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DESIGN FOR PRODUCTION: A TOOL FOR REDUCING MANUFACTURING CYCLE TIME

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ABSTRACT : This paper describes a decision support tool that can help a product development team reduce manufacturing cycle time during product design. This design for production (DFP) tool determines how manufacturing a new product design affects the performance of the manufacturing system by analyzing the capacity requirements and estimating the manufacturing cycle times. Performing these tasks early in the product development process can reduce product development time. The paper presents a comprehensive DFP approach and describes the components of the DFP tool, which gives feedback that can be used to eliminate manufacturing cycle time problems. We present an example that illustrates the tool's functionality.

Keywords : DFM, queuing, redesign, product development, cycle time.

1 Introduction

Product development teams (also known as integrated product and process teams) employ many methods and tools as they design, test, and manufacture a new (or improved) product. Many manufacturers now realize that time is a critical and valuable commodity. Developing a new product and bringing it to market requires a large amount of time, and delays in this time-to-market can cost a manufacturer much profit. The manufacturing cycle time (sometimes called the flow time) is the interval that elapses as the manufacturing system performs all of the operations necessary to complete a work order. This manufacturing cycle time has many components, including move, queue, setup, and processing times. Reducing the manufacturing cycle time has many benefits, including lower inventory, reduced costs, improved product quality (process problems can be found more quickly), faster response to customer orders, and increased flexibility. In addition, a shorter manufacturing cycle time means that the first batch of finished goods will reach the customers sooner, which helps reduce the time-to-market.

Much effort is spent to reduce manufacturing cycle time by improving manufacturing planning and control systems and developing more sophisticated scheduling procedures, and these efforts have shown success. However, it is clear that the product design, which requires a specific set of manufacturing operations, has a huge impact on the manufacturing cycle time. Product development teams need, early in the product development process, methods that can estimate the manufacturing cycle time of a given product design. If the predicted manufacturing cycle time is too large, the team can reduce the time by redesigning the product or modifying the production system. Estimating the manufacturing cycle time early helps reduce the total product development time (and time-to-market) by avoiding redesigns later in the process. Thus, the product development team should include this activity in their concurrent engineering approach as they address other life cycle concerns, including testing, service, and disposal.

Since a large portion of manufacturing cycle time is due to queuing, and queuing occurs at heavily utilized resources, evaluating the capacity of production system resources is closely related to the issue of estimating manufac-

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*Author to whom all correspondence may be addressed turing cycle times. In addition, a production system may have insufficient available capacity to achieve the desired throughput. We use the term design for production (DFP) to describe methods that evaluate a product design by comparing its manufacturing requirements to available capacity and estimating manufacturing cycle time. DFP can also make redesign suggestions that decrease capacity requirements (which can increase the maximum possible output), reduce the manufacturing cycle time, or otherwise simplify production.

DFP will become more important as product variety increases and product life cycles decrease. Factories are faced with an explosion of varying cycle times because of increased product variety, and historical cycle times will not be accurate enough for a new product to be manufactured in the future, when the product mix will be different. Also, because production lines outlive individual products, it is important to design new products that can be manufactured quickly using existing equipment.

Previous researchers have developed various DFP methods for different problem settings, and this paper briefly reviews the relevant literature. The paper's primary contribution is to describe a decision support tool that performs DFP analysis. The tool quantifies how introducing a new product increases congestion in the factory. This tool employs an approximate queuing network model that estimates the manufacturing cycle time of the new product. This provides feedback that the product development team can use to reduce manufacturing cycle time. The tool can be used during conceptual design and requires less data than simulation models. In this paper we focus on products that are produced in one facility. We provide an example that demonstrates the approach.

Section 2 discusses previous work on DFP methods. Section 3 presents the overall approach, and Section 4 describes the decision support tool that estimates manufacturing cycle time and provides feedback to the product development team. Section 5 discusses computational experiments done to validate the mathematical models, and Section 6 demonstrates the approach. Section 7 concludes the paper.

2 Design for Production

In general, DFP refers to methods that determine if a manufacturing system has sufficient capacity to achieve the desired throughput and methods that estimate the manufacturing cycle time. These methods require information about a product's design, process plan, and production quantity along with information about the manufacturing system that will manufacture the product.

Design for manufacturing (DFM) is used to improve a product's manufacturability. Both DFM and DFP are related to the product's manufacture. DFM evaluates the materials, the required manufacturing processes, and the ease of assembly. (For a recent review of DFM, see van Vliet *et al.* [18].) In short, it evaluates manufacturing capability and measures the manufacturing cost, and it focuses on the individual operations that manufacturing requires. DFP evaluates how many parts the manufacturing system can output and how long each order will take. That is, it evaluates manufacturing capacity and measures the manufacturing time. DFP requires information about the manufacturing system as a whole. Like DFM, DFP can lead a product development team to consider changing the product design. In addition, DFP can provoke suggestions to improve the manufacturing system.

DFM approaches that generate process plans and estimate processing times can be the first DFP step, since some DFP methods use this information. Traditional DFM approaches can also improve manufacturing cycle time since they minimize the number of parts and reduce the processing time of each operation. We distinguish DFP approaches by their focus on evaluating manufacturing capacity and manufacturing cycle time.

DFP methods can be done concurrently with DFM. Boothroyd *et al.* [1] recommend that design for assembly analysis occur during conceptual design so that the product development team can reduce the part count. DFP at this stage will determine the capacity and manufacturing cycle time savings that follow. They suggest that design for manufacture then occur during detailed design to reduce manufacturing costs. Using DFP methods at that point can guide the DFM efforts by identifying the manufacturing steps that cause throughput and cycle time problems, where processing time reductions will significantly reduce manufacturing cycle time.

Finally, we distinguish DFP from lead time quoting, due date determination, and other order promising techniques that occur after the product design is specified.

Other researchers have used various names to describe DFP approaches, including design for existing environment [17], design for time-to-market [5], design for localization [11], design for speed [13], design for schedulability [10], and design for manufacturing system performance [16]. Some of these researchers have reported case studies in which product designs were modified to improve production.

Previous work on manufacturability evaluation and partner selection for agile manufacturing developed two approaches for estimating manufacturing cycle time of microwave modules and flat mechanical products. Given a detailed product design, the variant approach [3, 4] first calculates Group Technology codes that concisely describe the product attributes. Then, this approach searches a set of existing products manufactured by potential partners and identifies the ones that have the most similar codes. The manufacturing cycle time of the most similar existing products gives the product development team an estimate of the new product's manufacturing cycle time.

The generative approach [7, 12], however, creates a set of feasible partner-specific process plans for the given product design and calculates the cycle time at each step in each plan. Given a production quantity, the approach calculates the required processing time for an order of that size and adds the processing time to historical averages for the setup and queue times at that resource in that manufacturing facility. The approach then sums these times over all the steps in each process plan, which gives the product development team an opportunity to see how choosing different partners affects the manufacturing cycle time. This approach does not consider the available capacity that the manufacturing resources have or adjust the queue times as utilization increases.

Herrmann and Chincholkar [6] present a set of models that can be used to estimate the manufacturing cycle time of a new product. The report discusses the relative merits of using fixed lead times, mathematical models, discrete-event simulation, and other techniques.

Govil and Magrab [5] developed an approach for determining the maximum production achievable in a given time horizon. This approach assumes that the cycle time at each manufacturing operation is one time period. The lead time for purchased parts may be multiple periods. This approach uses the assembly structure to create a tree of purchasing and manufacturing operations, and the manufacturing cycle time is the length of the longest path through this tree.

Veeramani *et al.* [19, 20] describe a system that allows a manufacturer to respond quickly to requests for quotation (RFQs). The approach is applicable for companies that sell modified versions of standard products that have complex sub-assemblies (like overhead cranes). Based on customer specifications for product performance, the system generates a product configuration, a three-dimensional solid model, a price quotation, a delivery schedule, the bill of materials, and a list of potential design and manufacturing problems. The system verifies that the design can be feasibly manufactured by the shop and does some shop floor scheduling to determine the completion date.

3 Approach

Based on previous work and our research in this area, we present the following comprehensive DFP methodology for product design:

1. Create a product design that satisfies the product's functional requirements and DFP design guidelines. Specify the desired throughput and workorder (batch) size.
2. For the given product design, generate a manufacturing process plan. For each operation, identify the required resources and estimate the setup and processing times.
3. Using this data, information about other products that will be manufactured at the time the new product is introduced, and data about the manufacturing system, determine if the manufacturing system has sufficient capacity to achieve the desired production rate.
    - If not, identify the throughput limiting process (workstation). Consider redesigning the product to avoid this station, redesigning the product to reduce the capacity requirements, or add capacity to this station. If the product is redesigned, return to Step 2. If sufficient capacity is added, go to Step 4.
4. Using similar information, estimate the manufacturing cycle time of the new product.
    - If the cycle time is unacceptably large, identify the process (workstation) with the largest cycle time or ratio of cycle time to processing time. Consider redesigning the product to avoid this station, redesigning the product to reduce the processing time, or adding capacity (which will lower utilization and cycle time). If the product is redesigned, return to Step 2. If capacity is added, repeat this step.

Note that the most preferred option is to change the design (inexpensive if done early) and that the least preferred option is to add capacity (which can be expensive).

Also, for DFP analysis, the process plan may be approximate and incomplete. The necessary information is the sequence of operations, the resources required, and estimates of the time required. It may lack some details like process parameters, fixturing instructions, or other operational attributes that require a detailed design to determine.

4 Decision Support Tool

Unlike previous DFP methods, our decision support tool analyzes the capacity requirements, estimates the manufacturing cycle time of the new product, and provides feedback to the product development team. The decision support tool has five modules: the user interface, the process planner, the aggregation module, the approximate queuing network model, and the analysis module. See Figure 1. These modules are described in the following subsections. The tool uses an approximate queuing network model similar to those described by [2, 8, 9, 15]. Section 6 describes the application of this tool to a specific example.

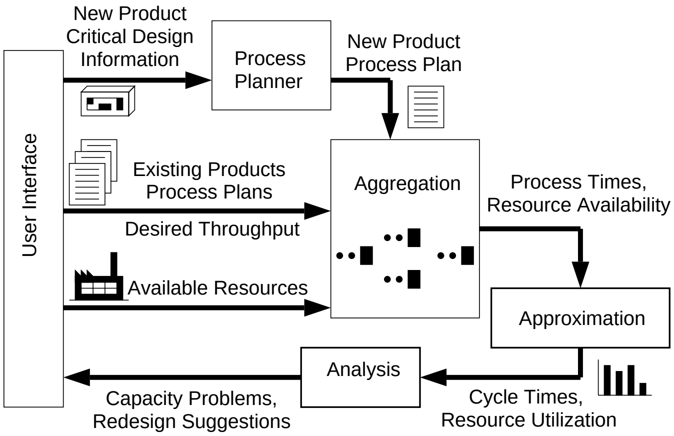

Figure 1: The Decision Support Tool

4.1 User Interface

Through the user interface, the product development team can enter and modify the required data and can view the feedback that the tool provides. This section describes the data requirements, while Section 4.5 describes the feedback that the analysis module provides.

The decision support tool requires the following data about the manufacturing system that will produce the new product. For each workstation, the number of resources available, and the mean time to failure and mean time to repair a resource. For each existing product, the batch size (number of parts), the desired throughput (parts per day), and its process plan. (Note that the set of existing products refers to the other products that the system will be producing when it produces the new product.) A process plan specifies the sequence of workstations that each job must visit, the mean setup time (per batch) at each workstation and its variance, the mean processing time (per part) at each workstation and its variance, and the yield at each workstation (the ratio of good parts produced to parts that undergo processing). The relevant notation follows.

I = the set of all products (existing and new)
T_i = desired throughput of product i (parts per hour)
B_i = batch size of product i at release (parts)
c_i^r = SCV of batch interarrival times for product i
J = the set of all stations (workstations)
n_j = the number of resources at station j
m_j^f = mean time to failure for a resource at station j
m_j^r = mean time to repair for a resource at station j
R_i = the sequence of stations that product i must visit
R_{ij} = the subsequence that precedes station j
t_{ij} = mean part process time of product i at station j
c_{ij}^t = SCV of the part process time
s_{ij} = mean batch setup time of product i at station j
c_{ij}^s = SCV of the setup time
y_{ij} = yield of product i at station j

For the new product, the product development team must provide the domain-specific critical design information that the process planner needs to generate a process plan for the new product. The critical design information should be available during the conceptual design stage. For an example, see Section 6.

4.2 Process Planner

The process planner uses domain-specific knowledge and algorithms to construct the process plan of the new product and estimate the setup and processing times of each operation required to manufacture the new product. (As noted before, the process plan may be incomplete.) The input is the critical design information of the new product like the geometry and topology of the various parts that constitute the product (see Table 2 for an example). The process plan specifies a sequence of workstations that each batch must visit. The notation is the same as that used for the existing process plans.

There exist many models and techniques for estimating part processing times. Many existing DFM approaches include this activity. Estimating the processing time of a manufacturing step given a detailed design is usually different from estimating the processing time given a conceptual design. For a detailed design, highly detailed process planning, manufacturing process simulation, or time estimation models can be employed [7, 12]. For a conceptual design, however, less detailed models must depend upon a more limited set of critical design information [5].

4.3 Aggregation

The aggregation module requires the process plans for the existing products (which the user interface provides) and the new product (which the process planner provides). Aggregation calculates, for each product, the total processing time of each batch at each station. This comprises the time for which the product is actually processed at the station and the time it has to wait at the station. It also calculates, for each station, the average processing time, weighted by each product's arrival rate. Finally, it modifies the aggregate processing times by adjusting for the resource availability.

This current tool assumes that the manufacturing system will complete a large number of batches of the new product. No batch visits a station more than once. This model assumes that the product mix and the resource availability do not change significantly over a long time horizon. If the product mix or the resource availability were changing significantly then different models may be more appropriate [6]. Of course, it may be possible to divide the time horizon into two or more periods where the system reaches steady-state. In this case, this model can be used for each time period. Alternatively, one can neglect the aspects of the system that are evolving and use the steady state model to approximate the system. The relevant notation and equations follow.

Y_{ij} = cumulative yield of product i through R_{ij}
Y_i = cumulative yield of product i through R_i
x_i = release rate of product i (batches per hour)
A_j = availability of a resource at station j
V_j = the set of products that visit station j
t_{ij}^+ = total process time of product i at station j
c_{ij}^+ = SCV of the total process time
t_j^+ = aggregate process time at station j
c_j^+ = SCV of the aggregate process time
t_j^* = modified aggregate process time at station j
c_j^* = SCV of the modified aggregate process time

$$Y_{ij} = \prod_{k \in R_{ij}} y_{ij} \tag{1}$$

$$Y_i = \prod_{k \in R_i} y_{ij} \tag{2}$$

$$x_i = T_i/(B_i Y_i) \tag{3}$$

$$A_j = \frac{m_j^f}{m_j^f + m_j^r} \tag{4}$$

$$V_j = \{i \in I : j \in R_i\} \tag{5}$$

$$t_{ij}^+ = B_i Y_{ij} t_{ij} + s_{ij} \tag{6}$$

$$(t_{ij}^+)^2 c_{ij}^+ = B_i Y_{ij} t_{ij}^2 c_{ij}^t + s_{ij}^2 c_{ij}^s \tag{7}$$

This last equation, which is used to calculate c_{ij}^+, holds because the variance of the total process time is the sum of the variance of the part process times and the variance of the job setup time.

$$t_j^+ = \frac{\sum_{i \in V_j} x_i t_{ij}^+}{\sum_{i \in V_j} x_i} \tag{8}$$

$$(t_j^+)^2 (c_j^+ + 1) = \frac{\sum_{i \in V_j} x_i (t_{ij}^+)^2 (c_{ij}^+ + 1)}{\sum_{i \in V_j} x_i} \tag{9}$$

$$t_j^* = \frac{t_j^+}{A_j} \tag{10}$$

$$c_j^* = c_j^+ + 2A_j(1 - A_j)\frac{m_j^r}{t_j^+} \tag{11}$$

The arrival process at each station depends upon the products that visit the station. Some products are released directly to the station, while others arrive from other stations. The departure process depends upon the arrival process and the service process.

V_{0j} = the set of products that visit station j first
V_{hj} = the set of products that visit station h immediately before j
λ_j = total batch arrival rate at station j
λ_{hj} = arrival rate at station j of batches from station h
q_{hj} = proportion of batches from station h that next visit station j
c_j^a = SCV of interarrival times at station j
c_j^d = SCV of interdeparture times - station j

$$\lambda_j = \sum_{i \in V_j} x_i \tag{12}$$

$$\lambda_{hj} = \sum_{i \in V_{hj}} x_i \tag{13}$$

$$q_{hj} = \lambda_{hj}/\lambda_h \tag{14}$$

$$c_j^d = 1 + \frac{u_j^2}{\sqrt{n_j}}(c_j^* - 1) + (1 - u_j^2)(c_j^a - 1) \tag{15}$$

$$c_j^a = \sum_{h \in J} ((c_h^d - 1) q_{hj} + 1) \frac{\lambda_{hj}}{\lambda_j} + \sum_{i \in V_{0j}} c_i^r \frac{x_i}{\lambda_j} \tag{16}$$

Solving the above set of equations yields the complete set of c_j^a and c_j^d for all stations.

If the shop is a flow shop, and all products visit the same sequence of stations, then we can renumber the stations $1, 2, ..., J$. $V_j = I$ and $V_{j-1,j} = I$ for all stations, and the last equation can be simplified as follows:

$$c_1^a = \frac{\sum_{i \in I} c_i^r x_i}{\sum_{i \in I} x_i} \quad (17)$$

$$c_j^a = c_{j-1}^d, 2 \le j \le J \quad (18)$$

4.4 Approximation

The approximate queuing network model calculates the utilization and the average cycle time at each workstation. The utilization incorporates the capacity requirements, while the average cycle time reflects the congestion and variability that are present.

u_j = the average resource utilization at station j

CT_j^* = the average cycle time at station j

$$u_j = \frac{\lambda_j t_j^*}{n_j} \quad (19)$$

$$CT_j^* = \frac{c_j^a + c_j^*}{2} q(n_j, u_j) t_j^* + t_j^* \quad (20)$$

The term $q(n_j, u_j)$ is a coefficient which is derived from an exact analytical model for the M/M/n_j queuing system. For instance, $q(1, u_j) = u_j/(1 - u_j)$ and $q(2, u_j) = u_j^2/(1 - u_j^2)$. For larger values of n_j, the formula is more complex, but it can be calculated exactly. See, for instance, Panico [14].

4.5 Analysis

The analysis module suggests modifications to the new product design that can reduce capacity requirements and manufacturing cycle time. This requires domain-specific knowledge about the product attributes that affect the processing and setup times. The analysis module estimates the total average manufacturing cycle time for the new product and, using Little's Law, the average work-in-process inventory. Furthermore, this module determines how the manufacturing cycle time of the new product is sensitive to its part processing time at any station. In the general case, calculating an exact derivative is feasible but complex due to the equations that describe the arrival and departure processes. We will approximate the sensitivity as follows, denoting the new product as product i.

CT_i = the average cycle time of jobs of product i

W_i = the average work-in-process inventory of product i (in parts)

M_j = the ratio of CT_j^* to t_j^*

S_{ij} = the sensitivity of CT_i to t_{ij}

$$CT_i = \sum_{j \in R_i} CT_j^* \quad (21)$$

$$W_i = T_i CT_i \quad (22)$$

$$M_j = CT_j^* / t_j^* \quad (23)$$

$$S_{ij} = M_j \frac{x_i B_i Y_{ij}}{A_j \lambda_j} \quad (24)$$

Any station j where the utilization $u_j \ge 1$ has insufficient capacity to achieve the desired production rate of the existing products and the new product. If CT_i is unacceptably large, then consider the stations with the highest utilization u_j, cycle time CT_j^*, cycle time multiple M_j, and sensitivity S_{ij}. The operations that occur at these stations should be examined, and the user is given suggestions on how to reduce the processing times at these operations. See Section 6 for an example. Also, a high sensitivity identifies operations where more accurate time estimates may be needed.

The user interface receives the analysis module's output and provides it to the user. The user can use the decision support tool to evaluate changes to the new product design or changes to the manufacturing system (e.g., additional resources at a workstation or revised throughput levels and batch sizes).

5 Model Validation

The cycle time estimates are approximations based upon queuing system models. To demonstrate their validity, we examined a specific case and compared the results to those of a discrete-event simulation model.

The system is a single-product, single-stage, multiple-server queuing system. The number of resources (servers) being n_j = 2, 3, 4, or 5. Interarrival times were distributed with a gamma distribution with parameter $\alpha = 2$ (i.e., the interarrival times were Erlang-2). We varied the arrival rate λ_j so that the resource utilization u_j varied from 0.5 to 0.9. The SCV $c_j^a = 0.5$. The processing times were uniformly distributed between 0.9 and 1.1, so the mean processing time $t_j^* = 1.0$ hours, and the SCV $c_j^* = 0.0033$.

We performed five simulation runs for each queuing system at different values of λ_j. For each value of n_j and λ_j, we

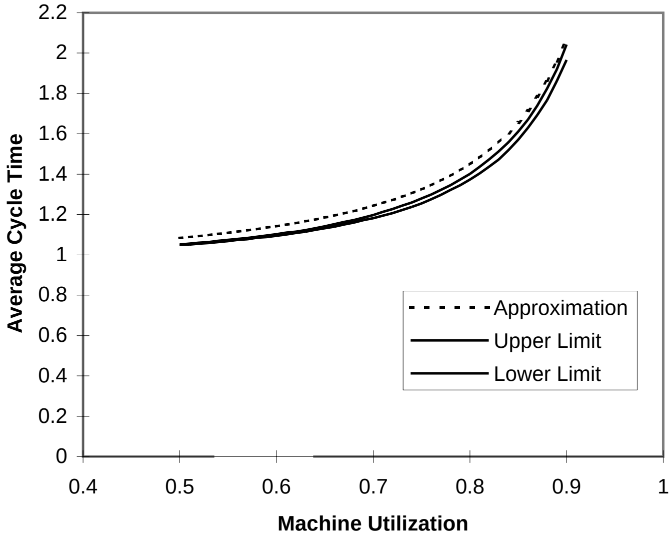

Figure 2: Simulation Results and Cycle Time Approximation for $n_j = 2$.

estimated CT_j^* from the model presented in Section 4.4 and constructed a 95 percent confidence interval from the simulation results. Figure 2 shows the results from $n_j = 2$. The results from the model and the confidence interval from the simulation runs for other values of n_j also follow the same trend as that depicted in Figure 2. These indicate that the approximation results have the same trend as the simulation values. Note that this validation addresses only the average cycle time at a single station under specific conditions.

6 Example

This section presents an example to illustrate the decision support tool functionality and demonstrates how a product development team would use the DFP decision support tool for a specific product design and manufacturing system. The product is a microwave module, and the manufacturing system is an electronics assembly shop. The information about the product and the system are based on our experience with an electronic systems manufacturer. This example uses data that our collaborators were able to provide and other synthetic data that we created. For details about the process planning and processing time estimation, see [7, 12].

Modern microwave modules (MWMs) have an artwork layer that includes many functional components of the circuit. The artwork lies on the dielectric substrate, which is attached to a ground plane that also serves as a heat sink. In addition to the integrated components, MWMs may carry hybrid components, which are assembled separately using techniques such as soldering, wire bonding, and ultrasonic bonding. Mounting these components often requires holes, pockets, and other features in the substrate.

6.1 The User Interface

The manufacturing company currently produces two types of microwave modules (Products 1 and 2) and is developing a third (Product 3). Through the user interface, the product development team specifies the required data, which is summarized here. Table 1 gives some data about the desired throughput levels of the three products.

The new product's aluminum substrate has a Teflon dielectric layer, six small pockets, five holes, ten surface mount components, and four other components.

Because the company purchases aluminum substrates that already have the dielectric layer, the process plan for any MWM follows the same fundamental sequence, unless a step is not necessary for a particular product:

1. Machine holes and pockets.
2. Plate (electroless plating and electroplating)
3. Etch (clean, apply photoresist, expose, develop, etch, clean)
4. Automated Assembly (mount and solder surface mount components)
5. Manual Assembly (attach other components)
6. Test (and tune as necessary)

Each processing time has some variability as well. The processing times of the manual assembly and test operations are exponentially distributed. The other processing times are uniformly distributed and can vary by plus or minus 20 minutes. The yield at each station is 1.0.

The facility manufacturing these microwave modules is a batch manufacturing system. The facility purchases the Teflon-coated aluminum substrates. There is a CNC machine tool that can machine the required holes and pockets. The facility has an electroless plating workstation, an electroplating workstation, an etch workstation, a workstation for automated assembly, and a workstation for manual assembly. The automated assembly workstation has a screen print machine, a pick-and-place machine, and a reflow oven. The material handling between these machines is automated. The manual assembly workstation has two employees who can attach other component types. The facility has four technicians who test and tune microwave modules.

6.2 Process Planner

The process planner uses the critical design information about the new product, shown in Table 2, to determine

Table 1: Desired Product Throughput

Product i	1	2	3
Throughput T_i (parts/hour)	2.5	2.5	0.625
Batch size B_i (parts/batch)	5	10	10
Release rate x_i (batches/hour)	0.5	0.25	0.0625

Table 2: Critical Design Information

Length (in.)	6
Width (in.)	2.5
Number of approach directions	1
Number of large pockets	0
Number of small pockets	6
Number of holes	5
Average hole depth (in.)	0.1
Plating thickness (in.)	0.0001
Artwork area fraction	0.25
Surface mount components	10
Other components	4

Table 3: Process Plans

Product i	1	2	3	Aggregate	
Batch processing time (mins)	t^+_{1j}	t^+_{2j}	t^+_{3j}	t^*_j	c^*_j
$j = 1$: Machining	47	64	64	68	0.25
$j = 2$: Electroless Plating	33	33	33	37	0.49
$j = 3$: Electroplating	45	50	35	50	0.23
$j = 4$: Etch	43	60	47	49	0.08
$j = 5$: Automated Assembly	41	58	100	59	0.20
$j = 6$: Manual Assembly	8	15	60	17	1.10
$j = 7$: Test and Tune	180	330	330	244	0.12

Table 4: Resource Utilization

Station	j	Util. u_j	Cycle Time (mins) CT^*_j
Machining	1	0.90	438
Electroless Plating	2	0.50	53
Electroplating	3	0.68	85
Etch	4	0.66	69
Auto. Assembly	5	0.74	85
Manual Assembly	6	0.09	14
Test and Tune	7	0.80	268

Table 5: Sensitivity Analysis

Station	j	Multiple M_j	Sensitivity S_{3j}
Machining	1	6.58	6.33
Electroless Plating	2	1.43	1.24
Electroplating	3	1.68	1.41
Etch	4	1.41	1.09
Auto. Assembly	5	1.56	1.30
Manual Assembly	6	1.01	0.77
Test and Tune	7	1.13	0.87

Table 6: Cycle Time Comparison

Station	Average Cycle Time (mins)		
	Two Products	Three Products	Two Tools
Machining	253	438	77
Electroless Plating	52	53	61
Electroplating	84	85	104
Etch	68	69	78
Automated Assembly	66	85	93
Manual Assembly	10	14	14
Test and Tune	246	268	272
Total	779	1012	699

the necessary operations and to estimate the part processing times and setup times at each workstation. This new product requires all seven operations. The process planner uses previously developed rules and algorithms for MWM process planning [7, 12].

6.3 Aggregation and Approximation

From the data that the user interface and the process planner provide, the aggregation module determines the batch processing times and the average processing time at each workstation. The results are shown in Table 3. Note that the modified aggregate process time t^*_j can be greater than the t^+_{ij} because the resource availability is less than one.

The approximation module calculates the average resource utilization and average cycle time at each station. Table 4 displays these results.

6.4 Analysis

Since all $u_j < 1$, all of the stations have sufficient capacity to process the new product. The analysis module sums the workstation cycle times to estimate the total average manufacturing cycle time for the new product. In this example, the total is 1,012 minutes (16.9 hours). The average work-in-process inventory is 10.5 parts. The module calculates the cycle time multiples at each workstation, shown in Table 5, and identifies the machining station as a problem, since the cycle time multiple and sensitivity are very large. The analysis module suggests that the product development team consider redesigning the product to reduce the machining requirements by reducing the number of small pockets and holes.

For comparison, the product development team can view a baseline scenario by setting the desired throughput of Product 3 to zero. Table 6 shows the average cycle time at each station when the facility manufactures no Product 3 and when the facility adds Product 3. Again, machining is clearly a problem, since almost all of the cycle time increase occurs at that station. Also, the product development team can determine the effect of adding a second CNC machine tool. Table 6 shows the average cycle time at each station in that scenario also. The average cycle time at machining is reduced greatly, while the average cycle times at some other stations increase slightly due to increased variability. The analysis module now identifies the electroplating station (which has the largest multiple and sensitivity) and the test and tune station (which has the largest utilization) as the problem stations.

7 Summary and Conclusions

Product development teams need, early in the product development process, methods that can estimate the manufacturing cycle time of a given product design. If the predicted manufacturing cycle time is too large, the team can reduce the time by redesigning the product or modifying the production system. Estimating the manufacturing cycle time early helps reduce the total product development time (and time-to-market) by avoiding redesigns later in the process. Design for production (DFP) methods evaluate a product design by comparing its manufacturing requirements to available capacity and estimating manufacturing cycle time. DFP methods can be done concurrently with DFM. DFP during conceptual design can determine the capacity and manufacturing cycle time savings that result from reducing the part count. Using DFP methods during detailed design can guide DFM efforts by identifying the manufacturing steps that cause throughput and cycle time problems, where processing time reductions will significantly reduce manufacturing cycle time.

We have developed a decision support tool that performs DFP analysis. Unlike previous approaches, the tool quantifies how introducing a new product increases congestion in the manufacturing system. This requires only the critical design information needed to create a process plan and estimate processing times, so it can be used early in the product development process. This tool employs an approximate queuing network model that estimates the manufacturing cycle time of the new product. The tool also calculates the capacity requirements and estimates the average work-in-process inventory. This provides feedback that the product development team can use to reduce manufacturing cycle time. The tool can quickly evaluate changes to the new product design or changes to the manufacturing system.

This current tool assumes that the manufacturing system will complete a large number of batches of the new product. No batch visits a station more than once. This model assumes that the product mix and the resource availability do not change significantly over a long time horizon. Note that forecasts of product mix and resource availability may change during the product development process. The DFP analysis should be updated when new information becomes available.

Future work needs to specify models for complex assemblies and for settings where the manufacturing system of interest includes multiple manufacturing facilities. These settings will become more important as products are designed for supply chains and virtual enterprises.

These models and methods need to be integrated into a more comprehensive designer assistance tool that can help a designer make tradeoffs between different designs or redesign suggestions and select the one that best meets the requirements of performance, manufacturing cost, and time. In addition, this could include decision support for manufacturing system design when a new facility will be constructed to make the new product. Eventually, this could be linked to an Enterprise Resource Planning system that can provide the necessary data.

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