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INTERFACING SIMULATION WITH COSTING SOFTWARE TO DRIVE THE TRANSFORMATION FROM PROTOTYPE MANUFACTURING TO HIGH VOLUME MANUFACTURING

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ABSTRACT

Often companies are faced with the situation of “ramping-up” production of a new product. Although this may seem like it should be a simple task, making the transition from a manufacturing environment that makes small volumes of some product well to an environment that must make large volumes well entails many decisions regarding equipment, scheduling and control and manufacturing philosophy. Many factors influence these decisions, including the need to meet production volume goals and costs associated with achieving these goals. This paper will discuss how discrete event simulation data can be interfaced with a costing software package to guide manufacturing line design decisions in a company transitioning from small volume, job-shop like manufacturing of a product to larger production run volume manufacturing.

1 MOTIVATION

Products that are complex and intricately designed are often initially produced in a prototype, low-volume mode. This is especially true if the end product is very costly. The idea is to try to perfect each manufacturing process step, e.g. improve yield rates, change specific types of equipment, etc., while running low volumes such that the impact of making a system modification that adversely affects performance is minimized. Theoretically, it should be a simple procedure to then move from the low-volume prototype production to high-volume production by simply adding equipment and labor. However, the transition is much more complex.

At high volumes, some problems may emerge that were not apparent in the low-volume case. For example, material handling activities may become constraining bottlenecks due to longer transport times with increased size of the facility and increased demand for handling. Completely different material handling equipment might be needed. Also, utilization of the resources may increase to the point that system variability, which was not an issue at utilization of 50%, begins to adversely affect system performance. Where work in process is rarely a problem in low-volume production, higher volumes often mean more congestion and longer queues, resulting in high work in process costs, floor space considerations and longer part flowtime. These are important considerations for any company ramping-up production. For the system considered in this paper, there is an additional key consideration of minimizing cost per part.

Lockheed Martin Government Electronic Systems (LM-GES) is developing the capability for high-volume manufacturing of high density interconnect (HDI) modules. This is an integral part of a larger Navy Manufacturing Technology (MANTECH) program to build phased array radar transmit/receive (T/R) modules. The HDI modules are a component in the larger T/R modules. With increased pressure from Congress and the public to bring Defense costs down, a primary goal of this project is to be cost effective with HDI manufacturing, not just to meet production volume goals.

Simulation has long been used as a system design tool, since it offers the opportunity to investigate many system alterations before large capital investments are made. Often, potential changes in system design are based upon performance measures such as queue lengths, flowtimes or due date targets. However, the simulation model described in this paper will be used to link some of these common system performance measures with system costs to provide a cost-driven decision tool for the design of the high-volume facility.

2 ENVIRONMENT

The manufacturing environment for the HDI module is similar to other electronic manufacturing environments. Processing can be thought of as a series of 'processing modules' with each module containing several processing steps. Parts moving through the system then repeat these modules as needed to create the several layers that comprise the end product. Also, processing is done in a clean room type environment.

Currently, LM-GES has a prototype facility for HDI manufacturing. The simulation models described here used flow and processing time data from this prototype facility. The Navy MANTECH program is sponsoring several parallel tasks that are focused at improving individual HDI process steps. As these improvements are realized, the simulation models will be updated accordingly, and will be used to assist in the design of the high volume HDI facility.

The manufacturing line will be dedicated to this one product. There is a very small amount of rework throughout the system and some scrap. Processing that occurs on equipment has very stable processing time (i.e. little or no variability). However, some steps are labor intensive with some associated processing time variability. All laborers are capable of performing general purpose tasks. In addition, there are some steps that require specialized skills. Each laborer is capable of performing at least one specialized skill in addition to general purpose tasks.

As previously mentioned, costs are very important considerations. The main performance measure that will drive system design decisions is total cost per part. Total cost of any product is the sum of many other costs, which are discussed in the next section.

3 COST CONSIDERATIONS

Costing estimating for projects is not a new concept in the defense industry. In fact, cost estimating software packages exist that are used to report costs for auditing and proposal purposes. One such package is the Envision™ MCM Cost Modeling Program. This software was written by The Dow Chemical Company and distributed and supported by TechSearch International, Inc. (Dow 1995) Typical input for these cost packages includes process steps, mean processing time, equipment, material, labor used and projected utilization and yields. While Envision™ is used by LM-GES to estimate how many pieces of equipment and how much labor are needed as a minimum to produce a given number of parts per day, it is limited in its ability to report true operational costs. For example, the cost package does not include processing time variability, competition for scarce resources or accurate material handling considerations. Although a total cost and cost per part are reported, the package lacked the capability to provide more detailed data regarding system performance that would help design the high-volume manufacturing facility.

Discrete event computer simulation was identified as a tool that could provide modeling capabilities to include processing variability, material handling and competition for resources in a more detailed and more accurate system analysis. Many operational system performance measures of interest could be reported, such as flowtimes, tardiness and work in process. However, the simulation outputs must be coupled with appropriately detailed costs to truly allow for system design to be driven by cost per part. LM-GES partnered with the Manufacturing Systems Division at the Applied Research Laboratory (ARL) at Penn State University to approach this problem.

Initially, an extensive interface between Envision™ cost estimating software and the simulation model was anticipated. However, it was determined that the more detailed and extensive simulation output could be used more effectively if it became the input to a spreadsheet containing cost equations specifically developed for this application. The existing cost estimating software was used, however, to get an initial estimate of pieces of equipment, number of laborers and so forth as input to a baseline simulation model.

Total cost of manufacturing a product is comprised of many different costs. The particular costs chosen for the model described here are believed to capture the vast majority of the system costs as well as being costs of high interest or visibility. The cost categories used were work in process, labor, scrap and tardiness penalty. For proprietary reasons, the actual costs can not be reported in this paper. However, the methodology regarding how to calculate the costs is accurate.

Work in process (WIP) costs were calculated based upon the number of layers in the product. The estimated final cost of the end product was taken from Envision™ output. It was assumed that when the parts are beginning to be processed they contain 50% of their final costs. Each additional layer adds 10% more value. A holding cost rate of 30% was used (Sipper and Bulfin 1997).

For the analysis presented here, one hundred lots entered the system and the analysis period ended when all 100 lots were completed. The length of the simulation run represents the cycle time (or makespan) from the start of processing of the first lot until the end of processing of the 100^{th} lot. Labor costs were calculated by taking the length of the simulation run converted to hours and multiplying by the number of workers and an hourly labor rate. This was possible because there is only one labor grade for this facility. Also, since this is a dedicated line, all labor time while the facility is running is charged to this product, even though laborers are idle part of the time. In other words, workers are paid for 8 hours per day regardless of how much of that time is spent in value added activities.

Scrap was calculated by taking the number of scrap parts and multiplying by a cost estimate based on Envision™ output. The tardiness penalty assumed in this paper was $30,000 per lot. This large value reflects the importance of this component in the final assembly that it feeds.

4 MODELING AND ANALYSIS

This section describes the simulation model developed for this project and goes through a sample system design analysis.

4.1 The Simulation Model

A model of this system was created using Arena™ Professional Edition Version 3.01 (Systems Modeling 1996). Because this model was to allow for layout experimentation by changing various system parameters, input parameters were assigned variable names. Time was devoted early in the project to identify the system parameters that might logically be changed and to develop a logical naming scheme. Processing times, resource capacities and laborer skills were entered as variable names that identified the particular resource and process step. Having these model input variables all together in one location offers flexibility when doing "what if" analysis for designing the system. When a new system scenario is being considered, the analyst simply goes to the variable list to make a change in a parameter value rather than searching through the entire model.

The model was organized into 'processing modules' with each module containing several processing steps to parallel the way LM-GES thinks about the physical system. These process modules are repeated as needed to build up several layers. So, entities may loop back through all the steps in a module more than once. There is also some entity looping due to a small rework percentage. There are approximately 400 processing steps organized into 20 modules.

As mentioned in the previous section, all runs for this analysis represent 100 lots being processed. Setting a fixed number of lots to be processed allows quick assessment of cycle time changes and it is consistent with the way LM-GES currently tracks system performance measures.

To enable calculation of the costs described in the previous section, several specific performance measures were collected and transferred into an Excel operational cost estimating file developed specifically for this project. First, work in process was reported by layer. Second, the simulation run length was needed to calculate labor costs. Third, two different types of scraps were tracked and reported representing scrap of one section of the part and scrap of the entire part. Finally, the number of tardy lots was reported. Although the due date setting process is somewhat negotiable between vendor and customer, due date was set in this analysis using a total work flow allowance (Baker 1995). Specifically, the due date was set to the ready time plus 2.25 times the total of mean processing times for all processing steps.

4.2 Analysis

As previously mentioned in Section 3, actual costs can not be reported in this paper due to proprietary reasons. What is presented here, however, is a methodology to couple simulation output data with specific operational costs and a sample analysis to illustrate how the costs might drive system design decisions. Also, investment in equipment for the initial design was assumed to be a sunk cost of doing business and not directly included in the cost per part calculation. However, alternative designs that require additional equipment should have that incremental equipment investment directly included in the cost per part calculation. Similarly, implementation costs of design changes (e.g. cost to physically move equipment) should also be directly included in the cost per part calculation. Next, a sample analysis is presented illustrating a series of changes made to the model by evaluating the outputs after each run. The key driver is cost per part.

Table 1 summarizes operational costs calculated in the Excel spreadsheet for different system designs. A dollar value for different cost components, total cost and total cost per part are reported along with percentage of final cost for each component. By analyzing both the cost per part and how much each component cost contributes to that cost in both straight dollars and as a percent of total cost, an informed choice can be made regarding what system design change to try next. The simulation data used in the calculations was taken from an average of 10 replications.

The simulation was first run using an initial estimate of pieces of equipment, number of laborers and so forth from Envision™, with orders for all 100 lots released to the floor at time 0 (start of the simulation). Scenario 1 of Table 1 shows the resulting data for this system design. The largest component of total cost is labor at almost $500,000 or 51%. WIP and Tardiness penalty each represent about one-quarter of the total costs. The small contribution of scrap to the costs represents the small percentage of quality problems in this system, resulting in high yield. However, for some alternate designs or other systems in electronics manufacturing, scrap may be more significant.

A "greedy heuristic" mentality was used to pursue system design changes that had zero or little implementation cost. One such change that required no implementation cost was a new order release strategy that attempted to reduce both WIP costs and tardiness penalty.

Table 1. Summary of Operational Costs for Alternative System Designs

Cost Category	Scenario 1 Initial System Design			Scenario 2 Interarrival time = 500 minutes			Scenario 3 Interarrival time = 1000 minutes			Scenario 4 Interarrival time = 1500 minutes		
	Perf. Measure Value	Cost ($)	% of total cost	Perf. Measure Value	Cost ($)	% of total cost	Perf. Measure Value	Cost ($)	% of total cost	Perf. Measure Value	Cost ($)	% of total cost
WIP	82 lots	225,049	23	73 lots	189,118	23	69 lots	178,540	22	64	169,697	21
Labor	67,654 minutes	498,283	51	66,045 minutes	486,432	58	65,238 minutes	480,489	61	66,253 minutes	487,964	60
Scrap	12	8,000	1	6 lots	3600	.1	6	5,200	1	13	8,600	1
Tardiness Penalty	8.5 lots	255,000	25	5.25 lots	157,500	19	4.25	127,500	16	4.75	142,500	18
Total Cost		986,332			836,651			791,729			808,761	
Cost/part (% reduction from Scenario 1)		-			15			20			18	

Cost Category	Scenario 5 Interarrival time = 1000 minutes, one less worker			Scenario 6 Interarrival time = 1000 minutes, 2 skills per worker			Scenario 7 Interarrival time = 1000 minutes, added equipment		
	Perf. Measure Value	Cost ($)	% of total cost	Perf. Measure Value	Cost ($)	% of total cost	Perf. Measure Value	Cost ($)	% of total cost
WIP	70	187,309	22	70	184,352	21	72	182,556	27
Labor	67,764 min	42,7794	51	66,298	488,296	57	60,109	442,713	66
Scrap	12	8,000	1	13	8,600	1	12	8,000	1
Tardiness Penalty	7.25	217,500	26	6	180,000	21	1.25	37,500	6
Total Cost		840,603			861,248			670,769	
Cost/part (% reduction from Scenario 1)		15			13			32	

To test this, the interarrival rate was incremented by 500 minutes for subsequent trials. However, it was assumed that orders for all 100 lots still arrived at time 0, thus the due date for all 100 lots was still the same. Scenario 2 in Table 1 represents an interarrival time of 500 minutes. Cost per part decreased by 15%. This was due to approximate changes in WIP costs of $36,000 and changes in tardiness penalty of $98,000. Also, cycle time reduced slightly by about 1600 minutes.

Since there was a reduction, interarrival time was increased by 500 to 1000 minutes for Scenario 3. This time the cost per part decreased by 20% from Scenario 1. WIP costs reduced by about $11,000 and tardiness was $30,000 less. As a percentage of total cost, WIP remained about the same across these 3 scenarios (~22%) with labor increasing from 51% to 61% and tardiness decreasing from 26% to 16%.

To achieve more reduction, the interarrival time was increased again to 1500 minutes for Scenario 4. However, cost per part increased as compared to Scenario 3 due to slightly increased cycle time and increased tardiness penalty. Although not reported here, and interarrival times of 2000 and 4000 minutes were also tested with cost per part increasing significantly.

A closer examination of Scenario 3, which had the least cost per part, reveals that labor cost contributes 61% of total cost. The two elements of this cost are cycle time and total number of workers. Further analysis of worker utilization values from the detailed simulation output showed a range of 48%-75%. Reducing the number of workers seems to be a reasonable option due to the relatively low utilization of some workers. Scenario 5 represents the release strategy of interarrival time of 1000 minutes and one less worker. Although there was approximately a 1500 minute increase in cycle time, labor costs reduced by more than $50,000. However, that savings was more than offset by the increase in tardiness penalty of $90000, with a cost per part of 15% that of Scenario 1.

Still searching for inexpensive implementations, a modification to worker capability was made. In the original system each worker could perform general purpose tasks plus 1, 2, or 3 specialized tasks. Scenario 6 limited each worker to being capable of performing general purpose tasks plus only 1 other specialized skill, with interarrival times of 1000 minutes. However, this actually produced an increase of more than $50,000 in tardiness penalty with slight increases in labor cost (due to increased cycle time) and WIP cost.

Going back to the least costly design, Scenario 3, other options for reducing cycle time were considered. Evaluation of the detailed simulation output for equipment utilization and queues showed one piece of equipment with significantly larger utilization and queue. Therefore, adding an additional identical piece of equipment produced Scenario 7. The cost per part decreased by 32% compared to Scenario 1, primarily due to a $90,000 decrease in tardiness and a $38,000 decrease in labor due to reduced cycle time. Although this is a significant improvement in operational costs, the equipment cost must be considered.

Engineering economics concepts can be used to determine the annual equivalent cost of the equipment and divide that by the projected annual production for a per part cost that can be added to the operational per part cost. For example, if we assume this equipment will be in service 3 years with $1000 per year maintenance costs and a 10% interest rate, then up to $300,000 could be invested in this equipment before it equals the per part cost of Scenario 3.

5 CONCLUDING REMARKS

This paper illustrates how discrete event simulation modeling and cost estimating software and calculations can be interfaced to provide appropriate cost data to be used during a system design process. The application was developed as part of a project with Lockheed Martin Government Electronics Systems to assist in moving from prototype manufacturing of HDI modules to high volume production.

Although the particular cost modeling program, simulation model and Excel spreadsheet operational cost calculation are specific to this project, the general methodology is applicable in many instances. First, using the output from a more aggregate cost modeling program to determine an initial system design for the simulation model provides an intelligent starting point rather than something subjective. Also, using information from a program that is already used and accepted by the company improves the buy-in and confidence in the final results. Second, the simulation output used here to calculate operational costs is very common to many simulation packages. Although the particular dollar values used to calculate cost might differ, the simulation output needed (e.g. WIP values) is the same. Third, using a spreadsheet to calculate operational costs gives a user the flexibility to include as many cost calculations as needed and at an appropriate level of detail. Fourth, once the costs are evaluated in the spreadsheet, the user can go back to additional simulation output (e.g. resource utilization) to further guide the system design change process.

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