Integration of Simulation, Statistical Analyses, and Optimization into the Design and Implementation of a Transfer-Line Manufacturing System

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INTEGRATION OF SIMULATION, STATISTICAL ANALYSES, AND OPTIMIZATION INTO THE DESIGN AND IMPLEMENTATION OF A TRANSFER-LINE MANUFACTURING SYSTEM

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ABSTRACT

Achieving efficiency of initial investment and operational expense with respect to a transfer-line manufacturing system presents many challenges to the industrial or process engineer. In this paper, we describe the integration of simulation, statistical analyses, and optimization methods with traditional process design heuristics toward meeting these challenges. These challenges include investigation of the possibility of combining selected operations, scheduling arrivals to the process from upstream operations, quantity and configuration of machines appropriate to each operation, comparing effectiveness of various line-balancing alternatives, sizes and locations of in-process buffers, choice of material-handling and transport methods, and allocation of manufacturing personnel to various tasks such as material handling and machine repair.

We then describe our approach to meeting these challenges via the integration of analytical methods into the traditional methods of manufacturing process design. This approach comprised the gathering and analysis of input data (both qualitative and quantitative), the construction, verification, and validation of a simulation model, the statistical analysis of model results, and the combination of these results with engineering cost analysis and optimization methods to obtain significant improvements to the original process design.

KEYWORDS

Transfer Line, Line Balancing, Process Simulation, Process Design

1 Introduction

During the past forty years, manufacturing systems have been one of the largest application areas of discrete process simulation, typically addressing issues such as type and quantity of equipment and personnel needed, evaluation of performance, and evaluation of operational procedures [1]. Furthermore, simulation analysis is increasingly allying itself with other traditional methods of manufacturing process design such as line balancing, layout analysis, and time-and-motion studies [2].

In this paper, we first present an overview description of the existing and proposed production system under study and its operational flow. Next, we specify the project goals and performance metrics of the system, and review the data collection and approximations required to support these modeling objectives. We then describe the construction, verification, and validation of the simulation models. In conclusion, we present the results obtained from the statistical analyses of the model output, the use of those results in actual process design, and indicate further work directed to continuous improvement. An analogous application of simulation to the NP-hard problem of balancing a manual flow line is documented in [3]. Use of simulation to gather data needed to balance an assembly line is described in [4]. Other examples of studies likewise illustrating synergistic alliance of simulation with other analytical and/or heuristic techniques examine scheduling of production in a hybrid flowshop [5], determination of constraints in a foundry [6], and determination of the minimum number of kanbans required to meet production requirements [7]. "Kanban," the Japanese word for "card," refers to a manual system of cards used to control a pull system and keep work-in-progress at each machine constant as a function of time [8].

2 Overview of Production System

The production system studied for improvement with the help of simulation modeling produces an automotive component. The production system utilizes the material process flow of the traditional transfer line frequently found in the automotive industry.

2.1 Transfer Line

Production flow systems, in the form of transfer lines, are used extensively in automotive and other high volume industries. Efficient operation of such lines is important to the financial success of firms competing in these industries.

Consider a manufacturing line where n operations (such as drilling of holes, smoothing of surfaces, spot welds, etc.) must be performed on each component processed. These n operations are to be performed by m machines, where $m << n$. In general, the n operations take widely varying amounts of time.

In a transfer line, the n operations are assigned to the m machines such that the work assigned to each machine takes about the same amount of time. For example, a particular machine may be assigned the task of drilling several different holes in succession. Achieving such a set of assignments of operations to machines is called "line balancing," and success in line balancing is vital to high efficiency [9]. The balancing is important because of an essential characteristic of a transfer line: no movement of components from machine to machine may occur until *all* components are ready to move (i.e., *all* machines have completed *all* operations assigned to them). For example, if one machine goes down, all movement stops. This balancing may have to accommodate precedence relationships among operations. For example, if three operations are drill hole "A," drill hole "B," and drill hole "C," those operations can presumably be done in any order (absence of precedence relationship). However, two operations "drill hole 'A'" and "thread hole 'A'" have a precedence relationship – the hole must be drilled before it is threaded. "Flexible transfer line" has long been desired [10]. Today the increased speed of machining operations and application of modular design are now improving flexibility of transfer lines [11].

2.2 Existing Production Line

The existing production system is a "lights out" system; that is, it is fully automated with respect to machine operations and hence no operators are used in the production of the component. Operators are on staff to repair workstations when downtime occurs.

The existing production line consists of four pairs of workstations in parallel (OP10 and OP20), which perform drilling operations on the component. The components enter the production system in batches of two. Once the last drilling operation is complete at OP20, the components feed into the main line, singly, using first-in first-out (FIFO) logic. The component will experience a discrete stop at each of the six additional workstations. The workstation at the upstream end of the main line is a wash machine (OP30) followed by a leak tester (OP40), assembly table (OP50), drill machine (OP60), leak tester (OP70), and inspection table (OP80). Like the operations themselves, transfers of components from workstation to workstation are fully automated. Figure 1 illustrates the operational flow of the existing production system. Some examples of precedence relationships appear within this line. For example, the inspection operation (OP80) must follow every other operation, and hence must come last. Likewise, testing for leaks must be done both before and after drilling, creating pairwise precedence relationships, one between operation 40 and operation 60; and one between operation 60 and operation 80.

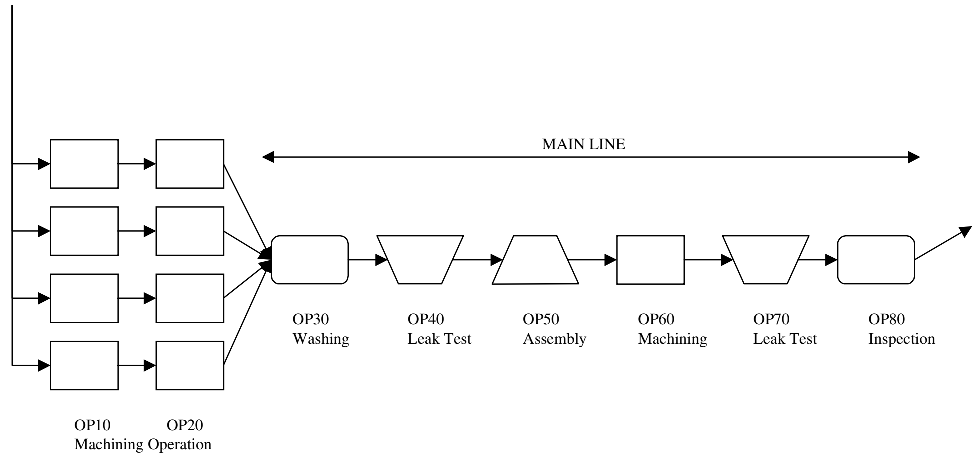

Figure 1 Diagram of Existing Production System

2.3 Proposed Production System

The objective of the proposed production system is to maintain "lights-out" production and increase the throughput. The proposed production system combines the drilling operations (OP10 and OP20) at the beginning of the transfer line. The components will enter the system singly to one of eight workstations (OP100), which will perform the drilling operations that currently require two separate operations in the existing production system. After the drilling operations are completed, the parts enter a proposed buffer area with FIFO logic, which has a defined capacity. This buffer represents a proposal to increase throughput of the component by "working-around" the shortfall of a transfer line. The main line remains the same as in the existing production system. Emerging from the buffer, the components feed into the main line, singly, experiencing a discrete stop at each of the six workstations. The workstation at the beginning of the main line is a wash machine (OP200) followed by a leak tester (OP300), assembly table (OP400), drill machine (OP500), leak tester (OP600), and inspection table (OP700). Automatic transfer of components between workstations will remain the same as in the existing production line. The use of operators, again, is only for repair of workstations experiencing downtime. Figure 2 shows a diagram of the proposed production system with the buffer area and new material flow.

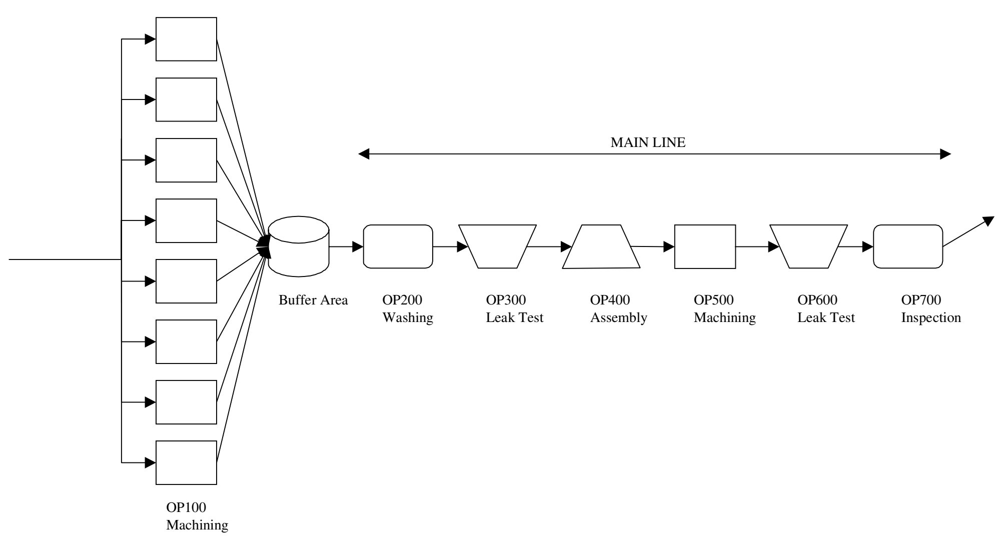

Figure 2 Diagram of Proposed Production System

3 Project Goals and Performance Metrics

The goals of this project were the assessment of the system relative to performance metrics and identification of the most cost-effective ways to improve system performance. The two most fundamental metrics were throughput, measured in jobs per hour (JPH), and average work-in-process (WIP), the number of components in the production system. Both metrics were readily available from each simulation run. Process engineers were keenly interested in discovering revisions to the system capable of reducing the inevitably positive correlation between these two performance metrics; i.e., achieving significant increases in JPH with only minor increases in WIP.

4 Collection and Approximation of Data

4.1 Existing Production System

Pertinent data for the existing production system were readily available. The operation cycle times and transfer times between machines were obtained from equipment specifications and verified with direct traditional motion and time studies [12]. However, downtime data were not directly available. Therefore, workers with direct line and production experience were asked to specify shortest plausible, most typical, and longest plausible repair times and times between failures. This preliminary approach to modeling downtime works tolerably well in the absence of ample historical data [13].

4.2 Proposed Production System

The collection of data for the proposed production system was approached differently. The operation cycle times for the main line in the existing and proposed systems remained nominally the same, based on preliminary conversations with equipment vendors. However, partly because these cycle times predicted by vendors were tentative and volatile, and primarily because the process engineers were highly interested in performance metric responses to plausible changes in these cycle times, the model users were provided menus for exploring the effects of various cycle times easily. Such detailed exploration of system sensitivity to changes in specification ("sensitivity analysis") is readily undertaken via design of experiments (DOE) [14].

5 Construction, Verification, and Validation of Models

Before the actual construction of the simulation models, all assumptions were explicitly listed, and the plant engineers and simulation analysts agreed upon them. Explicit acknowledgment and documentation of these assumptions is essential to simulation project success [15]. In this project, the following assumptions were:

- Downtimes and repair times are well approximated by triangular distributions
- Each workstation in the main line has a capacity of one component
- Operators are always available for machine repair, without reference to shift patterns
- Finished parts always leave the main line without hindrance or blockage
- Raw material is infinitely available (no starvation at the upstream system-environment interface point)
- There is no downtime involving workstation-to-workstation transfer; i.e., material-handling equipment experiences no downtime.

Three models were developed, two base models and one alternative model. The models were developed using ProModel®, a simulation software tool combining high analytical power, easy access to animation capability, excellent support, and the ability to construct a run-time user interface [16]. These and other considerations guiding choice of simulation software tool are summarized in [17]. All models were tailored to the client to answer "what if" scenarios using macros to initialize and change system parameters. This interface allowed the client to interact with the model to analyze whether the model correlates to the real world system by comparing the performance metrics of the systems. Significantly, using this technique allowed faster verification and validation of the model, thereby increasing its credibility – the willingness of engineers and managers to trust model output as guidance in making decisions involving economic risk [18]. The macros allowed the client to change the buffer capacity, mean times between failures (MTBF), mean times to repair (MTTR), number of operators on call, the number of workstations in operation at the new operation 100, and whether a specified machine experiences downtime.

The first base model was a replication of the existing system without variation (i.e., downtime). Omission of all stochastic variability from this first model permitted direct closed-form analytical validation [19], thereby increasing the model's credibility. The second base model added stochastic variation, consisting of unscheduled downtime, number of operators, and available buffer sizes. The third, alternative, model, representing the potential modifications to the productions system mentioned earlier, was likewise developed to include stochastic variability and to allow ease of experimentation.

Several techniques were used to verify these models (confirming their execution matches the analysts' intentions) and validate them (confirm their output is believable and representative of the real system under study) [20]. These technique included structured walkthroughs of model logic, use of stepwise execution and traces, and extensive interviews among the model builders and process engineers most familiar with the real system [21]. These verifications and validation techniques are a necessary component of high-quality manufacturing simulation practice [22].

6 Analysis of Results

Since this is a steady-state system, a warm-up period, chosen to be ten hours, was necessary to eliminate initial bias [23]. Following this warm-up period, all replications were run for an equivalent of 100 hours of production. Typically, between five and ten replications were required to construct suitably narrow confidence intervals for the key system performance metrics. The tables below (Tables 1 and 2), based on ten replications each, present the simulation results from the existing system (including stochastic variation) and the proposed system respectively.

Cycle time (min) upstream of main line	Balanced Main Line	3.5 cycle time (OP 60) within main line
20	1890	1482
30	1338	1327
40	1034	1020
50	848	846

Table 1 Existing Production System JPH

	1 Buffer		4 Buffers	
Cycle Time (min) upstream of main line	**Balanced**	**3.5 cycle time (OP 60)**	**Balanced**	**3.5 cycle time (OP 60)**
20	2061	1511	2082	1511
30	1435	1412	1482	1437
40	1106	1092	1142	1130
50	899	894	925	922

Table 2 Proposed Production System JPH

As mentioned above, introduction of the buffer areas attempted to increase throughput of the component by "working-around" the shortfall of a transfer line. Use of simulation suggested that throughput from the line could be improved with the introduction of additional and/or larger buffers between certain workstations on the line. These inferences were corroborated by theoretical work in which hypothetical transfer lines were mathematically modeled as continuous flow processes [24]. Since increases in buffer capacity characteristically entail an increase in work-in-process, the model outputs were examined in the context of economic tradeoffs between JPH and WIP. Derivatively, increases in buffer size typically entail, from the facility layout point of view, increasing the overall floor space required to accommodate the process. Therefore, the simulation results were also examined in the context of how best to increase JPH with only small WIP increases. Much of this exploration involved investigating which workstations would provide the greatest such improvement in return for investments made in increasing MTBF and/or decreasing MTTR. In the context of this study, the capital investment required to balance the line (versus allowing OP 60 to require more time) proved itself amply justified. Furthermore, the average 2¼% improvement in throughput [JPH] attainable by implementation of four buffers also produced a favorable rate of return relative to the consequential moderate increase in floor space and the slight increase in WIP involved. Further exploration involved study of centralized versus decentralized storage of WIP; this decision is well recognized as a frequent key determinant of production efficiency [25].

7 Conclusions And Indications For Further Work

Plans under development call for the migration of this production system to a cellular manufacturing configuration. The application of cellular manufacturing, a "divide and conquer" strategy of grouping machines, processes, and people into workcells with largely homogeneous responsibilities, holds much promise for significant improvements in efficiency [26]. Challenges of modeling and analyzing such cellular manufacturing systems are severe, and may call for the development of approximate analytical, "closed-form" numeric models in conjunction with discrete process simulation stochastic models [27].

More broadly, as a result of productivity improvements attributable to this project, simulation has achieved acceptance among a succession of process engineers as an analytical tool to be routinely used in conjunction with layout analysis, scheduling, time-and-motion studies, and traditional heuristics guiding process design and implementation. It is via "trial by application" that simulation must gradually, yet convincingly, earn acceptance as a manufacturing productivity improvement tool [28].

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Appendix: Trademarks

ProModel is a registered trademark of PROMODEL Corporation.

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Edward J. Williams holds bachelor's and master's degrees in mathematics (Michigan State University, 1967; University of Wisconsin, 1968). From 1969 to 1971, he did statistical programming and analysis of biomedical data at Walter Reed Army Hospital, Washington, D.C. He joined Ford in 1972, where he works as a computer software analyst supporting statistical and simulation software. Since 1980, he has taught evening classes at the University of Michigan, including undergraduate and graduate statistics classes and undergraduate and graduate simulation classes using GPSS/H™, SLAM II™, or SIMAN™. He is a member of the Association for Computing Machinery [ACM] and its Special Interest Group in Simulation [SIGSIM], the Institute of Electrical and Electronics Engineers [IEEE], the Institute of Industrial Engineers [IIE], the Society for Computer Simulation [SCS], the Society of Manufacturing Engineers [SME], and the American Statistical Association [ASA]. He serves on the editorial board of the *International Journal of Industrial Engineering – Applications and Practice*.