SIMULATION HELPS ASSESS AND INCREASE AIRPLANE MANUFACTURING CAPACITY

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ABSTRACT

Simulation has long been used in the manufacturing industry to help determine, and suggest ways of increasing, production capacity under a variety of scenarios. Indeed, historically, this economic sector was the first to make extensive use of simulation. Over the last several decades, and continuing today, the most numerous applications of simulation to manufacturing operations involve mass production facilities such as those fabricating motor vehicles or home appliances. Less frequently, but very usefully, simulation has been applied to customized manufacturing or fabrication applications, such as the building of ships to individualized specifications. In the case study described in this paper, simulation was successfully applied, in synergy with other techniques of industrial engineering, to assess and increase the throughput capacity of a manufacturer of custom-built personal jet airplanes with a four-to-six passenger (plus moderate amounts of luggage) carrying capacity.

Keywords: Manufacturing, "job shop," customization, capacity planning, discrete-event simulation, bottleneck analysis

1. INTRODUCTION

Very likely, the most long-standing user of simulation, as distinguished by economic sector, is the manufacturing sector (Miller and Pegden 2000). Within this sector, simulation analysis helps production and industrial engineers (and their managers) assess and improve production capacity, identify and ameliorate bottlenecks, improve deployment of resources (whether labor, equipment, or both), and hence strengthen a company's economic performance (Harrell and Tumay 1995). Frequently, these applications of simulation analyze a mass-production process, such as those producing automobiles or home appliances. Such processes are typically high-volume, have largely linear flow, and have a relatively low ratio of workers to machines. Somewhat less frequently, simulation analysis is applied to "job-shop" manufacturing, which typically involves a lower volume of production, with markedly higher cost and price per unit, directed toward often customized requests. Such manufacturing systems typically have more, and more highly skilled, workers relative to machines and equipment (El Wakil 2002). In view of the lower number of units produced and their higher prices and cost, each unit is "high stakes," meriting careful attention to work flow, buffer capacities, and buffer placements to streamline workflow and minimize total process time (Heragu 2008). Various examples of "job shop" simulation appear in the literature. Implementation of an application to model the custom production of trains (general, fast, freight, etc.) is discussed in (Lian and Van Landeghem 2002); significantly, this analysis combines value stream mapping with simulation. The application of simulation to design-build construction projects is discussed in (Orsoni and Karadimas 2006). The expansion plan of a marine container terminal, incorporating production of custom equipments to be installed therein, is discussed in (Ambrosino and Tànfani 2009).

In the study described here, discrete-event process simulation was successfully applied to the paint-shop processes involved in the manufacture of custom-built jet airplanes for personal and corporate use. Such airplanes are a publicly inconspicuous but economically and logistically important part of the overall aviation infrastructure (McCartney 2011). The manufacturing company aspired, in view of trends indicating increasing order volume, to produce two or even three airplanes per day, yet initially was unable to produce 1½ airplanes on average per day. Since the painting operation was already known to be a painfully obvious bottleneck, simulation analysis was concentrated on it, and coupled synergistically with other industrial engineering techniques such as value stream mapping, layout analysis, and lean manufacturing.

2. OVERVIEW OF PAINTING PROCESSES

The airplane manufacturing facility comprises three large buildings, and the painting processes occupy all of the intermediate (in the process flow sense) building. This building, in turn, is divided into four major "positions." Position 1 handles preparatory work: body work, washing, chemical coating, and thermal baking (hardening) of the chemical coating. Position 2 handles the vast majority of the actual painting: wrapping, spraying the primer coat, two consecutive sprayings of the top coat (to achieve durability and opacity), and thermal baking of these three coats. Position 3 handles the painting of custom-ordered markings, such as signature stripes and corporate logos, on the airplane. The work done in this position is labor-intensive due to the necessity of frequently applying and then removing masking tape. Each of these first three positions involves work done in either of two parallel floor spaces within this building. Position 4 handles final detailing, cleaning and varnishing, and painting the airplane door and its frame. This basic work flow is shown in Figure 1, Appendix.

3. OBJECTIVES DEFINITION AND MODEL DEVELOPMENT

3.1 Setting Objectives and Scope

The project charter specified that the consultants (1) examine the overall process flow to determine the maximum number of planes per day (two? three?) given the current painting facility "footprint" (overall square meters and building cross-section) as a binding constraint, and (2) use simulation and allied techniques to suggest revisions to the painting process to achieve that maximum. Value stream mapping and time studies, conducted before the simulation model-building effort began, soon convinced both the consultants and the client managers that "two planes per day" would plausibly be achievable but "three planes per day" would not be. Given this firm and well-defined foundation for the simulation portion of the study, the consultants undertook the design and construction of the base-case simulation model. Much of the input data needed for this model, such as cycle times, worker requirements, buffer capacities, and transfer times for airplanes between workstations, had just been collected during the value stream mapping and time studies. Indeed, the "double use" of these data is one of many strong justifications for using simulation synergistically with other industrial engineering analysis methods (Chung 2004). All additional data needed was collected during a two-month period whose final two weeks coincided with the base model development described in the next section. As the construction of the base case model began, client and consultant engineers brainstormed promising modifications of the current system.

3.2 Choice of Software

The clients and the consultants concurred on the use of the WITNESS® simulation software for model development. This software provides convenient high-quality animation, logical support for both "pull" and "push" operational logic, the ability to build reusable sub-models, and a powerful "labor" construct capable of modeling operationally complex rules for the deployment and transit of both laborers and portable pieces of equipment (Mehta and Rawles 1999). A small, vivid, and typical example of WITNESS® flexibility appears in the following "output rule" (a rule specifying whether, to where, and when a machine sends an entity [here, an airplane] which has just finished processing at that machine:

```
IF vPaint_02_Done = 0
 PUSH to PAINT_02_1
ELSE
 Wait
ENDIF
```

This output rule relies on the current value of the variable vPaint_02 to decide whether to send the airplane downstream (in this case, to machine PAINT_02_1) or to hold the airplane at its current location until the variable becomes equal to zero.

WITNESS® also provides automatic collection and graphical display of system metrics such as minimum, average, and maximum queue lengths, number of cycles undertaken by each machine, utilization of each labor resource, and total entities throughput.

The animation layout constructed within the WITNESS® simulation model is shown in Figure 2 in the Appendix.

3.3 Choice of Stochastic Distributions

Arrival of WITNESS® "parts" (planes) to the model was based on historical records of planes leaving the upstream operation. Historical time-to-fail (or number-of-cycles-to-fail) and time-to-repair data were entered into a distribution fitter, ExpertFit® (Law and McComas 2003) to determine suitable closed-form distributions (if indeed, such existed) using techniques such as Kolmogorov-Smirnov and Anderson-Darling goodness of fit tests for maximum-likelihood estimators (Leemis 2004). As examples of these data, the paint booths routinely require a filter change every thirty airplanes on average, with out-of-service time averaging eight hours. Similarly, the preparation booths routinely require a filter change every twenty airplanes on average, with out-of-service time averaging four hours. Routine preventative maintenance lasting four hours on average is done at the paint booths weekly. Major equipment breakdowns, lasting an average of three days, occur on average every three months at paint booths and once a year at preparation booths. With few exceptions, times-to-fail were modeled with exponential or Weibull distributions, and times-to-repair were modeled with gamma (of which the Erlang is a special case), Weibull, or log-normal distributions.

3.4 Model Development Timing

Setting of the objectives and construction of the base case (reflective of the current system) model required two calendar weeks and three person-weeks. During those two weeks one simulation analyst worked on the model full time and another contributed additional work on the model part time.

4. MODEL VERIFICATION AND VALIDATION

4.1 Documentation of Assumptions

As data collection efforts drew to a close, the clients and the analysts agreed upon and documented the following assumptions pertinent to building the model of the base case system:

1. Planes are always available from upstream to be painted (consistent with the long-standing recognition that the paint shop was the bottleneck *blocking* upstream processes).
2. No downstream blocking occurs relative to planes leaving the painting operations (consistent with the long-standing recognition that the paint shop was the bottleneck *starving* downstream processes).
3. Labor resources are not the constraint (consistent with anecdotal evidence, and also with the observation that – contrary to many manufacturing contexts – in this context, capital equipment is more expensive and harder to obtain than the relatively unskilled labor needed for various operations [e.g., the application and removal of masking tape mentioned above]).
4. Equipment preventive maintenance and unscheduled downtime data are still valid as provided from historical data.

4.2 Verification, Validation, and Credibility

Early in the project, even the most casual observations of the painting process convinced both clients and consultants that the system was conceptually steady-state (indeed, some queues were *never* observed empty). As initial settings for verification and validation of the base model, warm-up time was set to one month and run time (with gathering of performance statistics) to one year. Typical techniques were then used for model verification and validation. As a fundamental basis for initial high-level verification and validation, the “observed” versus “estimated” collective cycle times for each of the four positions (shown in Figure 1, Appendix) were examined for reasonably close agreement. These methods included running the model with all variability eliminated for easy checking against spreadsheet computations, running one entity through the model. Structured walkthroughs held by the two modelers and their technical leader, careful examination of the animation, extreme condition tests, and discussion of plausibility of preliminary results with the client’s process engineers (including Turing tests) all proved useful to the tasks of verification and validation (Sargent 2004). After routine errors (e.g., mismatched variable names) were found and corrected, the analysts graphed performance metrics of the base model against simulated time. These graphs demonstrated that accurate determination of performance metrics, with sufficiently narrow 95% confidence intervals required increasing the warm-up length to two months and the run length to two years of simulated time, with 10 replications for each situation to be examined. Note that even with a two-year statistics-gathering run length, on average only only two major equipment breakdowns will occur at preparation booths. The usual analytical recommendation is that the most unusual event in a system be expected to occur five or six times during each replication (Law 2004). As a countermeasure, with replication length already two years, the analysts checked that several different but representative numbers of these breakdowns occurred among the replications – an approach conceptually akin to stratified sampling. Next, the model achieved credibility with the client engineers and managers by predicting currently observed performance metrics within 4%.

5. RESULTS AND IMPROVEMENTS

In agreement with current observation, the base case model indicated average production of 1.45 planes per day – and also correctly indicated severe blocking (19% of time each paint booth blocked) just downstream from both paint booths (the key operations in Position 2) and hence just upstream from the detailing operation of Position 3. Meanwhile, results of layout analysis had suggested workflow enhancements, *not* involving capital expenditure, having the potential to create buffer space for at least one plane, maybe two, between the pair of paint booths and the detailing operation. Accordingly, the first two alternative scenarios modeled introduced an as yet hypothetical buffer at this point. Introducing this buffer into the model required less than ½ day of modeling time. Setting the buffer capacity to 1 yielded average production of 1.64 planes per day, with paint booth blocked time reduced from 19% to 9%. Increasing the buffer capacity to 2 yielded average production of 1.75 planes per day, with paint booth blocked time further reduced to 4%.

Next, the collaborating engineers (consultants and clients) turned their attention to the possibility of adding a second paint-detailing station within Position 3. This modification to the model was similarly added, verified, and validated for reasonableness of results within one day. However, its results proved disappointing, especially considering that a second detailing station represented significant capital and operating expense. Indeed, this addition did reduce blocked time at both upstream booths to less than 2%. However, the key performance metric “average planes per day” increased to only 1.81 from 1.75.

6. CONCLUSIONS

The client’s engineers promptly implemented the workflow enhancements suggested by the layout analysis, and concurrently created and used a buffer of capacity 2 between the paint booths and detailing operations. The key performance metric “average planes per day” promptly increased from 1.45 to 1.74, an increase of 20% with no capital investment required. Blocked time at the paint booths also decreased as predicted by the simulation study. Although most welcome, this throughput increase fell short of the "two planes per day" aspirations. Therefore, client and consultant engineers agreed upon follow-up studies, now in progress. These studies are investigating these throughput improvement opportunities:

Standardization of various operations to minimize variability of time required.

Workplace organization and visual controls, partly to manage inventories of paint and partly to minimize wasted time ("muda") searching for tools.

Development of templates for setup of striping operations (part of detailing) to minimize detailing time; this suggestion came from a client engineer familiar with the practice of "SMED" [Single Minute Exchange of Die] as practiced in many manufacturing industries and pioneered by the Japanese engineer Shigeo Shingo (Collier and Evans 2007).

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MARCELO ZOTTOLO, born in Buenos Aires, Argentina, came to the United States to finish his college studies. He was graduated from the University of Michigan - Dearborn as an Industrial and Systems Engineer in December 2000, and subsequently earned his master's degree in the same field in June 2004. He was awarded the Class Honors distinction and his Senior Design Project was nominated for the Senior Design Competition 2001. This project studied the improvement of manufacturing processes for the fabrication of automotive wire harnesses, ultimately proposing an automation tool leading to improvements in future designs. Additionally, he was co-author of a paper on simulation in a distribution system which earned a "best paper" award at the Harbour, Maritime, and Simulation Logistics conference held in Marseille, France, in 2001. He is now a Consulting Project Manager at PMC with a solid background in data-driven process improvement methodologies to optimize the performance of different systems. He is experienced in the concurrent application of lean thinking, theory of constraints, workflow measurement, and simulation modeling across multiple economic sectors including retail, service, healthcare, insurance, and manufacturing. His responsibilities include leading teams in building, verifying, validating, and analyzing simulation models in Enterprise Dynamics®, WITNESS®, ProModel®, and SIMUL8® for large corporate clients; he also presents in-house training seminars. His email address is mzottolo@pmcorp.com

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APPENDIX

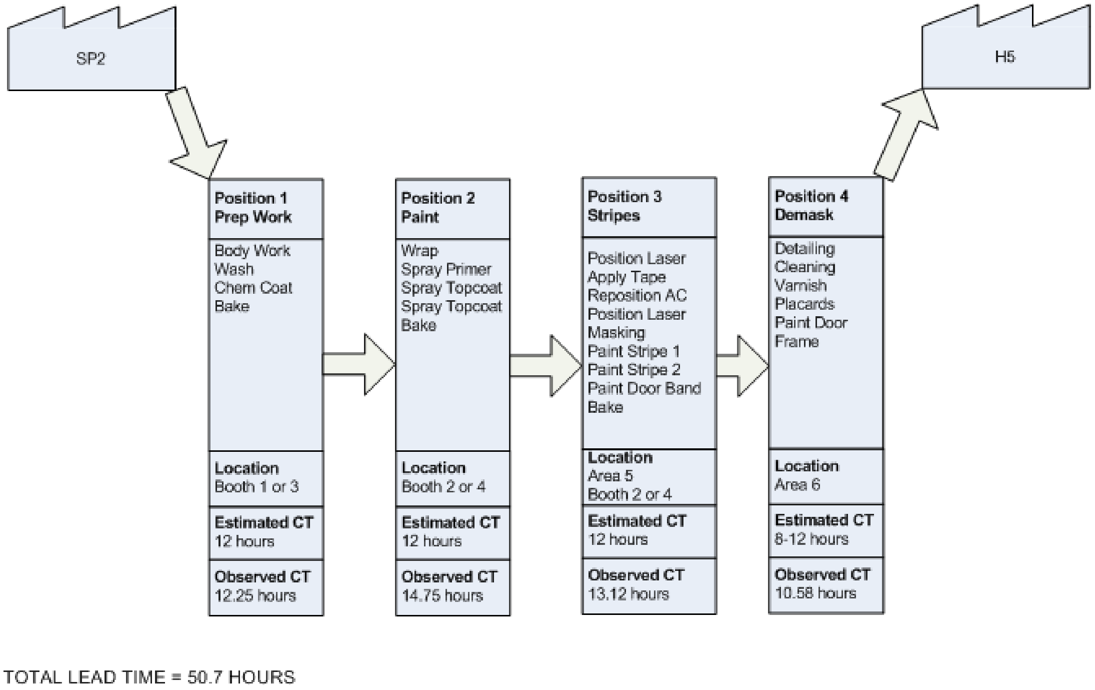

Figure 1: Overview of Work Flow

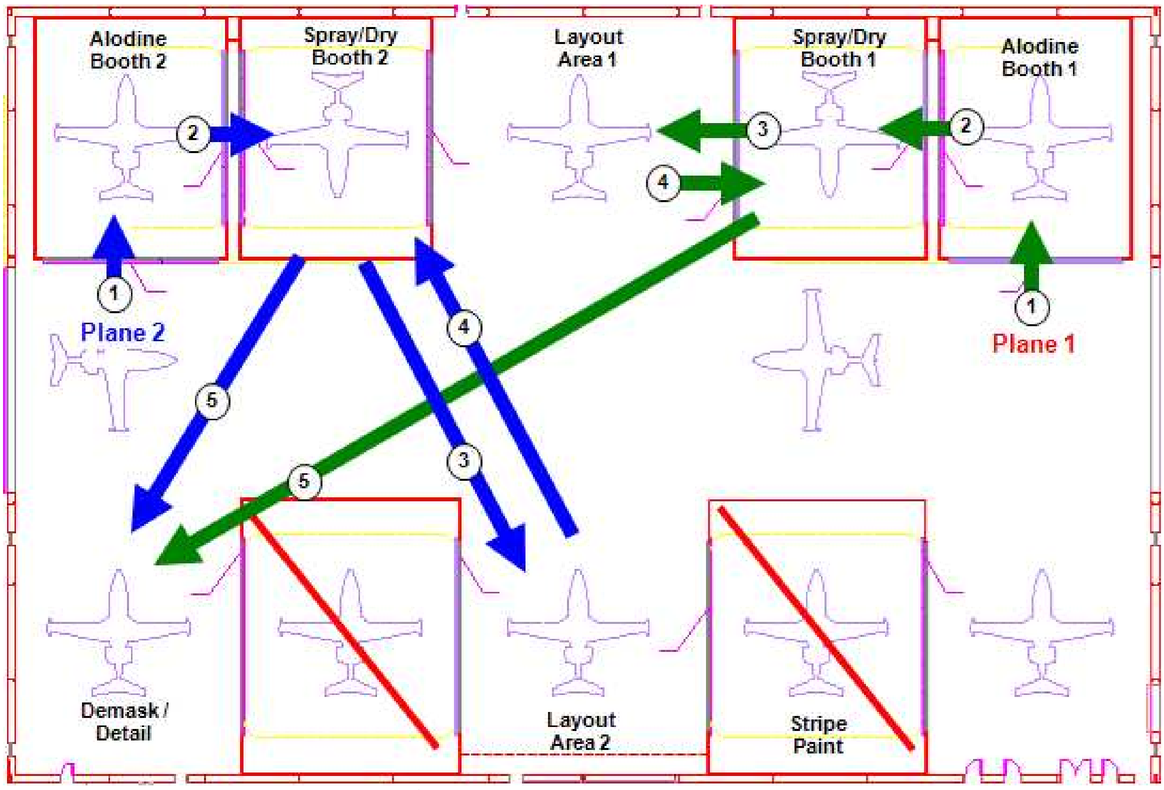

Figure 2: Abstraction of Work Flow Used in WITNESS® Simulation/Animation