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Reducing Manufacturing Cycle Time during Product Design

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Abstract

This paper describes an approach that can reduce manufacturing cycle time during product design. Design for production (DFP) determines how manufacturing a new product design affects the performance of the manufacturing system. This includes design guidelines, capacity analysis, and estimating manufacturing cycle times. Performing these tasks early in the product development process can reduce product development time. Previous researchers have developed various DFP methods for different problem settings. This paper discusses the relevant literature and classifies these methods. The paper presents a systematic DFP approach and a manufacturing system model that can be used to estimate the manufacturing cycle time of a new product. This approach gives feedback that can be used to eliminate cycle time problems. This paper focuses on products that are produced in one facility. We present an example that illustrates the approach and discuss a more general approach for other multiple-facility settings.

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 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 in the product development process 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 queueing, and queueing occurs at heavily utilized resources, evaluating the capacity of production system resources is closely related to the issue of estimating manufacturing 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 suggest improvements 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. This paper discusses the relevant literature and classifies these methods. The paper's primary contribution is to present a systematic and rigorous DFP approach that quantifies how introducing a new product increases congestion in the factory. This approach employs an approximate queueing 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. In this paper we focus on products that are produced in one facility. We provide an example that demonstrates the approach. The paper discusses more general settings and presents ideas for needed research in this area.

Section 2 discusses design for manufacturing approaches, while Section 3 discusses previous work on DFP methods. Section 4 presents a systematic DFP approach that estimates manufacturing cycle time. Section 5 describes an illustrative example. Section 6 discusses some extensions for more general settings. Section 7 concludes the paper.

2   Design for Manufacturing

Design for manufacturing methodologies are used to improve a product's manufacturability. Three important issues dominate the discussion of design for manufacturing (DFM), also called design for manufacturability. Can the manufacturing process feasibly fabricate the specified product design? How much time does the manufacturing operation require? How much does the operation cost? (For this discussion, we will use the term manufacturing to describe both fabrication and assembly, and we will include design for assembly as part of design for manufacturing.)

DFM guidelines help a product development team design a product that is easy to manufacture, while other DFM approaches evaluate the manufacturability (feasibility, time, and cost) of a given product design with respect to a specific manufacturing process. Some manufacturability evaluation approaches give the product development team feedback on what aspects of the design make it infeasible or difficult to manufacture.

DFM compares a product's manufacturing requirements to existing manufacturing capabilities and measures the processing time and cost. DFM approaches can be used during

the conceptual design and the detailed design steps. Generally, DFM approaches focus on the individual manufacturing operations. For examples and more information see Boothroyd *et al.* [5], Bralla [6], and Kalpakjian [23]. DFM has been very useful for reducing the unit manufacturing cost of many products, and successful product development processes require tools like DFM [37].

In an attempt to increase the awareness of manufacturing considerations among designers, leading professional societies and some manufacturing firms have published a number of manufacturability guidelines for a variety of manufacturing processes [1, 4, 6, 34, 42]. Researchers have developed several different approaches to evaluate manufacturability of a given design. Existing approaches can be classified roughly as follows:

Direct or rule-based approaches [21, 22, 36] evaluate manufacturability from direct inspection of the design description: design characteristics that improve or degrade the manufacturability are represented as rules, which are applied to a given design in order to estimate its manufacturability. Most existing approaches are of this type. Direct approaches do not involve planning, estimation, or simulation of the manufacturing processes involved in the realization of the design.

Indirect or plan-based approaches [15, 16, 18, 20, 31] do a much more detailed analysis: they proceed by generating a manufacturing plan and examine the plan according to criteria such as cost and processing time. If there is more than one possible plan, then the most promising plan should be used for analyzing manufacturability, and some plan-based systems generate and evaluate multiple plans [13, 14]. The plan-based approach involves reasoning about the processes involved in the product's manufacture.

The direct approach appears to be more useful in domains such as near-net shape manufacturing, and less suitable for machined or electromechanical components, where interactions among manufacturing operations make it difficult to determine the manufacturability of a design directly from the design description. In order to calculate realistic manufacturability ratings for these latter cases, most of the rule-based approaches would require large sets of rules.

3   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.

Both DFM and DFP are related to the product's manufacture. DFM evaluates the materials, the required manufacturing processes, and the ease of assembly. In short, it evaluates manufacturing capability and measures the manufacturing cost. And it focuses on the individual operations that manufacturing requires. On the other hand, 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. Moreover, this approach 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.* [5] 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 here can guide these efforts by identifying the manufacturing steps that cause throughput and cycle time problems, where processing time reductions will signficantly 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 [41], design for time-to-market [12], design for localization [27], design for speed [32], design for schedulability [25], and design for manufacturing system performance [39]. Some of these researchers have reported case studies in which product designs were modified to improve production.

Nielsen and Holmstrom [32] discuss reducing the variety of inbound materials and moving customization operations to the end of the manufacturing process. This requires the manufacturer to design the product so combinations of options don't increase the variety of procured material and to design a manufacturing process that can produce any combination quickly. They discuss a case study from the automobile industry. They do not present any approach for evaluating manufacturing cycle time.

Lee *et al.* [27] describe an inventory model that was used to determine the inventory

savings achievable if the company redesigned its printers and moved customization activities from the factory to the distribution centers.

The remainder of this section will describe previous work on three areas of DFP: design guidelines, capacity analysis, and estimating manufacturing cycle times.

3.1 Design Guidelines

Design guidelines help the product development team create a better product design. Many design guidelines exist for specific manufacturing processes, and they remind designers to leave sufficiently large corner radii, to avoid undercuts, and to minimize the number of components, for example.

Kusiak and He [25] suggest rules that designers can follow to reduce a product's manufacturing cycle time. In addition, these rules attempt to simplify the production scheduling problems that plague most production systems. For example, the rules state that one should minimize the number of machines needed to manufacture a product (which yields fewer moves and less queue time) and allow the use of substitute manufacturing processes (which gives the production system the flexibility to route an order to another operation to avoid a long queue at a bottleneck resource or unavailable machine).

3.2 Capacity Analysis

Capacity analysis compares the manufacturing system's capacity to the product design's requirements. The manufacturing system's capacity depends upon the time available at each required resource and the time already allocated to fabricating other products. The product design's requirements depends upon the setup and processing time at each operation and the desired production rate. Capacity analysis can determine sufficient capacity exists, estimate the maximum feasible production level, suggest other release dates, and suggest changes that would increase the manufacturing system capacity. Of course, the available capacity is not the same for each resource, since some resources are busier than others and sometimes there exist multiple, identical resources that can share the workload. In addition, the capacity requirements are not the same for each resource since setup and processing times can vary greatly from one operation to the next. In addition, the available capacity may change from one time period to the next as the product mix changes.

Taylor *et al.* [41] use a capacity analysis model to determine the maximum production quantity that an electronics assembly facility can achieve. The analysis is done for a set of existing products and the detailed design of a new product. If the maximum production quantity is insufficient, the product design is changed so that its manufacture avoids a bottleneck resource, which increases the achievable production quantity to an acceptable level.

This work does not estimate manufacturing cycle time.

Bermon *et al.* [3] present a capacity analysis model for a manufacturing line that produces multiple products. Their approach is not focused on product design but it is oriented towards decision support and quick analysis. They define available capacity as the number of operations that a piece of equipment can perform each day. Given information about the equipment available, the products, and the operations required, their approach allocates equipment capacity to satisfy the required throughput and availability constraints. They incorporate cycle time by constraining allocated capacity (utilization) to a level strictly below the available capacity. The difference is the contingency factor. Instead of setting this contingency factor in some ad hoc manner, as some manufacturers do, they describe a method to calculate a contingency factor for each tool group. The ideal contingency factor prevents the average queue time at that tool group from exceeding a predetermined multiple of the processing time. To model the relationship between utilization and queue time, their approach uses a queueing model approximation. Thus, their approach can determine if the manufacturing line has sufficient capacity to meet the required production and achieve reasonable manufacturing cycle times.

Many authors have described capacity planning methods that are part of traditional manufacturing planning and control systems [19, 45]. These methods determine how much, when, what type, and where a manufacturing system should add capacity to meet throughput requirements. Typical objectives include minimizing equipment costs, inventory, and cycle time. Different capacity planning models vary, and the more accurate methods require more data and more computational effort. These approaches do not consider how the product design affects the manufacturing system performance.

3.3   Estimating Manufacturing Cycle Time

Previous DFP approaches estimate manufacturing cycle time either by modeling the steady-state performance of the manufacturing system or by scheduling or simulating manufacturing systems that are evolving as the product mix changes over time.

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 [8, 9] 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 [18, 31], 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 on 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 [17] 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.

Singh [38] calculates the time at a manufacturing operation as the sum of the setup time and the run time (the part processing time multiplied by the lot size). This approach ignores any time due to queueing or moving.

Govil [12] 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.

Meyer *et al.* [30] describe an approach for comparing microwave module designs. Each different design uses a different set of electronic components. The approach generates process plans that are feasible with respect to the characteristics of the selected components. They evaluate each design and process plan based on the cost, the system reliability, and the maximum lead time required to procure any of the selected components.

Veeramani *et al.* [43, 44] 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 subassemblies (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. The authors claim that, to generate the delivery schedule for that order, the system uses data about shop floor status, current orders, and alternative process plans to determine the time needed to produce the new order. Although no details are given, it appears that the system does some shop floor scheduling to determine the completion date.

Elhafsi and Rolland [11] study a make-to-order manufacturing system and build a model

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that can determine the delivery date of a single customer order. The model takes into account the production lines' existing workloads and allocates portions of the order to different lines to minimize the cost and estimate the expected delivery date. Each line is modeled as a single-server queueing system.

The U.S. Air Force is developing the Simulation Assessment Validation Environment (SAVE), which integrates a set of virtual manufacturing tools. The SAVE program will help product development teams develop affordable weapon systems (like fighter aircraft) by giving them the ability to evaluate cost, manufacturing cycle time, inventory levels, rework, and other manufacturing metrics. The SAVE approach uses detailed factory simulation models to estimate manufacturing cycle time.

Soundar and Bao [39] describe a plan to address the question of determining how the product design affects the manufacturing system. They propose using mathematical and simulation models to estimate a variety of different performance measures, including manufacturing cycle time. Though the approach is quite general, the paper does not describe any examples or results.

4   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 (job) 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 adding 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.

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- 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).

Capacity analysis. Section 4.1 presents the manufacturing system model needed for capacity analysis and estimating manufacturing cycle time. Any station j where the utilization $u_j \geq 1$ has insufficient capacity to achieve the desired production rate of the existing product and the new product.

Estimating manufacturing cycle time. Section 4.1 presents the manufacturing system model needed for capacity analysis and estimating manufacturing cycle times. The average manufacturing cycle time of a job of product i is CT_i. If CT_i is unacceptably large for one or more products, then consider the stations with the highest utilization (u_j), cycle time (CT_j^*), cycle time multiple (M_j), and sensitivity (S_{ij} for the new product i). The processes that occur at these stations should be examined.

4.1 Manufacturing System Model

We use the following queueing network model to estimate the average cycle time of products through the factory. The approximation aggregates the products and calculates the average cycle time at each station. This model uses previously proposed approximations described by [19, 24].

This manufacturing system model assumes that the manufacturing system will complete a large number of work orders (jobs) of the new product. No job 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 [17]. 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.

Note that a critical piece of data for estimating manufacturing cycle times is the processing time of each step required to manufacture the given product design. There exist many models

and techniques for estimating processing times. Many of the 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 [18, 31]. For a conceptual design, however, less detailed models must depend upon a more limited set of critical design information [12]. For existing products, the processing and setup times should be available from existing process plans.

For more information on queueing network models, see Papadopoulos *et al.* [35] and Buzacott and Shanthikumar [7], who present queueing network models for manufacturing systems. Connors *et al.* [10] modeled semiconductor wafer fabrication facilities using a sophisticated queueing network model to analyze these facilities quickly by avoiding the effort and time needed to create and run simulation models. They present numerical results that show how the queueing network model yields similar results to those that a simulation model yields. Queueing network models are also the mathematical foundation of manufacturing system analysis software like rapid modeling [40]. Koo *et al.* [24] describe software that integrates a capacity planning model and queueing network approximations. They report that the approximations are reasonable when variability is moderate. However, few researchers have described how to apply this body of work to product design and manufacturability evaluation.

Data Requirements. The manufacturing system model requires the following data: 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 and the new product, the job size (number of parts) and the desired throughput (number of parts per hour of factory operation). The sequence of workstations that each job must visit. The mean setup time (per job) at each workstation and its variance. The mean processing time (per part) at each workstation and its variance. The yield at each workstation that a job must visit (the ratio of good parts produced to parts that undergo processing).

$$
\begin{aligned}
I &= \text{the set of all products (existing and new)} \\
T_i &= \text{desired throughput of product } i \text{ (parts per hour)} \\
B_i &= \text{job size of product } i \text{ at release} \\
c_i^r &= \text{SCV of job interarrival times for product } i \\
J &= \text{the set of all stations} \\
n_j &= \text{the number of resources at station } j \\
m_j^f &= \text{mean time to failure for a resource at station } j
\end{aligned}
$$

$$
\begin{aligned}
m_j^r &= \text{mean time to failure for a resource at station } j \\
R_i &= \text{the sequence of stations that product } i \text{ must visit} \\
R_{ij} &= \text{the subsequence that precedes station } j \\
t_{ij} &= \text{mean part process time of product } i \text{ at station } j \\
c_{ij}^t &= \text{SCV of the part process time} \\
s_{ij} &= \text{mean job setup time of product } i \text{ at station } j \\
c_{ij}^s &= \text{SCV of the setup time} \\
y_{ij} &= \text{yield of product } i \text{ at station } j
\end{aligned}
$$

Aggregation. Aggregation calculates, for each product, the processing time of each job at each 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.

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

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

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

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

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

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

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

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

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.

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

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

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

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

Arrival and Departure Processes. 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.

$$
\begin{aligned}
V_{0j} &= \text{the set of products that visit station } j \text{ first} \\
V_{hj} &= \text{the set of products that visit station } h \text{ immediately before } j \\
\lambda_j &= \text{total job arrival rate at station } j \\
\lambda_{hj} &= \text{arrival rate at station } j \text{ of jobs from station } h \\
q_{hj} &= \text{proportion of jobs from station } h \text{ that next visit station } j \\
c_j^a &= \text{SCV of interarrival times at station } j \\
c_j^d &= \text{SCV of interdeparture times at station } j
\end{aligned}
$$

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

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

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

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

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

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:

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

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

Performance Measures. The performance measures of interest are the average utilization of resources and the manufacturing cycle time. The average cycle time of a job depends upon the cycle time at each station it visits.

$$u_j = \text{the average resource utilization at station } j$$

$$CT_j^* = \text{the average cycle time at station } j$$

$$CT_i = \text{the average cycle time of jobs of product } i$$

$$u_j = \frac{t_j^*}{n_j} \sum_{i \in V_j} x_i \tag{19}$$

$$CT_j^* = \frac{1}{2}(c_j^a + c_j^*)\frac{u_j^{(\sqrt{2n_j+2}-1)}}{n_j(1-u_j)}t_j^* + t_j^* \tag{20}$$

$$CT_i = \sum_{j \in R_i} CT_j^* \tag{21}$$

Sensitivity. With the above model, we can determine 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.

$$M_j = \text{the ratio of } CT_j^* \text{ to } t_j^*$$

$$S_{ij} = \text{the sensitivity of } CT_i \text{ to } t_{ij}$$

$$M_j = CT_j^*/t_j^* \tag{22}$$

$$S_{ij} = M_j \frac{x_i B_i Y_{ij}}{A_j \lambda_j} \tag{23}$$

Comparison. The queueing network approximations used here offer some advantages and also have limitations. Compared to simulation models or more sophisticated queueing network analysis techniques, these approximations are less accurate, especially for very complex systems, and cannot provide the same range of performance measures. However, they require less data and less computational effort than the simulation models and other analysis techniques. Therefore, they are more appropriate for situations where a decision-maker needs to compare many scenarios quickly.

5 Example

This section demonstrates some of the manufacturing system models 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 [18, 31].

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.

5.1 The Product

The manufacturing company currently produces two types of microwave modules (Products 1 and 2) and is developing a third (Product 3). Consider the microwave module (MWM) shown in Figure 1. The product's aluminum substrate has a teflon dielectric layer. The substrate has six features: two holes $h1$ and $h2$, two (intersecting) rectangular pockets $p1$ and $p2$, and two cutouts $c1$ and $c2$. In addition, the MWM has two surface-mount components and one other component. Because the company purchases aluminum substrates that already have the dielectric layer, the process plan for the MWM follows:

1. Machine holes and pockets.

2. Plate (electroless plating and electroplating)

3. Etch (clean, apply photoresist, expose, develop, etch, clean)

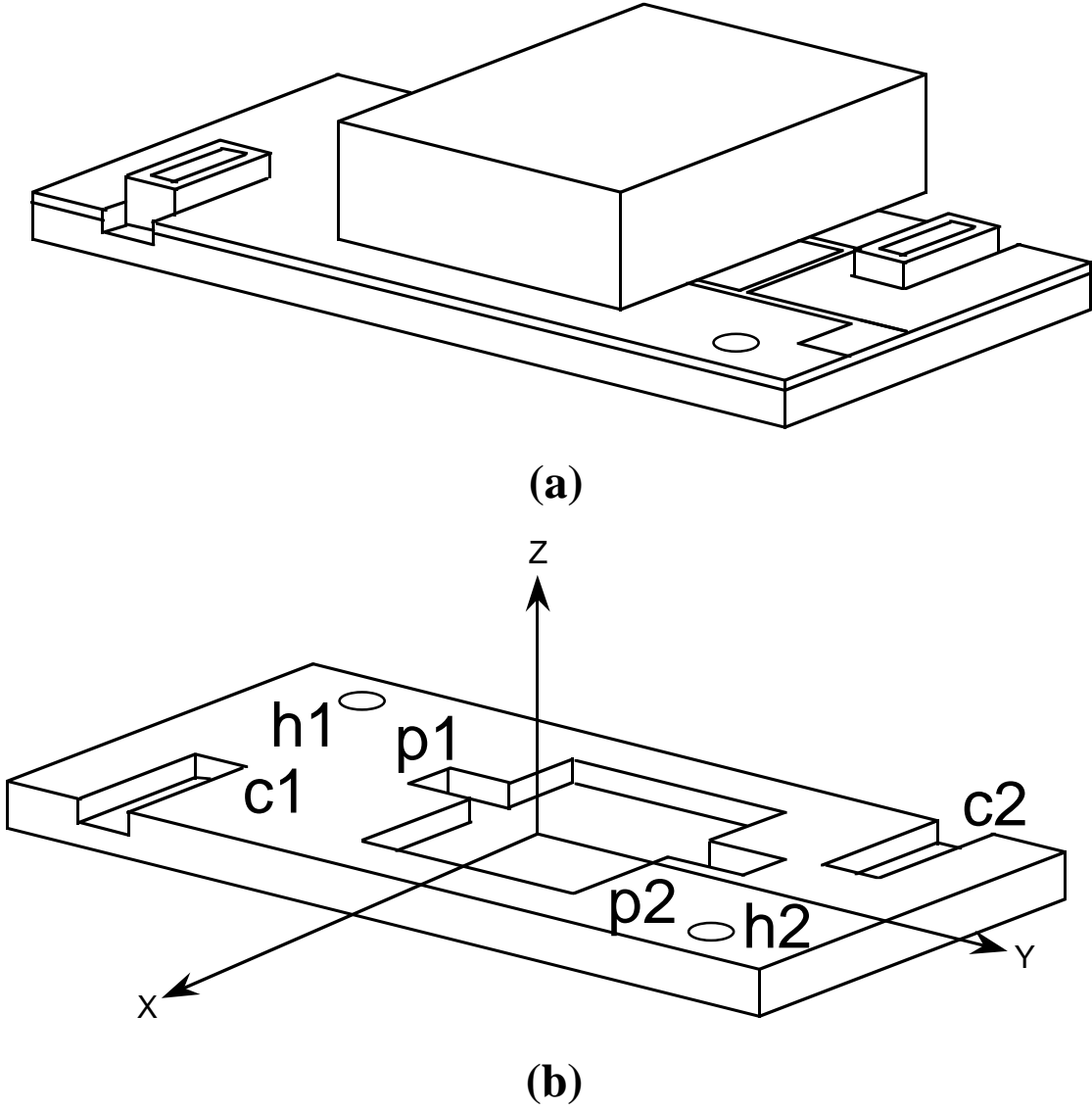4. Automated Assembly (mount and solder surface mount components)

(a)

(b)

Figure 1: New product: (a) assembly, (b) substrate

Table 1: Products and Process Plans

Product i	1	2	3
Throughput T_i (parts/hour)	2.5	2.5	1.25
Batch size B_i (parts/job)	5	10	10
Release rate x_i (jobs/hour)	0.5	0.25	0.125
Job processing time t_{ij}^+ (mins)			
$j = 1$: Machining	40	95	75
$j = 2$: Electroless Plating	32	32	32
$j = 3$: Electroplating	60	60	60
$j = 4$: Etch	45	55	55
$j = 5$: Automated Assembly	50	0	75
$j = 6$: Manual Assembly	25	50	50
$j = 7$: Test and Tune	180	330	330

5. Manual Assembly (attach other components)

6. Test (and tune as necessary)

Table 1 gives critical information about the products and the mean processing times of each operation. 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.

5.2 The Manufacturing System

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.

5.3 Capacity Analysis

Using the queueing network model presented above, we can calculate the average resource utilization at each station. Table 2 displays these results. Since all $u_j < 1$, all of the stations have sufficient capacity to process the new product.

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Table 2: Resource Utilization

Station	j	Utilization u_j
Machining	1	0.89
Electroless Plating	2	0.47
Electroplating	3	0.88
Etch	4	0.72
Automated Assembly	5	0.57
Manual Assembly	6	0.26
Test and Tune	7	0.89

Table 3: Cycle Time Estimates: Queueing Network Model

Station	j	Cycle time (mins) CT_j^*	Multiple M_j	Sensitivity S_{3j}
Machining	1	323	5.31	7.59
Electroless Plating	2	39	1.21	1.73
Electroplating	3	132	2.20	3.15
Etch	4	60	1.21	1.73
Automated Assembly	5	55	1.40	1.99
Manual Assembly	6	38	1.07	1.53
Test and Tune	7	564	2.31	3.30
Total		1211		

5.4 Estimating the Manufacturing Cycle Time

We will use the queueing network model to estimate the manufacturing cycle time. For comparison purposes, we also estimate manufacturing cycle time using past performance and a discrete-event simluation model.

Queueing network model. We used the queueing network model to estimate the average cycle time at each workstation. Based on the routing for the new product, we estimate the average manufacturing cycle time as the sum of these workstation cycle times. Table 3 summarizes these calculations. The total is 1211 minutes, or 20.2 hours. This table also shows the cycle time multiple and the sensitivity for the new product. Note that the machining and testing stations have the largest cycle times, cycle time multiples, and sensitivities.

Past performance. Table 4 shows the average cycle time at each station when the facility manufactures only Products 1 and 2. We can estimate the average manufacturing cycle time of the new product as the sum of these cycle times. That sum is 750 minutes, or 12.5 hours. Note that this is significantly different from the estimate that the queueing network model

Table 4: Cycle Time Estimates: Past Performance and Simulation Model

Station	Cycle time (mins)	
	Past	Simulation
Machining	155	346
Electroless Plating	35	32
Electroplating	111	137
Etch	51	59
Automated Assembly	54	82
Manual Assembly	34	49
Test and Tune	310	706
Total	750	1411

provides.

Simulation. We also created a discrete-event simulation model of the facility and the products and ran five replications to estimate the average manufacturing cycle time of the new product. Table 4 shows the cycle time at each workstation for Product 3. The sum is 23.5 hours, with a 95 percent confidence interval of (21.9, 25.0) hours. The estimate that the queueing network model provides is close to this.

Redesign suggestions. Based on these results the product development team might investigate the cycle times at machining and at testing. The utilization, cycle times, and cycle time multiples are all large. The team might consider redesigning the product to reduce the machining requirements by reducing the number of holes and pockets. Substitute components may not need these features. In addition, the team might consider redesigning the product to make testing and tuning simpler. Other options include purchasing tools and equipment that will simplify testing and tuning, and retraining a manual assembly person to perform testing (since the manual assembly area is not busy).

6 A Generalized DFP Approach

This section presents a general DFP approach that extends the approach presented above. Given a product design and a desired production rate, the goals are to determine if the manufacturing system has sufficient capacity to achieve this rate and to estimate the manufacturing cycle time of each batch. In this case, however, the manufacturing system may be a set of different facilities that form a supply chain. This could be a number of factories owned by one corporation, or a set of suppliers, subassembly facilities, and a final assembly facility.
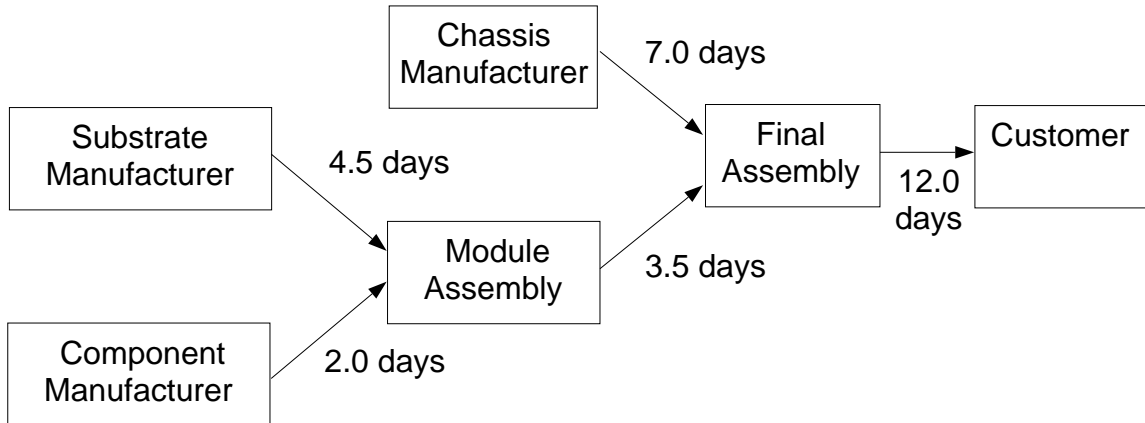
Figure 2: Network Model of a Supply Chain

We can model the supply chain as a network, where each facility is a node, and there is a dummy facility representing the customer (as shown in Figure 2). Include a directed arc between nodes p and q if facility p sends a product to facility q. (A product could be a component, a subassembly, or the finished product.)

Then follow the general DFP methodology presented in Section 3. To determine if the entire manufacturing system has sufficient capacity, determine if each participating facility has sufficient capacity for the product that it makes.

To determine the manufacturing cycle time across the system, estimate the manufacturing cycle time of a job at each facility and the transportation time between each facility. The length of each arc is the sum of these times. The manufacturing cycle time across the system is the longest path in the network. In the example shown in Figure 2, the longest path is 20 days.

7 Summary and Conclusions

This paper presented a specific approach that determines how manufacturing a new product design affects the performance of the manufacturing system. Design for production (DFP) includes design guidelines, capacity analysis, and estimating manufacturing cycle times. Performing these tasks, like other DFM techniques, early in the product development process can reduce product development time.

Previous researchers have developed various DFP methods for different problem settings. This paper discussed the relevant literature and classifies these methods. The paper presented a DFP approach that clearly distinguishes between the capacity analysis and manufacturing cycle time analysis, and the approach provides feedback on how to avoid cycle time problems.

The approach, unlike previous DFP approaches, uses a queueing network model to estimate the manufacturing cycle time of a new product and the congestion that the new product introduces at each workstation. This paper focused on products that follow a simple routing and are produced in one facility. We presented an example that illustrates the technique and discussed a more general approach for supply chains.

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 decision support 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. This requires methods that can determine the process plan for the new product and estimate the processing time of each operation. In addition, we could integrate decision support for manufacturing system design when a new facility will be constructed to make the new product.

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