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SUBSYSTEM DECOMPOSITION IN SIMULATION OF A PCB ASSEMBLY LINE

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ABSTRACT

Simulation modeling of large complex systems is time consuming. In this paper we examine a modeling decomposition approach that would expedite the modeling process. We discuss some of the theoretical and practical problems of decomposition and provide an example found in printed circuit board assembly.

1 INTRODUCTION

Simulation modeling for manufacturing system analysis has long born the reputation of being a slow yet powerful tool. Many companies have found that, while modeling efforts can produce better system designs and operating strategies, the engineering time required to develop models is prohibitively expensive. As a result, there is a driving effort in the simulation community to produce simulation products which are faster to use. Many simulation vendors now market manufacturing simulators which are easier to use than general purpose languages and contain many time saving features. These simulators can significantly speed the modeling process, but often suffer from modeling flexibility restrictions. Recently, simulation researchers have extensively studied object oriented software systems and their promise for speeding the modeling process. While few commercial software packages are yet available, initial research prototypes have shown that such systems could significantly expedite the modeling process. Nevertheless, building models of large and complex systems still requires significant effort and probably always will.

Whereas considerable effort has been expended developing tools which facilitate rapid modeling, far less work has been concentrated on methodologies for improving the modeling process itself. We have observed that many practitioners still seem to believe that full-scale modeling is the best way of approaching many problems. This is not surprising, since developing models which contain only the salient features of a system has long been considered an art (*Morris (1967)*). Simulation texts often contain introductory chapters warning modelers of the pit falls of large and highly detailed models, yet few texts delve into approaches for containing model size and detail. For example, *Pegden, Shannon, and Sadowski (1990)* begin in chapter 1 by warning their readers of over modeling:

> Take the example of a manufacturing facility that consists of 400 machines and that processes 3,000 different parts during a year. The novice might believe that the model must also have 400 machines and run long enough to process 3,000 parts. Not only is this supposition untrue, but it also probably represents the single most common source of simulation study failure.

The warning is real. Large models take so long to develop and validate that they are often abandoned before completion. This is particularly true when a modeling project is undertaken to support the design of a new facility. The modelers often cannot keep up with the design team and thus the model recommendations are not available in time to influence major decisions. Unfortunately few texts contain more than warnings and vague advice.

One time saving scheme that has been proposed by several authors is model decomposition or partitioning. Decomposition refers to the process of breaking a large system down into subsystems and modeling each subsystem independently. *Conway et al. (1990)* describes decomposition as a process of finding natural fault lines. This approach holds much promise, yet again, little is known about how to go about safely breaking large modeling projects into smaller pieces. *Johnson and Lofgren (1992)* report a successful use of subsystem modeling in the planning of a new distribution center. The success of the simulation project was attributed to the use of subsystem models rather than full-scale modeling of the entire facility. By partitioning the system into manageable subsections, the individual models could be developed by different teams, speeding the design process. However, an important question arises in conjunction with the practice of subsystem modeling. The question is whether the sum of subsystems adequately represents the entire system. Or conversely, how does one decompose a large system into subsystems while preserving the effects of interdependence between the subsystems?

In this paper, we examine the problem of partitioning an upstream serial transfer line from a downstream jobshop. This problem is motivated by an example of a printed circuit board assembly system. The first stages of a typical surface mount technology assembly system is shown in Figure 1. Blank boards enter the line at the solder paste machine where a thin layer of paste is applied. The boards are then conveyed into one (or more) component placement machines where the parts are placed onto the boards. After an inspection, the boards pass through an oven where the components are solidified onto the board. Finally, the boards are cleaned to remove flux residues. After this first automated section, the boards may visit a number of manual and semi-automated stations where odd components are added, inspection and rework performed, along with other miscellaneous operations. This section often more closely resembles a jobshop type of environment.

Often when such lines are designed, simulation is used to help in the planning process. Since the automated pick and place machines along with the oven and cleaning machines are very expensive (with costs in the hundreds of thousands), a model of the system is very useful for determining capacity requirements and to look at problems caused by product mix such as the effect of product sequencing policies on machine setup. Later, when the real system is up and running, a model may be used to further analyze daily scheduling. Also a model may be used to develop process improvements for the downstream part of the system and for workforce planning in the more manually intensive portion of the line. The question we address in this paper is can the model of the automated portion of the system be safely decomposed from the manual downstream portion of the system? This would allow models of the upstream and the downstream systems to be developed concurrently by different engineering teams, with each model tailored to the specific objectives of the subsystems. An obvious question concerning such a decomposition is how does the performance of the upstream automated line effect the downstream manual stations.

We begin in Section 2 of this paper by examining some of the theoretical aspects of partitioning two such systems. Next in Section 3, we examine an example of a surface mount PCB assembly line found at Hewlett-Packard. Using data from this shop, we experimentally explore the effects of decomposition. Finally, we conclude in Section 4.

2 SYSTEM DECOMPOSITION

Researchers have studied some aspects related to the partitioning problem. *Conway et al. (1988)* examined the effect of buffers between servers in a serial production line. They found that small buffers placed symmetrically around the servers increase the line throughput. Such buffers between two servers decoupled the servers into two subsystems, allowing the servers to work somewhat independently of each

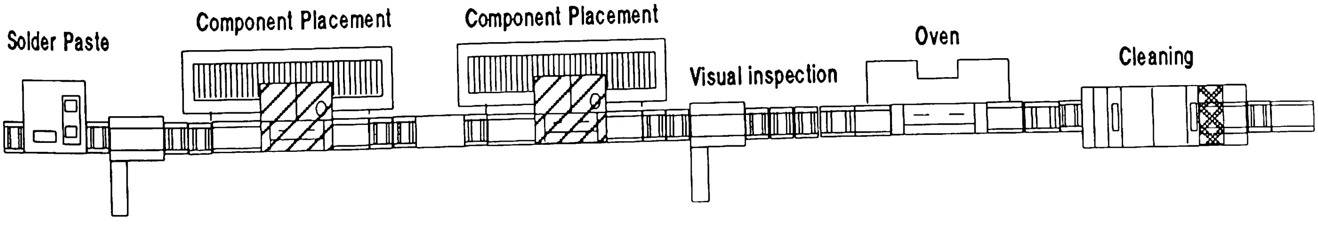

Figure 1: A Typical Surface Mount PCB Assembly Line

other. As *Conway et al. (1990)* later note, if the buffer always has waiting parts, the two servers can be safely decoupled and analyzed independently of each other. For example, if one machine is a known bottleneck, the system can be partitioned at that point. However, outside of this case, far less is known about how large systems can be safely partitioned.

One problem in partitioning a system into two subsystems is the effect of upstream correlation (generated in an upstream subsystem) on the downstream subsystem. In a decomposed system, the departure distribution in one subsystem is the arrival distribution in its succeeding subsystem. Hence, when decomposing a complex system, it does not appear reasonable to assume that the arrival distributions of the subsystems are identically and independently distributed. *Disney and Kiessler (1987)* studied the cross correlation effects on decomposition of a queueing network using a Markov renewal approach. Building on this approach, recent work by *Patuwo et. al. (1990, 1991)* and *Szekli et. al. (1992,1993)* show that positive correlation in the arrival process can significantly increase mean queue lengths and average flow time.

Hendricks (1992) recently studied the output process of tightly coupled serial lines and found the departure times are often negatively correlated. Negative correlation implies that a long period between the exit of a part from the line is often followed by a short period for the next part exit. This negative correlation was most prominent in systems with small buffers between the machines, as is true in the upstream portion of a PCB assembly lines. However, the theoretical system Hendricks examined was a greatly simplified version of a real line where the machines were all assumed to have exponential processing times and the effects of setups, machine failures, and multiple product types were ignored. This finding leads to two interesting questions: Does this negative correlation exist in more realistic systems such as our surface mount line and if it does, what effect does it have? In the following section we consider these two questions using a model of a surface mount line.

3 DECOMPOSING A PCB ASSEMBLY SYSTEM

The PCB line we examine in this section is one of several such lines found at Hewlett-Packard. This particular line manufactures many different types of boards in small lot sizes. During the time this model was constructed, over 150 different boards were being produced in build quantities ranging from 4 to 125 boards every five to eight days. The requirements for each board vary dramatically, making the efficient management of the line challenging. Figure 2 shows the flow of the boards through the entire system. The upstream portion of the system from the solder stencil through cleaning is a tightly coupled serial trans-

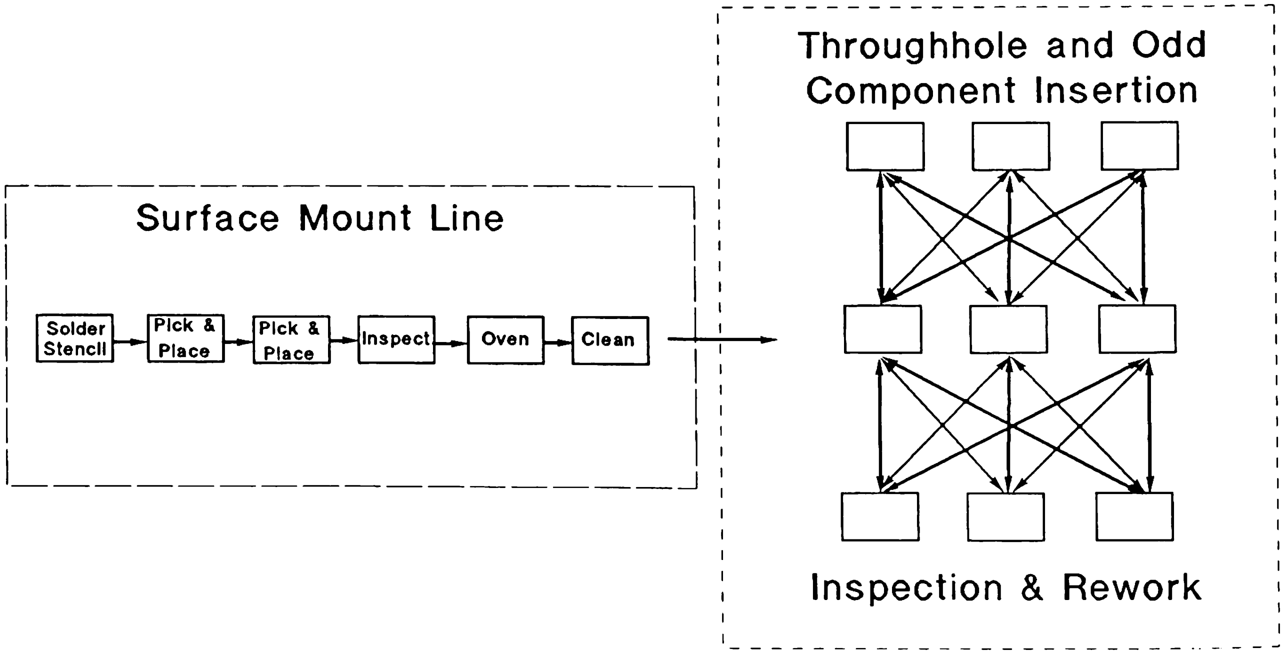

Figure 2: The Flow of Boards Through the PCB Assembly system

fer line, with finite buffers between the machines. In most cases there is room for 2-4 panels between each machine. The downstream portion of the line is less well defined and acts more like a jobshop. The workstations are primarily manual, with different board types visiting different stations.

A model of the upstream subsystem was built to examine capacity requirements and to examine the effect of setup improvements (*Baxter and Johnson (1993)*). This SIMAN model is driven by a build file which contains a list of board types and lot quantities to be produced during the simulation. Between each board type, the upstream portion of the line goes down while the placement machines are loaded with the correct components and the software for the board geometry is downloaded into the machines' memory. The model includes this downtime along with downtime caused by operator error and machine failure (eg. jams and misplacements). Extensive data collection was performed on the real system to provide accurate processing times for each board type along with setup times and repair times. The processing times for the various boards are nearly constant while the setup times, manual inspections, and repair times for the machines were found to be stochastic. In most cases, this randomness was described with uniform or triangular distributions based on the data from the real system.

3.1 Output Process of Upstream Subsystem

Using this model, we first examined the output process of the boards exiting the cleaning station. Interestingly, as *Hendricks (1992)* found for a very simplified serial transfer line, we found that the output process contained a small, but statistically significant, amount of negative correlation. Figure 3 shows a typical histogram of the output process. As may be ascertained from the plot, the time between exits is nearly exponentially distributed with a mean of 9.36 minutes between boards. Using a Kolmogorov-Smirnov goodness-of-fit test, we could not reject the hypothesis that it was exponentially distributed at a 95 percent confidence level. This is interesting in itself, since this part of the line had little processing time variability. More interesting, Figure 4 shows the correlation structure for the first ten lags. Notice that for the first three lags the correlation is negative and then the correlation alternates around zero in a decreasing fashion. Using a test procedure developed by *Fishman (1978)*, we found that the lag 1 correlation was significantly different from zero at the 95 percent confidence level.

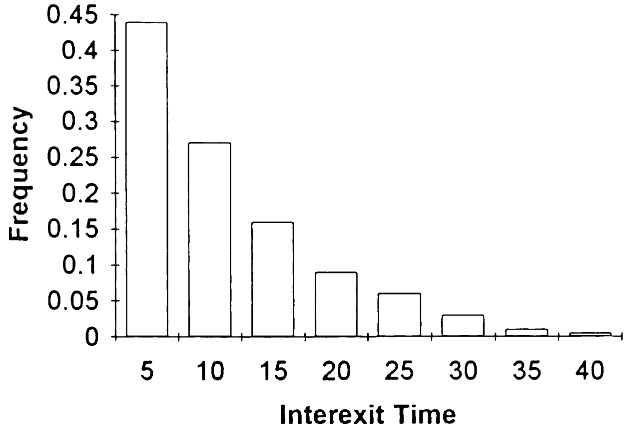

Figure 3: Histogram of Time Between Exits from Upstream Subsystem

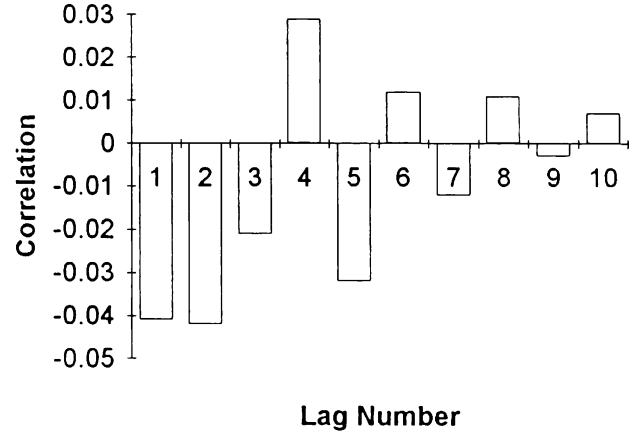

Figure 4: Plot of Exit Process Correlation for Increasing Lags

3.2 Downstream Subsystem

Next we modeled the downstream manual stations to determine how the output process from the upstream line effects the downstream process. The processing sequence in the downstream subsystem varies from board to board depending on its requirements and the processing times are stochastic. Since we did not have complete processing data for this subsystem, we developed a model that is representative of the types of subsystems often found in PCB assembly. The model contains nine workstations with the processing times at the workcenters being normally distributed (processing variances were set well below the mean processing times). The boards visited a random number of stations in a random sequence to represent the various types of routings and the randomness generated by rework. We constructed the model such that the average utilization of each station ranged around a realistic target of 85 percent.

Using the downstream model, our goal was to investigate the effect of decomposing the two subsystems and ignoring the correlation in the output process of the upstream subsystem. We first ran the downstream model by itself, using an input distribution that was exponentially distributed with a mean interarrival time of 9.36 minutes. Note that in this case, the interarrival times are independently generated. Since the effect of correlated arrivals would primarily effect the average work-in-process (WIP) levels and flowtimes, we targeted those for our analysis. We hypothesized that the negative correlation would reduce both the average flowtime and WIP levels since the alternation of long/short interarrival times should balance out some of the downstream processing variabilities and reduce congestion. The decomposed downstream model predicted an average flowtime of 312 with a 95 percent confidence interval of 5 and an average total WIP of 33.4 units (plus or minus 0.6). These results were based on 30 replications of 100 simulated weeks, truncating the first week to mitigate the effect of the initial transient.

Next we combined the upstream and downstream models to determine the effect of the correlated arrivals to the downstream system. The combined model predicted a slight drop in the average flowtime and WIP for the downstream subsystem (305 (4) minutes and 32.7 (0.4) units respectively). However, as can be seen from the confidence interval halfwidths, this decrease is not statistically significant.

Next we varied the utilization of the downstream system by changing the mean processing times at the downstream stations. Table 1 shows the average utilization of the downstream workcenters along with the flowtime and WIP predictions made by the downstream and combined models. Again we can see that the decomposition of these two subsystems seems to have little effect over the range of downstream utilizations from 65 to 95 percent.

Table 1: Summary of Experiments

	WIP and Flowtime			
Util	Downstm	Combined	Downstm	Combined
.65	11.6 ± .1	11.8 ± .1	109 ± 1	110 ± 1
.75	17.8 ± .2	18.2 ± .1	167 ± 1	169 ± 1
.85	33.4 ± .6	32.7 ± .4	312 ± 5	305 ± 4
.95	119 ± 8	120 ± 8	1113 ± 72	1122 ± 71

4 CONCLUSION

We discussed the process of decomposing a model of a large system into subsystem models. Decomposition would allow the smaller models to be built independently and thus speed the modeling process. We examined the problems of decomposing an upstream serial transfer line from a downstream jobshop as found in PCB assembly. Through experimentation with a model of a real PCB assembly system, we found that the tightly coupled upstream subsystem produced a negatively correlated output process. This finding is consistent with theoretical results from simple serial systems. We investigated the effect of this correlation as an input to the downstream subsystem and found that it appears to slightly reduce the WIP levels and average board flowtimes. This implies that a decomposed model of the downstream system which ignores the correlated arrival process may be slightly pessimistic in its predictions of flowtime and WIP. Nevertheless, in this case we feel that the difference would be practically negligible.

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