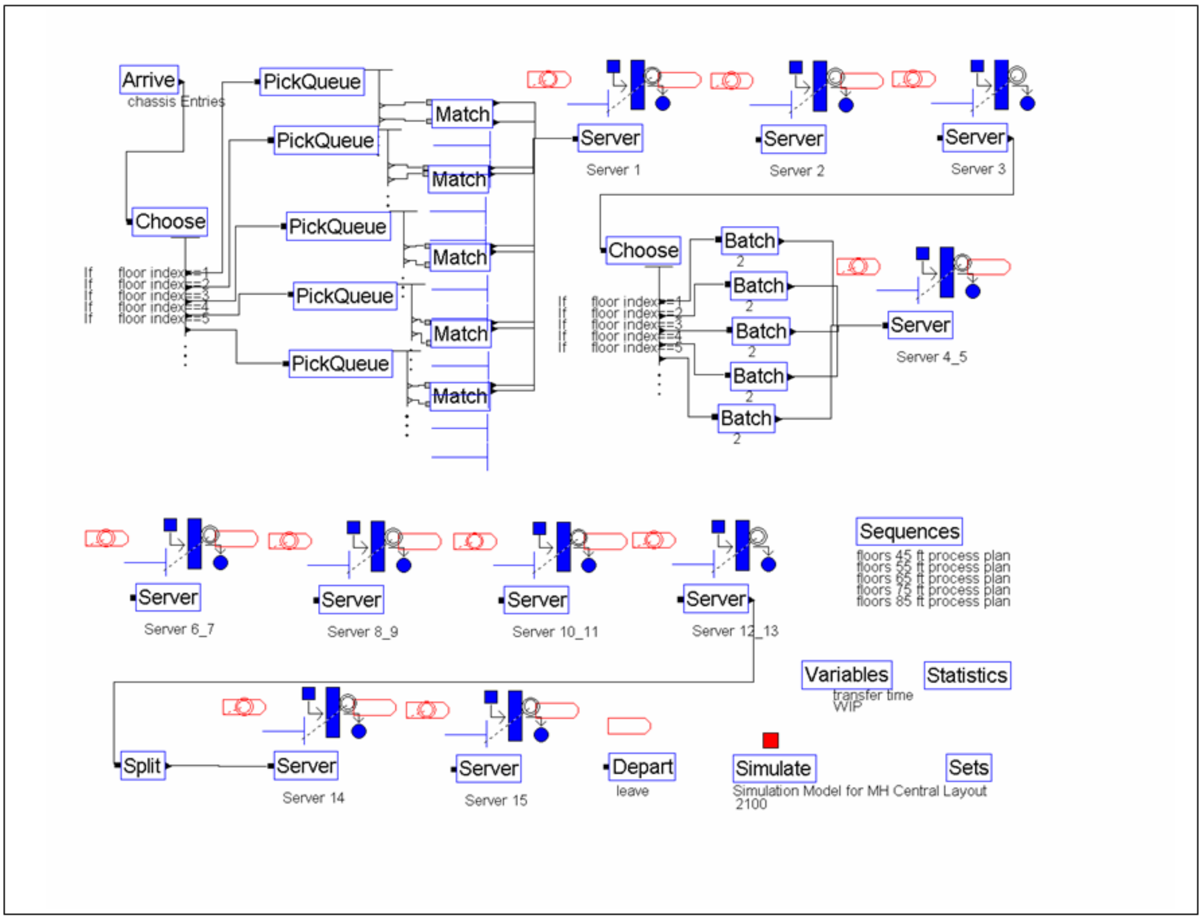


Figure 5. Simulation model layout.

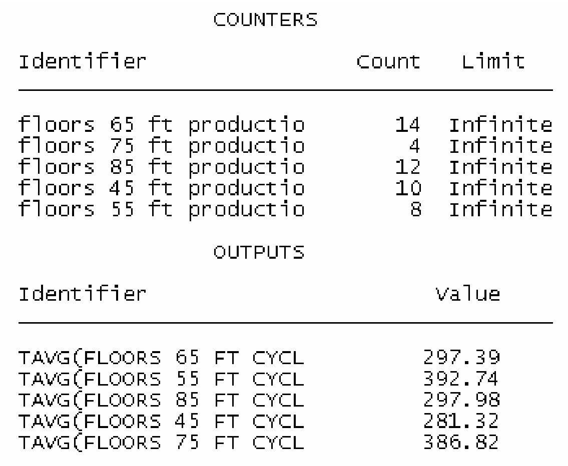
As shown in Figure 3, all the stations after station 3 are observed to be *double section* processing stations. The double section processing describes the station that processes one full house (i.e., two sections) simultaneously. Therefore, in the simulation model, a cluster of different modules is used (i.e., Choose Module and Batch Module) to capture the logic of the double section concept. The two entities leave the Batch Module as one entity. After stations 12-13, the two entities are split, using a Split Module, into two independent entities and then processed independently at the last two stations 14 and 15, the appliances and final cleaning stations, respectively.

All entities leave the last station and enter into the Leave Module. The function of the Leave Module is to collect different statistics for the specified performance measures listed in the Module's menu and in the Sets Module menu.

The Simulate Module is added to the model as an independent component. The function of the Simulate Module is to specify the number and length of replications needed to make the model run over a specific period of time. The model collects the performance measures of interest in the form of a report at the end of the run as depicted in Figure 6.

4. Results and Discussion

The run results for 100 replications are included in Figures 6-11. Figure 6 shows the output values of the production counter relative to each product size. The total production rate is equal to 48 sections per week. One week's production is equivalent to 7 hours per day, five days per week. Additionally, the average cycle time for relative product size appears in the output part of Figure 6. The average cycle time of the biggest size units i.e., 85 ft. is 297.98 minutes compared to the smallest size units of 45 ft. with average cycle time of 281.32 minutes. The 55 ft and 75 ft floors are observed from Table 6 to have the maximum average cycle time. This might be attributed to the creation of small numbers of these two sizes (4 and 8 respectively) at the arrive module, compared to other sizes of 10 -14 sections count each. Although the average floor cycle times lie between 300-400 minutes approximately; it is imperative to equalize the average time among the different sizes. Consequently, decreasing the time span of the interval in order to make the production operation leaner and smoother. Therefore, it is suggested to analyze closely the applied technology, and to propose changes to sequence, tooling, and other manufacturing factors to achieve this goal.



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                         COUNTERS

Identifier                         Count    Limit
_______________________________________________________

floors 65 ft productio               14   Infinite
floors 75 ft productio                4   Infinite
floors 85 ft productio               12   Infinite
floors 45 ft productio               10   Infinite
floors 55 ft productio                8   Infinite

                         OUTPUTS

Identifier                                 Value
_______________________________________________________

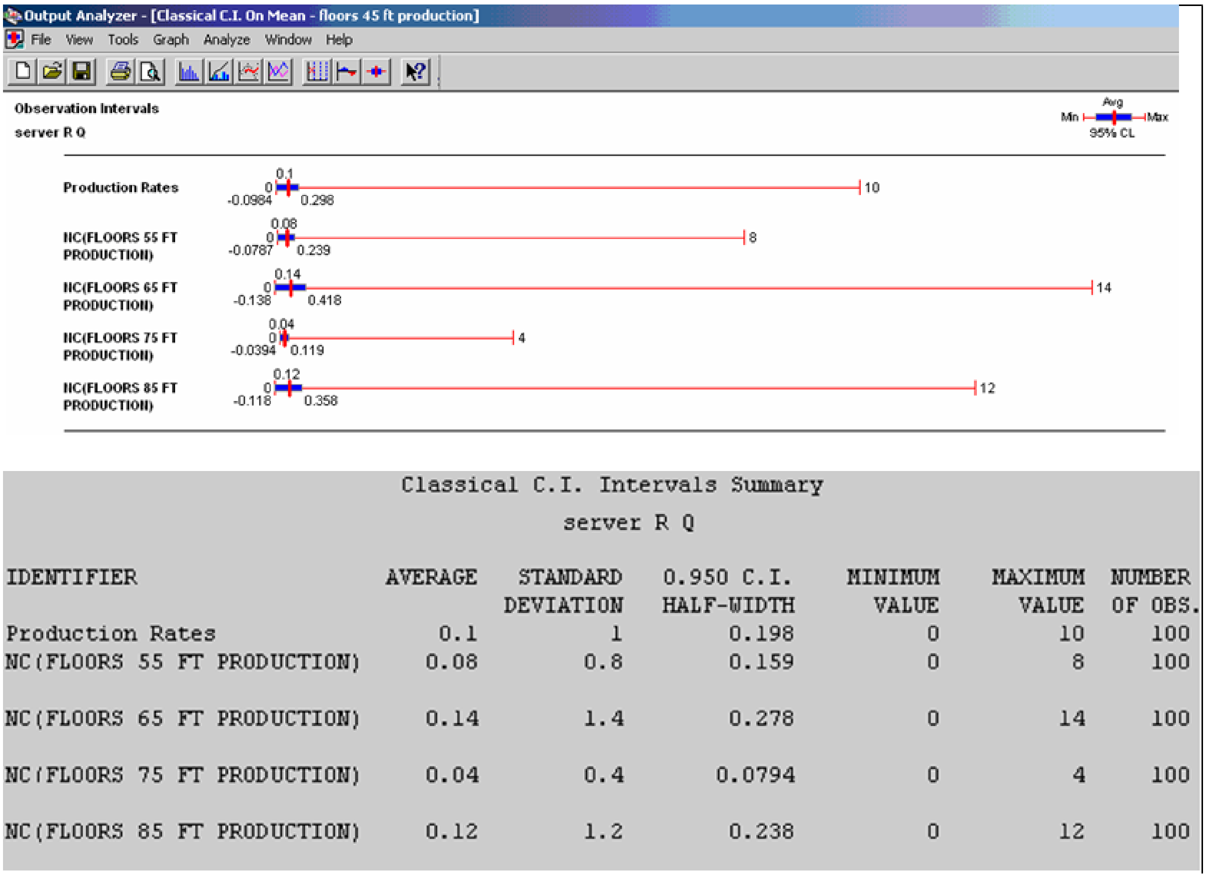
TAVG(FLOORS 65 FT CYCL                    297.39
TAVG(FLOORS 55 FT CYCL                    392.74
TAVG(FLOORS 85 FT CYCL                    297.98
TAVG(FLOORS 45 FT CYCL                    281.32
TAVG(FLOORS 75 FT CYCL                    386.82
```

Figure 6. Production measures of the simulation model.

The confidence intervals (CI) of the number of housing units waiting in the server queue relative to each product size are displayed in Figure 7. The production rates vary for each product size according to the percentages assigned at the Arrive Module (the assigned model mix).

The CI for the truncated production values over the 100 runs are depicted in Figure 8. The production measure of the model matches the actual production of the factory. The actual production rate at the factory was observed to be 9-10 sections per day. Therefore, the model is considered to be a good representation of the real system; thus, could be used in system improvement scenarios.

Figure 9 shows the run result statistics of the average product cycle time. The average product cycle time ranges from 281.32 minutes to 392.74 minutes. However, Figure 10 displays the 95% CI of the average station cycle time.



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                         Classical C.I. Intervals Summary
                                   server R Q

IDENTIFIER                    AVERAGE   STANDARD    0.950 C.I.   MINIMUM    MAXIMUM  NUMBER
                                        DEVIATION   HALF-WIDTH     VALUE      VALUE  OF OBS.
Production Rates                  0.1          1        0.198          0         10     100
NC(FLOORS 55 FT PRODUCTION)      0.08        0.8        0.159          0          8     100

NC(FLOORS 65 FT PRODUCTION)      0.14        1.4        0.278          0         14     100

NC(FLOORS 75 FT PRODUCTION)      0.04        0.4       0.0794          0          4     100

NC(FLOORS 85 FT PRODUCTION)      0.12        1.2        0.238          0         12     100
```
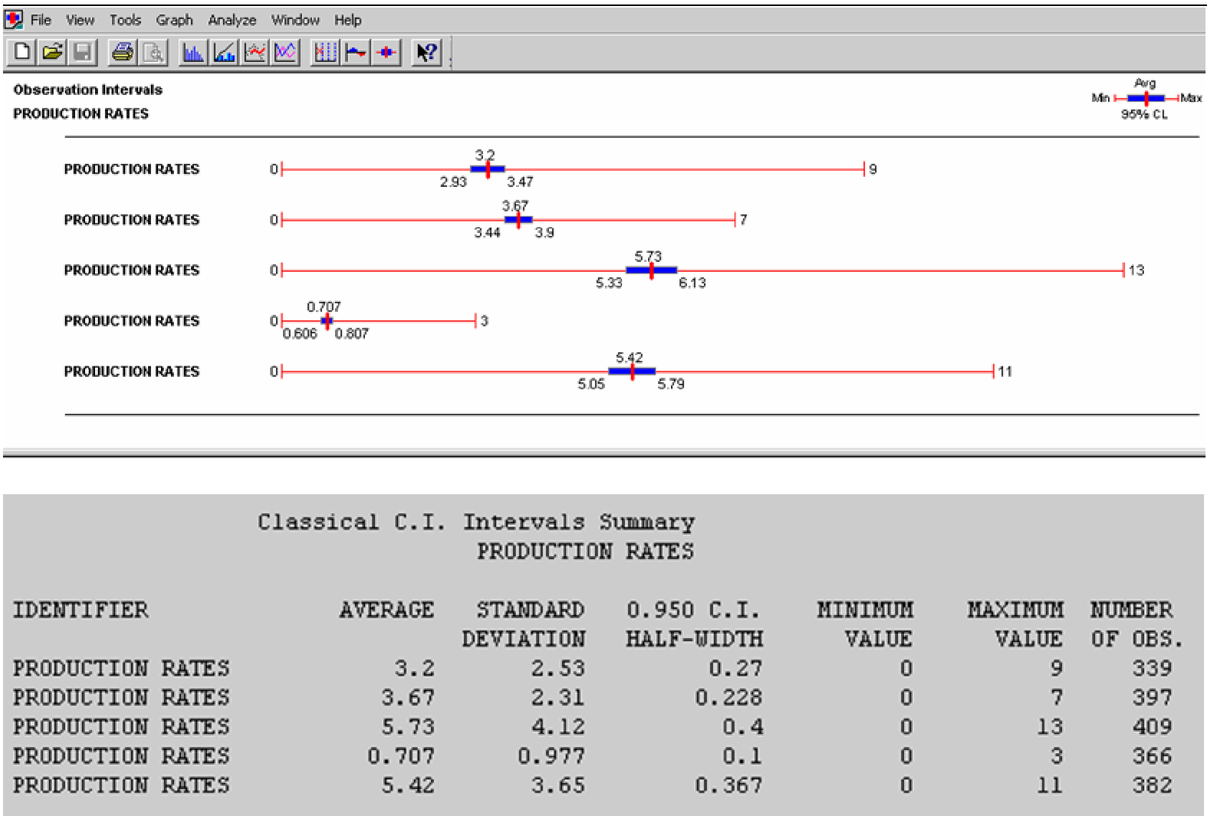

Figure 7. The 95% Confidence Intervals of the number of units waiting in Server Queue.

The results compare the cycle time of the different product sizes. It is concluded from the figure that the CI of the different products should be similar in order to obtain a bottleneck-free system.



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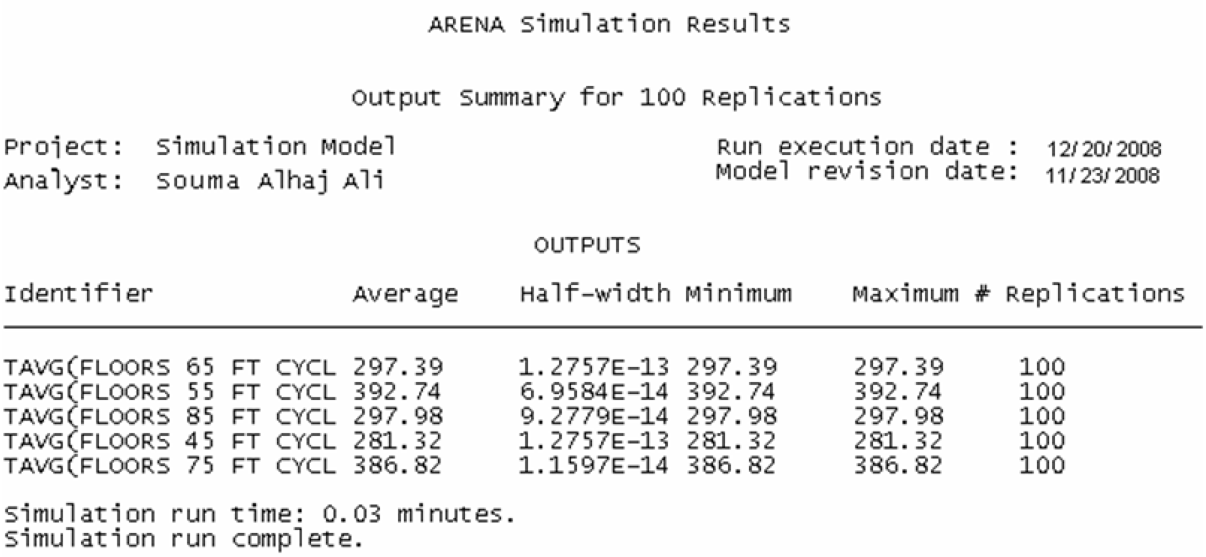
                      Classical C.I. Intervals Summary
                                    PRODUCTION RATES

IDENTIFIER                    AVERAGE   STANDARD   0.950 C.I.   MINIMUM    MAXIMUM   NUMBER
                                        DEVIATION  HALF-WIDTH     VALUE      VALUE   OF OBS.
PRODUCTION RATES                  3.2       2.53        0.27         0          9      339
PRODUCTION RATES                 3.67       2.31       0.228         0          7      397
PRODUCTION RATES                 5.73       4.12         0.4         0         13      409
PRODUCTION RATES                0.707      0.977         0.1         0          3      366
PRODUCTION RATES                 5.42       3.65       0.367         0         11      382
```

Figure 8. The 95% CI Statistics for Truncated (Interpolated) productivity values.

The average queue time statistics, shown in Figure 11, indicate station 1 as the only bottleneck station having a relatively high average queue time. The average queue time of station 1 is approximately equal to one hour per week of operation, which can be considered as an acceptable delay value over five operating days. This observation doesn't pose a problem to the actual production because it is controllable by the workers at station 1. New floor sections are only provided to station 1 when required by the station.



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                             ARENA Simulation Results


                        Output Summary for 100 Replications

Project:  Simulation Model                      Run execution date :  12/20/2008
Analyst:  Souma Alhaj Ali                       Model revision date:  11/23/2008


                                     OUTPUTS

Identifier              Average    Half-width Minimum    Maximum # Replications
_______________________________________________________________________________

TAVG(FLOORS 65 FT CYCL 297.39      1.2757E-13 297.39     297.39     100
TAVG(FLOORS 55 FT CYCL 392.74      6.9584E-14 392.74     392.74     100
TAVG(FLOORS 85 FT CYCL 297.98      9.2779E-14 297.98     297.98     100
TAVG(FLOORS 45 FT CYCL 281.32      1.2757E-13 281.32     281.32     100
TAVG(FLOORS 75 FT CYCL 386.82      1.1597E-14 386.82     386.82     100

Simulation run time: 0.03 minutes.
Simulation run complete.
```
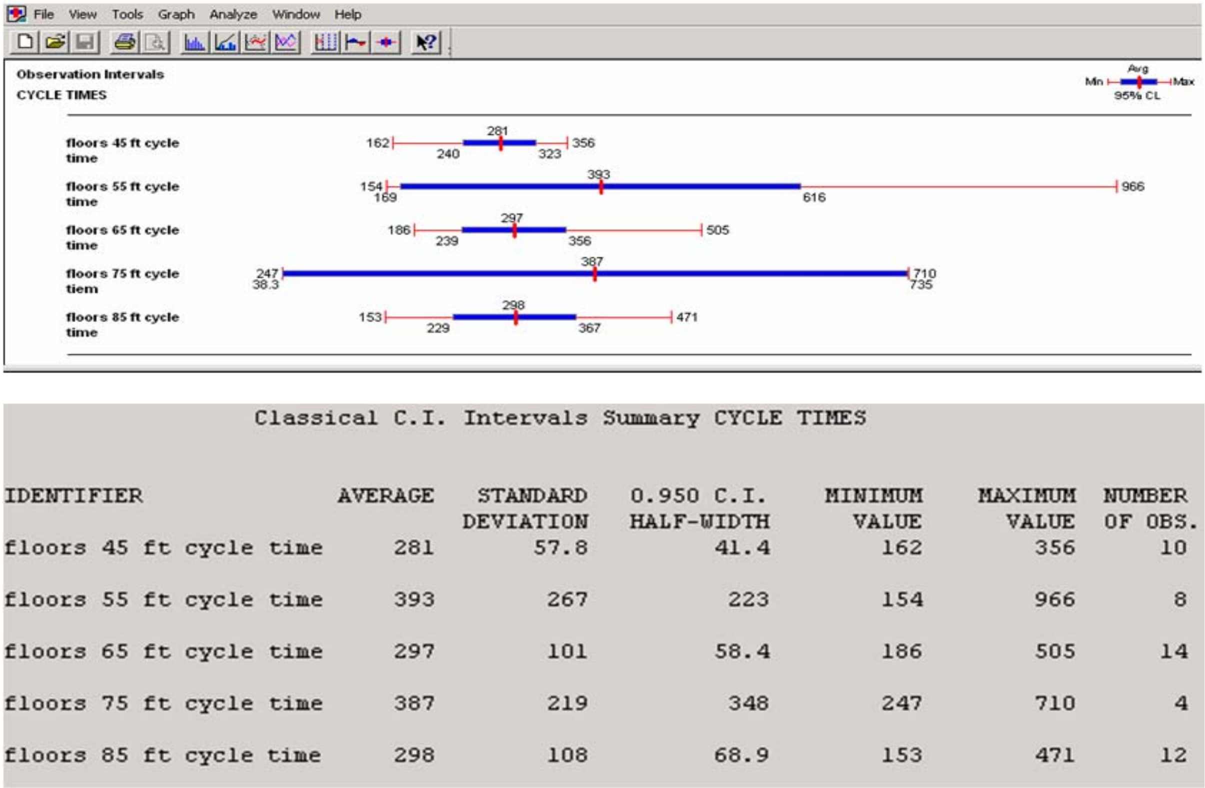

Figure 9. Run results for 100 replications of the simulation model.

The long queue time at station 1 is related to the waiting state for two entities to accumulate in the Batch Module, in order to be sent as one full house to station 1. Additionally, another cause of the long waiting time at station 1 is the long time duration between arrivals [Beta distribution [15.5 + 66 * BETA (0.967, 1.44)], coupled with a low batch size of one entity at a time. Therefore, station 1 does not have a bottleneck. The run report shows that most of the other system servers (stations) have an average queue time of zero. Additionally, the same is observed for the number in queue statistics at all the servers of the system.

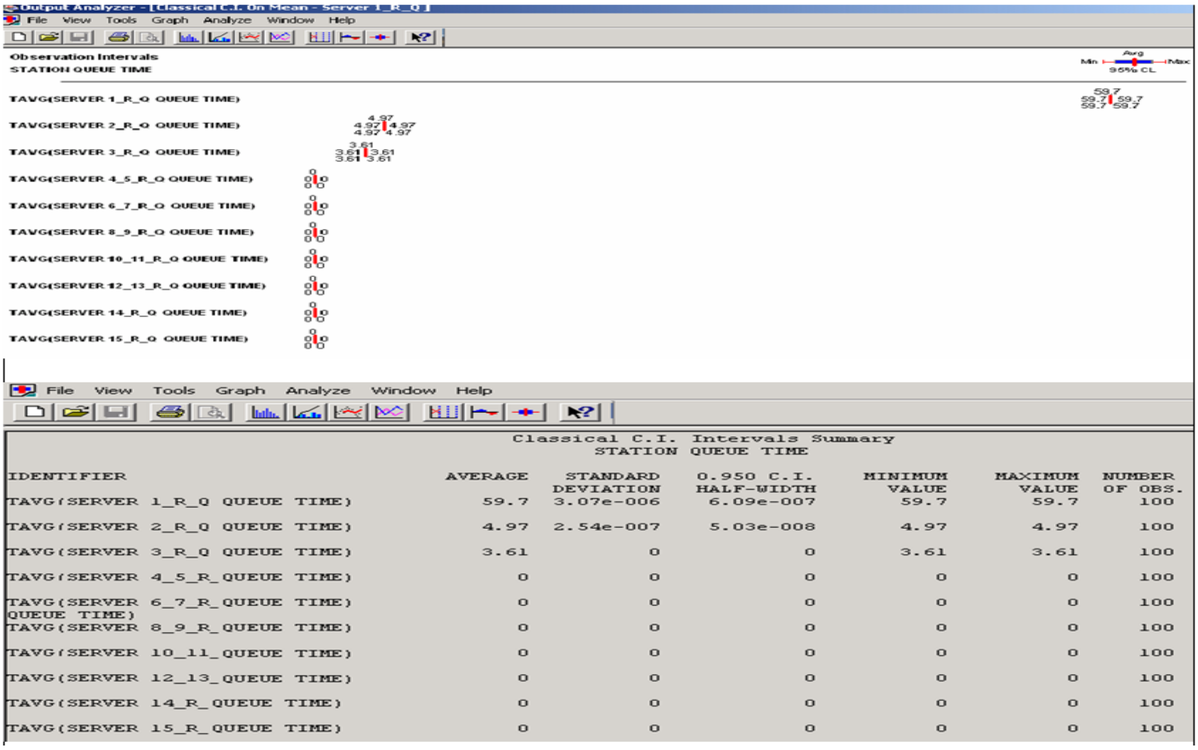
4.1. Sensitivity Analysis

The simulation model is sensitive to changes committed to station cycle times, which was done by entering the new time in the processor menu directly, because the model processes the entity according to the new value and not per the time distributions stored in the sequences module. Therefore, if the cycle time of a particular station is changed, a corresponding change to all the model performance measures will occur *i.e.*, the number of entities in queue, the average queue time for predecessor and successor stations, station utilization, and product cycle time.



```
                    Classical C.I. Intervals Summary CYCLE TIMES


IDENTIFIER                  AVERAGE   STANDARD    0.950 C.I.   MINIMUM    MAXIMUM   NUMBER
                                      DEVIATION   HALF-WIDTH     VALUE      VALUE   OF OBS.
floors 45 ft cycle time         281        57.8         41.4       162        356       10

floors 55 ft cycle time         393         267          223       154        966        8

floors 65 ft cycle time         297         101         58.4       186        505       14

floors 75 ft cycle time         387         219          348       247        710        4

floors 85 ft cycle time         298         108         68.9       153        471       12
```

Figure 10. The 95% Confidence Intervals of the mean product cycle times.



```
                                    Classical C.I. Intervals Summary
                                           STATION QUEUE TIME

IDENTIFIER                               AVERAGE    STANDARD    0.950 C.I.     MINIMUM     MAXIMUM   NUMBER
                                                   DEVIATION    HALF-WIDTH       VALUE       VALUE   OF OBS.
TAVG(SERVER 1_R_Q QUEUE TIME)               59.7   3.07e-006     6.09e-007        59.7        59.7      100

TAVG(SERVER 2_R_Q QUEUE TIME)               4.97   2.54e-007     5.03e-008        4.97        4.97      100

TAVG(SERVER 3_R_Q QUEUE TIME)               3.61           0             0        3.61        3.61      100

TAVG(SERVER 4_5_R_QUEUE TIME)                  0           0             0           0           0      100

TAVG(SERVER 6_7_R_QUEUE TIME)                  0           0             0           0           0      100
QUEUE TIME)
TAVG(SERVER 8_9_R_QUEUE TIME)                  0           0             0           0           0      100

TAVG(SERVER 10_11_QUEUE TIME)                  0           0             0           0           0      100

TAVG(SERVER 12_13_QUEUE TIME)                  0           0             0           0           0      100

TAVG(SERVER 14_R_QUEUE TIME)                   0           0             0           0           0      100

TAVG(SERVER 15_R_QUEUE TIME)                   0           0             0           0           0      100
```

Figure 11. The 95% Confidence Intervals of the mean station Queue Time.

However, it was observed that the production rate remains unchanged after modifying the processing time of a particular station. This is justified since the product cycle time is very long compared to the difference in station cycle time. Thus, it will not be substantial to cause any change to the production rate. Finally, committing any changes to the flow of logic or model constraints will consequently impact all the output performance measures including production rate.

5. Conclusions

A real time simulation model was developed for a MH production system. The model was validated by comparing the statistical measures of the simulation model with the factory output measures. The actual weekly production rates range was 45-52 sections per week. The production output measure of the simulation model was 48 sections per week, which falls within the actual production range. Therefore, the model can be used virtually in conducting what-if scenarios targeting system productivity improvement prior to implementation in a cost effective manner. The run results indicated that the system is free from bottlenecks. However, changes in the model mix would impact productivity and can be tracked down via the model. In addition, another proposition for improvement should seek alterations committed to the system layout, and to check improvements realized via the model. Scenarios targeting productivity improvement via the model are left for future work.

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