Proceedings of the 2005 Winter Simulation Conference
M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, eds.

VALIDATION OF THE RE-DESIGN OF A MANUFACTURING WORK CELL USING SIMULATION

Carrie Grimard

8101 Dorchester Road
Robert Bosch Corporation
North Charleston, SC 29418 USA

Jon H. Marvel

Department of Management
300 North Washington Street
Gettysburg College
Gettysburg, PA 17325 USA

Charles R. Standridge

301 West Fulton
School of Engineering
Padnos College of Engineering and Computing
Grand Valley State University
Grand Rapids, MI 49504 USA

ABSTRACT

Simulation can be used to validate the design or redesign of any complex system before it is implemented. Validation evidence is obtained if the simulation demonstrates that the system operation corresponds to its design. This evidence includes comparing both detailed system behavior and performance measure values to those stated in the design. The application of simulation to validating the redesign of an injector assembly and calibration production area is discussed. Simulation is necessary to validate the initial estimate of cell throughput since a single worker must perform multiple operations at multiple workstations. The feasibility of the pattern of movement by this worker between stations must be demonstrated and alternative patterns assessed. Controls on the amount of work in process inventory in the cell must be validated. Modeling challenges unique to part movement using one-piece flow, work in process inventory control, and the movement of both workers and parts are discussed.

1 INTRODUCTION

An important use of simulation, particularly in this era of lean manufacturing, is the validation of the design or redesign of complex manufacturing systems such as those found in a cellular manufacturing environment (Irani, Subramanian, and Allam 1999; Taj, et al 1998). This validation helps achieve the significant goal of minimizing the cycle time between the start of system design and realization of effective production at the desired throughput rate.

Toward this goal, simulation was applied to the validation of the redesign of an assembly and calibration cell that produces one variation of an injector assembly for a major automotive parts supplier as shown in Figure 1. The production cell consists of two areas. In the assembly area, batches of injectors are assembled in three steps: plunger valve match, AGS, and stator assembly. Each batch is loaded on one work in process (WIP) rack, which must be available before the first assembly operation begins. Full WIP racks are stored between the calibration area and the assembly area.

Applying the idea of constant WIP (CONWIP) (Hopp and Spearman 2003), the number of WIP racks is limited to control the amount of WIP. The minimum number of WIP racks that does not constrain the throughput must be found.

In the second cell, each injector is individually calibrated. The cell consists of two semi-automated workstations: VOP stand and calibrator as well as three manual workstations: nutstack assembly, pin mark, and shipping. A single worker performs all tasks within the cell. At the two semi-automated stations, the worker initiates the injector test cycle on a machine and removes the injector when the machine processing is completed. While the machine is processing the injector, the worker is free to perform other tasks. At each of the manual workstations, the worker performs a single task on the injector.

Worker walking time between stations was deemed to be insignificant for the initial design and analysis however, this time was included in the simulation model to model and assess the effect on throughput.

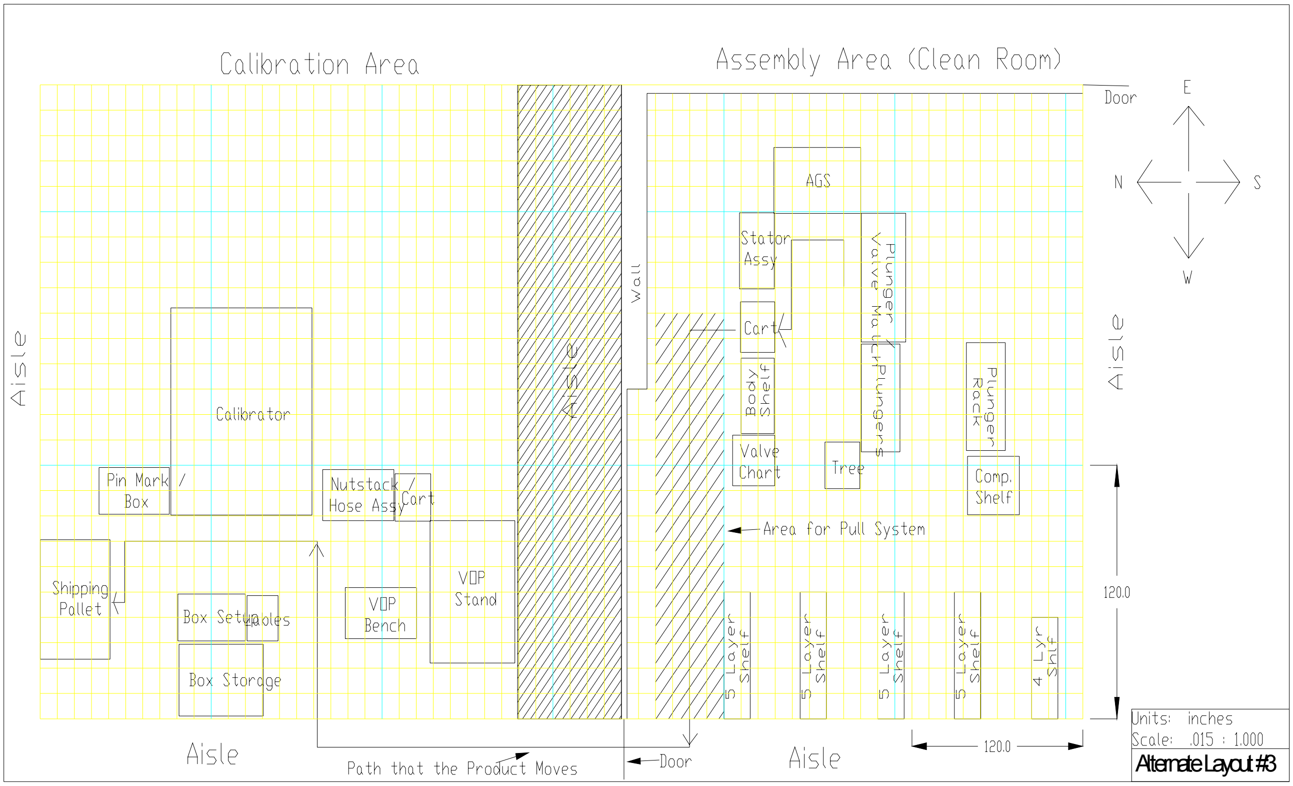

Figure 1: Layout of the Redesigned Work Cell

In addition, the following operational constraints must be taken into account. In keeping with the principle of one-piece flow (Sekine 1992), worker tasks at stations near the end of the processing route within the calibration cell are given higher priority than those at stations nearer the beginning of the processing route. In other words, the priority is to complete partially calibrated injectors before starting work on injectors waiting to begin calibration.

The simulation will be used to determine and validate the walking sequence through the assembly area when these priorities are applied. The desired walking sequence is from right to left: VOP stand, nutstack assembly, calibrator, pin mark, and shipping with tasks done at each station. From shipping the worker walks back to the VOP stand and the walking cycle begins again. In addition, the simulation will identify the number of different parts handled on each walking cycle and the sequence of operations at each station: start part on machine, remove part from machine and perform manual operation.

Each injector must cure for at least 24 hours from the end of the second operation in the assembly cell before initiation on the calibration machine. There is sufficient storage between the nutstack station and the calibration station for the 24 injectors contained on a WIP rack.

In addition, the number of WIP racks in the calibration area is further constrained. A second WIP rack may not enter the calibration cell until the first injector on the preceding WIP rack has been calibrated. This avoids starving the VOP and nutstack stations while minimizing the WIP in the calibration area. The calibration station has the longest operation time and thus is the bottleneck station.

An analysis of the operation of the proposed cell is needed to determine how close actual throughput will be to potential throughput as well as to determine the number of WIP racks to use. In addition, the analysis should validate the implementation of one-piece flow in the calibration cell.

2 MODELING ISSUES

The following modeling issues were of particular significance to this project.

1. Modeling the movement of both workers and injectors in the calibration area.
2. Modeling the CONWIP inventory control system with regard to the number of WIP racks.
3. Modeling the control of the number of WIP racks in the calibration area.

The model was built using a process world view perspective with the entities moving through the process from step to step. Entities represented one WIP rack full of parts in the assembly area and individual parts in the calibration area. The model was implemented using AutoMod (Banks 2004), student version 11.

The movement of the calibration area worker was modeled as follows. First consider the VOP stand station, one of the semi-automated stations. Worker tasks in priority order are as follows:

1. Remove a completed part from the machine.
2. Start a new part on the machine.
3. Walk the last completed part to the next station, nutstack.

The worker is modeled as a resource. A resource models any system element whose scarcity impedes the flow of entities (injectors in the calibration area). When a part arrives at a station, one of its attribute values is assigned the priority for acquiring the worker resource relative to all other stations. As was previously discussed, the closer the station to the end of the part route through the calibration area, the higher the priority. Thus, the VOP stand has the lowest priority.

At a semi-automated station, VOP stand or calibration, the part entity waits for the worker resource three times, one for each of the tasks shown above. This waiting occurs in the sequence: start a new part on the machine (2), remove a completed part (1), and travel to the next machine (3). Thus, when a part is ready to be removed from the machine, its priority for acquiring the worker is increased to slightly more than when the part arrived to the station. After the part is removed from the machine, its priority for acquiring the worker for travel to the next station is made slightly less than when it arrived to the station.

The time for the worker to walk from his current location to the station where he is to perform an operation on a part is included in the model. Thus immediately after acquiring the worker resource for a task, a time delay for the worker to walk to the station is included in the model. A matrix of the walking time between any two stations is included in the model. The walking time between a station and itself is recorded in the matrix as a zero value.

The AutoMod arriving procedure for the VOP stand follows. Note that in AutoMod the lower the value of the load attribute `priority`, the higher the priority of the load for obtaining a resource. The value of the variable V_Walking (start, end) is the worker walking time between any two stations: start and end. The value of the variable V_OperatorLocation is a numeric code representing the station at which the worker is currently performing a task.

```
begin
    /*PROCESSING AT VOP*/
    set priority = V_Priority(1)
    move into Q_VOP   /* move into VOP Q */
    get R_VOP
    get R_Worker      /* get worker */
    wait for V_Walking(V_OperatorLocation,1)
        /* walk to VOP */
    set V_OperatorLocation = 1

    wait for .50 min  /* assembly time*/
    free R_Worker     /*free worker*/
    wait for 10 sec   /*vop test time*/

    decrement priority by 1
    /* higher priority than starting part */
    get R_Worker   /*getting worker*/

    wait for V_Walking(V_OperatorLocation,1)
        /* walk to VOP */
    set V_OperatorLocation = 1

    increment priority by 2
       /* lower priority than starting part */
    free R_Worker
    free R_VOP

    wait for V_Infinitesimal
        /* delay forces worker to seek work */

    get R_Worker   /*getting worker*/
    wait for V_Walking(V_OperatorLocation,1)
        /* walk to VOP */
    wait for V_Walking(1,2)
        /* walk to Nutstack */
    set V_OperatorLocation = 2
    free R_Worker

    send to P_NUTSTACK /* next station */
end
```

Next consider a manual station such at nutstack. In this case the worker performs the manual operation at the station and walks the injector to the next station immediately upon completion of the operation. When a part arrives to the station, an attribute value is set with the priority for acquiring the worker relative to other stations.

The AutoMod arriving procedure for the nutstack station follows:

```
begin
    set priority = V_Priority(2)
    move into Q_NS /*move into Nutstack Q*/
    get R_Worker   /*get worker */
    wait for V_Walking(V_OperatorLocation,2)
        /* walk to Nutstack */
    set V_OperatorLocation = 2

    wait for 3.956 min  /*manual operation*/

    wait for V_Walking(2,3)
        /* walk to Calibrator */
    set V_OperatorLocation = 3

    free R_Worker
    send to P_CAL   /* next station */
end
```

The CONWIP control system can be modeled using a resource since it is a system element that impedes the flow of entities through the process. The capacity or number of units of the resource is set equal to the number of WIP racks. A WIP rack is allocated (made busy) before the first operation in the assembly cell can start. Thus, the WIP must always be no greater than the number of WIP racks. A WIP rack is freed (made idle) at the calibration station after the first injector on the rack as completed the calibration operation. Movement of WIP racks is handled by the worker assigned to the assembly area.

In the same way, the control on the number of WIP racks in the assembly area can be modeled as a resource with capacity or number of units set to 1. This resource must be acquired (made busy) before a WIP rack of injectors can enter the calibration area. The resource is freed (made idle) at the calibration station after the first injector on the rack has completed the calibration operation.

These two controls were implemented in AutoMod using counters, which can be viewed as a special type of resource. For example, the AutoMod statement.

```
increment C_CONWIP by 1
    /* acquire WIP control */
```

could be used to allocate a WIP rack. The counter has a capacity or upper limit. If incrementing the counter would cause its value to exceed the upper limit, the entity waits. When the counter value is decremented somewhere else allowing the increment operation to take place without exceeding the upper limit, the entity proceeds.

The AutoMod statement for freeing the inventory control at the end of its use is as follows:

```
decrement C_CONWIP by 1
    /* free WIP control */
```

3 THE SIMULATION EXPERIMENT

The simulation experiment was designed to determine the minimum number of WIP racks required to maximize the throughput of the calibration area as well as to validate that task sequence performed by the calibration area worker was consistent with the principle of one-piece flow. The simulation experiment is deterministic as no quantities are modeled by random variables. However, the work cell is sufficiently complex that simulation is necessary for understanding and validating its behavior (Pritsker 1989).

The cell operates twenty four hours per day five days a week. Work is not carried over from week to week. Thus, no injectors are in the cell at the start of a week. This provides the initial conditions for the experiment as well as the ending time of 120 hours.

The experiment input is the number of WIP racks allowed. Simulation results include the weekly throughput of the calibration area, utilization of the calibration area worker, the utilization of the WIP racks as well as the maximum number of WIP racks currently used, and the average time between the request for the calibration area worker to perform a task and when the worker starts walking to the station requiring the task. In addition, a time ordered listing (trace) of the start of each task performed by the calibration area worker is produced.

The maximum potential throughput of the calibration cell was determined as follows, with the aforementioned assumption that worker walking time can be ignored. The bottleneck station is the calibrator with a processing time of 4.25 minutes or 338 parts per 24 hour day. Each week the calibrator station can operate for no more than 4 days. Recall that a one day cure time is required for injectors prior to the calibrator station operation. Thus, the maximum weekly throughput of the cell is 338 * 4 = 1352 injectors.

The number of WIP racks may be estimated by dividing the daily maximum throughput of the calibration cell by the number of injectors per cart: 338/24 ≈ 14. This is appropriate since injectors must cure for 24 hours. Thus, it was decided to simulate the model for number of WIP racks in the range 10 to 15.

Figure 2 shows the throughput as a function of the number of WIP racks.

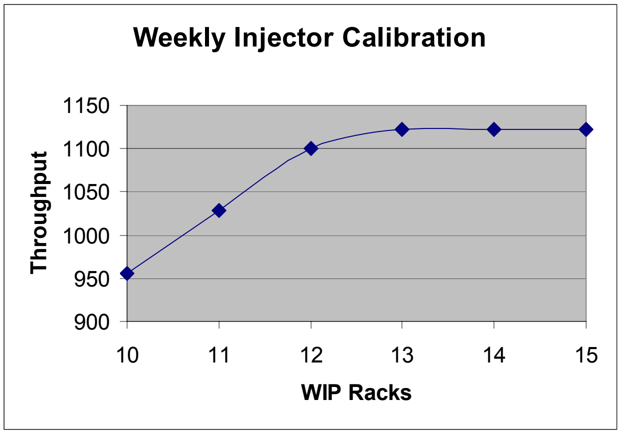

Figure 2: Throughput from the Simulation Experiment

The maximum throughput of 1122 injectors per week is achieved using 13 WIP racks, with an average number of 12.1 carts in use. This throughput is 230 injectors less than the initial estimate. The average time taken by the worker to respond to a request is 36.7 seconds which was the same (to one decimal place) regardless of the number of WIP racks used. The utilization of this worker is 100% for the four days of calibration area operation. Thus under the current design, 1122 injectors is the maximum throughput that can be achieved. One less WIP rack than the initial estimate is required.

Validation and verification evidence was gathered from the simulation results for the run with 13 WIP racks using the techniques described in Law and Kelton (2000), Sargent (2001), and Standridge (2004). The number of injectors that start processing in the calibration area equaled the number that completed processing plus the number in the area at the end of the simulation: 1152 = 1122 + 30. Animation was used to follow the movement of injectors through the calibration area which was seen to be correct. The 100% utilization of the calibration area worker is as expected.

The worker task pattern is shown in Table 1.

Table 1: Calibration Area Worker Task Pattern

Simulation Time (min)	Station	Task	Part ID
1785.51	VOP	Removal	81
1785.69	VOP	Operation	82
1786.19	VOP	Walk to Nutstack	81
1786.23	NUTSTACK	Operation	81
1790.19	NUTSTACK	Walking to Calibrator	81
1790.25	CALIBRATOR	Removal	58
1790.25	CALIBRATOR	Operation	59
1790.34	CALIBRATOR	Walk to Pin Mark	58
1790.38	PINMARK	Operation	58
1790.46	PINMARK	Walking to Pack	58
1790.50	PACK	Operation	58
1790.58	VOP	Removal	82

Note that the total time to complete one cycle through the calibration area from the start of the removal of one part from the machine at the VOP station to the start of the removal of the next part is 5.07 minutes. This is longer than the bottleneck operation time of 4.25 minutes at the calibration station. Thus, the simulation results show that the worker is the bottleneck.

The part ID number column shows that the worker has contact with four injectors on each cycle. One injector (81) is removed from the machine at the VOP station and a second injector (82) is loaded. The first injector (81) is taken to the nutstack station where the worker performs the required manual operation. Next, the worker walks the part to the calibrator and leaves it in the input buffer. The worker removes an injector (58) from the calibrator and starts the next injector (59) on this machine. The worker takes the injector that was removed from the machine (58) to the pin mark station and then the pack station, performing the necessary operation at each station. Thus, one-piece flow has been achieved.

Note that the injectors handled at the VOP machine and the calibrator have ID numbers that differ in value by about 24, the number of injectors on a WIP rack. This shows an aspect of the dynamics of the calibration area. For the first WIP rack of the week, the operations at the VOP and nutstack stations can be performed before the injectors have waited for the 24 hour cure time. Thus, the first WIP rack is emptied and stored in the buffer at the calibration station. When the first injector from this WIP rack completes calibration, the next WIP rack of injectors is allowed to enter the calibration area to avoid starving the VOP and nutstack stations.

One possible system alternative is to use a second worker at the nutstack station to attempt to increase throughput back nearer to the design potential. The nutstack station is chosen since it has the longest manual operation task. Upon completion of the operation, the worker would walk the part to the calibration station and then return.

This case was simulated with the following results. Throughput increased only to 1210 injectors, 88 greater than the throughput with one worker but still 142 injectors less than the maximum possible throughput.

The utilization of the second worker was 87.5% for four days. The utilization of the original worker is 21.9% as opposed to 100% previously. However, the average waiting time for the original worker to respond to a request to start a task is still 6.39 seconds. Thus, despite low worker utilization, throughput is still constrained by the reality that the worker is needed at two stations at once if the maximum possible throughput is to be achieved.

4 SUMMARY

Simulation is necessary to validate the operation of a variety of manufacturing cells common in this era of lean manufacturing. Such a validation helps to minimize the time required for the cell to achieve production capabilities at the required throughput level.

The validation of one such cell has been presented. The maximum realistic throughput has been determined by simulation. The minimum number of WIP racks required to meet this throughput has been identified. The reasons that the throughput potential of the cell as initially specified could not be achieved were determined. These have to do with a worker needing to be at multiple stations at once despite worker utilization of less than 25%.

A trace of the start of worker tasks is produced by the simulation. This trace shows that the sequence of worker tasks is consistent with the principal of one-piece flow. The number of parts handled by the worker in one cycle through the work area is identified.

REFERENCES

Banks, J. 2004. *Getting started with AutoMod, 2nd edition.* Chelmsford, MA: Brooks Automation.

Hopp W. J. and M. L. Spearman. 2000. *Factory physics, 2nd edition*. Boston, MA: McGraw-Hill.

Irani, S. A., S. Subramanian, and Y. S. Allam. 1999. Introduction to cellular manufacturing systems. In *Hand-*

book of cellular manufacturing systems, ed. S. Irani. New York: John Wiley & Sons, Inc.

Grimard, C. 2003. EMD assembly line. Unpublished masters project, School of Engineering, Grand Valley State University, Grand Rapids, Michigan.

Law, A. M. and W. D. Kelton. 2000. *Simulation modeling and analysis, 3rd edition.* New York: McGraw-Hill.

Pritsker, A. A. B. 1989. Why simulation works. In *Proceedings of the 1989 Winter Simulation Conference*, ed. E. A. MacNair, K. J. Musselman, and P. Heidelberger, 1-8. Institute of Electrical and Electronics Engineers, Piscataway, NJ.

Sargent, R. G. 2001. Some approaches and paradigms for verifying and validating simulation models. In *Proceedings of the 2001 Winter Simulation Conference*, ed. B. A. Peters, J. S. Smith, D. J. Medeiros, and M. W. Rohrer, 106-114. Institute of Electrical and Electronics Engineers, Piscataway, N. J.

Sekine, K. 1992. *One-piece flow: cell design for transforming the production process.* Portland, OR: Productivity Press.

Standridge, C. R. 2004. How factory physics helps simulation. In *Proceedings of the 2004 Winter Simulation Conference*, ed. R .G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, 1103-1108. Institute of Electrical and Electronics Engineers, Piscataway, NJ.

Taj S., D. S. Cochran, J. W. Duda, and J. Linck. 1998. Simulation and production planning for manufacturing cells. In *Proceedings of the 1998 Winter Simulation Conference*, ed. D.J. Mederios, E. F. Watson, J. S. Carson, and M. S. Manivannan, 973-978. Institute of Electrical and Electronic Engineers, Piscataway, N.J.

AUTHOR BIOGRAPHIES

CARRIE GRIMARD is a Manufacturing Engineer for Robert Bosch Corporation, and recently completed the Master of Science in Engineering degree in the School of Engineering at Grand Valley State University. Her professional work has primarily involved the injector and calibration cell described in this paper. Her email address is `Carrie.Grimard@us.bosch.com`.

JON H. MARVEL is an Assistant Professor of Management at Gettysburg College. Before joining the Gettysburg College faculty in 2004, he was a member of the faculties of Grand Valley State University and James Madison University. He also has over 14 years of industrial experience in a variety of engineering positions as well as a manufacturing consultant. He obtained his Ph. D. in Industrial Engineering at the University of Cincinnati. His primary interests are in the areas of production operations, applied data analysis and the application and integration of simulation into discrete part manufacturing solutions. His email address is `jmarvel@gettysburg.edu`.

CHARLES R. STANDRIDGE is a professor in the School of Engineering, Padnos College of Engineering and Computing, at Grand Valley State University. He has over 30 years of simulation experience in academia and industry. He has performed many simulation applications, developed commercial simulation software, and taught simulation at three universities. His current research interests are in the development of simulation cases management systems (SCMS). He is working with industry on the application of SCMS to lean manufacturing problems particularly inventory control and logistics. His teaching interests are in the concurrent use factory physics, lean manufacturing, and simulation in introductory undergraduate and graduate courses using a case-based approach. He also teaches in the area of engineering measurement and data analysis. He has a Ph.D. in Industrial Engineering from Purdue University. His email address is `standric@gvsu.edu`.