Proceedings of DETC 2001
2001 ASME Design Engineering Technical Conference
September 9-12, 2001 - Pittsburgh, Pennsylvania

DETC2001/DFM-21169

INCORPORATING MANUFACTURING CYCLE TIME COST IN NEW PRODUCT DEVELOPMENT

Mandar M. Chincholkar
Institute for Systems Research
University of Maryland
College Park, Maryland 20742.
mmc@eng.umd.edu

Jeffrey W. Herrmann*
Institute for Systems Research
University of Maryland
College Park, Maryland 20742.
jwh2@eng.umd.edu
(301) 405-5433

ABSTRACT

Manufacturing cycle time (the time that elapses from work order release to completion) affects the cost of developing and manufacturing a product. However, most cost models consider only the setup and processing times and ignore the move times and queue times, which form most of the manufacturing cycle time. This paper discusses the economic impact of manufacturing cycle time. It presents methods for estimating the manufacturing cycle time of a new product that will be made in a manufacturing system that makes other products as well. It identifies the benefits of reducing manufacturing cycle time and shows how those benefits yield increased profitability.

Keywords : manufacturing cycle time, design for manufacture, cost analysis, product design.

1 Introduction

Product variety is continuously increasing in today's global market. The required philosophy for a company's survival is the continual replacement of old products with new ones, either improved variations of the current products or completely different products. Product development has thus become a very crucial aspect of corporate competition. The design and development of a product is a very complex process involving numerous considerations such as market analysis, requirements definition, conceptual design, detailed design, materials and process selection, optimization, process control, testing and evaluation, costing, manufacturing and production, and marketing [1, 2, 3, 4]. Although described as a series of steps, the product development process is, in practice, a network of paths, including feedback loops, between the necessary activities. These feedback loops, though essential in the development, nevertheless increase the time required and costs involved from demand recognition to the actual product launch and often contribute a great deal to the costs involved in making the product.

Concurrent engineering and DFX methodologies aim to minimize these costly loops by empowering the designer with knowledge of post-design processes and systems. Thus, the downstream requirements may be kept under consideration while designing the product. These methodologies include analyzing the product and processes involved and their performance characteristics, identifying the problems and shortcomings in these and highlighting them, searching for solutions to these problems, proposing changes to the product or processes (redesign advice) and prioritizing these ideas based on the evaluation of the effects of these suggestions on the performance of the product.

One objective during product development is to reduce the time spent by the product in the manufacturing system, known as the manufacturing cycle time. 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. Thus, manufactur-

*Author to whom all correspondence may be addressed ing cycle time reduction has various impacts on product development.

Much effort is spent trying 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. Hence, understanding the relationship between the product design and the manufacturing cycle time is important to the effort of reducing the manufacturing cycle time for the product.

Manufacturing costs are in general difficult to estimate and depend on a number of factors [5]. Of particular significance are those which may be deemed "nonquantifiables." Manufacturing cost estimation procedures have concentrated more on the costs related to materials and processing. The manufacturing cycle time also affects cost and modeling this cost is highly relevant towards analyzing product profitability.

The "Westinghouse Curve," described by many authors including Bralla [3], graphs the relationship between the amount of resources allocated to the product and the different stages in its life cycle. From the curve it is seen that by the time a product concept is validated, well before the development is completed, 70 percent of the funds have already been allocated. Thus, there are great benefits to evaluating downstream costs early in the product life cycle. Designing the product for reduced manufacturing cycle time would significantly impact the returns on investment for the product. Using the knowledge at the design phase would have the greatest impact on resource allocation and manufacturing system changes needed to accommodate the new product.

While reducing manufacturing cycle time is an important objective, determining its impacts on costs and revenues is necessary for justifying investments in improvements, for making tradeoffs, and for evaluating product profitability comprehensively. In addition, measurements of manufacturing cycle time cost could be used in design optimization methods that maximize product profitability or minimize life cycle costs.

The remainder of the paper is organized as follows: Section 2 explains the Design for Production (DFP) methodology and its application to improving product development and Section 3 reviews techniques for estimating manufacturing cycle time. Section 4 outlines an application of the DFP approach in the domain of microwave modules. Section 5 discusses the economic impact of reducing manufacturing cycle time, and Section 6 concludes the paper.

2 Design For Production

In general, *Design For Production* (DFP) refers to methods that determine if a manufacturing system has sufficient capacity to achieve the desired throughput and approaches to estimate the manufacturing cycle time. These methods help a product development team evaluate alternatives and require information about a product's design, process plan, and production quantity along with information about the manufacturing system that will manufacture the product. Herrmann and Chincholkar [6] explain the concept in greater detail.

Both *Design for Manufacture* (DFM) and DFP are related to the product's manufacture. While DFM studies the feasibility of manufacturing the product designs, DFP evaluates manufacturing capacity and measures the manufacturing time. For such an evaluation, DFP requires information about the product designs as well as details of 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. One of the challenges faced by teams developing new products for introduction into the market is estimating the performance and profitability of the product during the preliminary stages of development. DFP is likely to prove to be a useful tool for such estimation and hence find wide application to new product introduction into an existing manufacturing system already producing other products.

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 and in turn can serve as input for a DFP tool. 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]. For a conceptual design, however, less detailed models must depend upon a more limited set of critical design information [8, 9]. For existing products, the processing and setup times should be available from existing process plans.

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. This is the underlying philosophy behind the DFP concept.

Evaluating the performance of an existing product or predicting the expected performance of a new product to be introduced into the market requires the consideration of various metrics. Since the aim of every organization is ultimately to make a profit from new product introduction, an important metric for such an evaluation is the return on investment from the new product. This in turn involves estimating the costs associated with and the gains from introducing the product into the market. Various costs, both direct and indirect, are associated with different aspects of the product development cycle including actual product manufacture. The cost associated with the manufacturing cycle time is one of the product costs.

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. Section 5 discusses the costs associated with the manufacturing cycle time. DFP helps the product development team attain the goal of reducing the manufacturing cycle time and the related cost.

Other researchers have used various names to describe DFP approaches, including design for existing environment [10], design for time-to-market [8, 9], design for localization [11], design for speed [12], design for schedulability [13], and design for manufacturing system performance [14]. DFP approaches may be distinguished from DFM approaches by their focus on evaluating manufacturing capacity and manufacturing cycle time.

3 Estimating Manufacturing Cycle Time

In order to use manufacturing cycle time as an evaluation tool for product design, it is necessary to be able to estimate this time accurately. The stochastic nature of a majority of the times that constitute the manufacturing cycle time make the task of finding the exact value difficult. Hence, due to the lack of exact analytical results, it is necessary to use approximations. Previous approaches estimate manufacturing cycle time either by approximating 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. Herrmann and Chincholkar [15] review a set of models that can be used to estimate the manufacturing cycle time for a product and that have been applied by some of these approaches. The report discusses the relative merits of using fixed lead times, mathematical models, discrete-event simulation, and other techniques that are commonly used for the purpose. Most studies, however, define manufacturing cycle time as only the sum of processing and setup times, paying little attention to other constituents such as queuing time or material handling time.

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 manufacturing cycle time. Intuitively, the product design requiring the largest total processing time on various resources might be expected to have the largest manufacturing cycle time. However, due to the contribution of the time spent by a part in queue, waiting to be processed, the manufacturing cycle time of such a product design (with the largest total processing time) is not necessarily the largest manufacturing cycle time.

In many cases, queuing networks are appropriate models for estimating cycle time. The queuing network approximations used offer some advantages and also have limitations. Compared to simulation models or more sophisticated queuing 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. The DFP tool presented in Section 4 uses this type of model.

4 DFP Application

This section describes a tool developed for estimating the manufacturing cycle time of a new product introduced into a manufacturing system that already produces an existing set of products. Section 4.1 first describes the tool and then presents the algorithm that it uses. Section 4.2 illustrates use of the tool in the domain of microwave modules.

4.1 Description

The product set to be input to the DFP tool comprises the set of existing products that the given manufacturing system is currently producing. The new product will be introduced into this set of existing products.

The manufacturing system for processing the products is represented by a queuing network model. 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.

The manufacturing system model requires the following data:

- For each workstation, the number of resources available, the mean time to failure for a resource and the mean time to repair the resource.

- For each existing product and the new product, job size (number of parts) and desired throughput (number of parts per hour of factory operation) along with the sequence of workstations that each job must visit.

- For each product-resource combination, the mean setup time (per job) at each workstation and its variance, the mean processing time (per part) at each workstation and its variance and yield at each workstation that a job must visit (the ratio of good parts produced to parts that undergo processing).

The DFP tool developed takes input in the form of critical product design information, manufacturing system information, and processing information. It includes domain specific functions for calculating processing times based on the critical design information. The flow chart is shown in Fig. 1. The routine that estimates processing times is application specific and will be explained in the example in Section 4.2. Unlike the highly specific tool described in Herrmann and Chincholkar [6], this tool supports scenarios in which the process plans have different operation sequences.

The tool first estimates system performance for the current product set. This represents the state of the manufacturing system before the new product has been introduced and serves as a reference for measuring the performance of the new product in the system and studying the effect that the new product introduction has on the existing product set. After this, the tool estimates the system performance when the new product has the specified throughput. The tool identifies whether the operations for the new product can be performed in the factory. It checks whether the machines required for the processes to make the new product, as specified by the user, are a part of the existing factory.

Once feasibility has been established, the utilizations of the various resources are calculated for the new product set (comprising the old product set and the new product). Additionally, the cycle times at each resource and for each product from the product set are also estimated. If the utilization of any resource is greater than one, the user is alerted to the need for increasing capacity at the resource. If the available capacity is sufficient for the specified throughput, the tool outputs the utilization of each resource and the cycle time for each product. The next step is to indicate to the user how the system behaves as the throughput of the new product varies. Thus, the tool confirms whether the

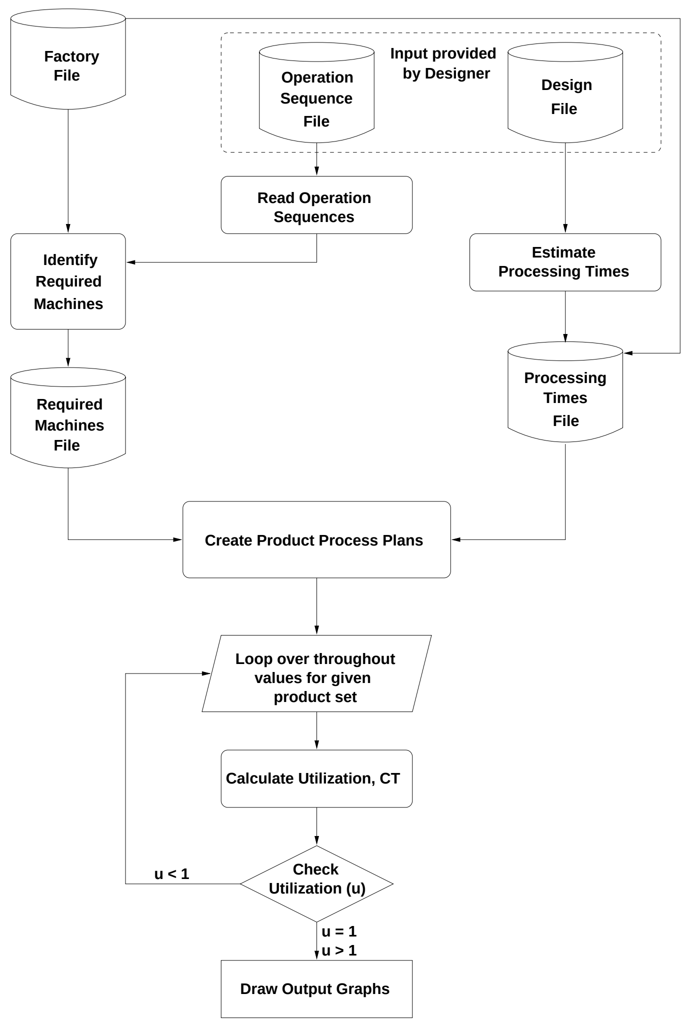

Figure 1: Flow Chart of DFP Implementation

new product is technologically feasible in the given manufacturing system, checks if there is capacity available to make it, and estimates the cycle times for each resource and product.

The DFP tool outputs the system performance results in two basic formats: for each resource, plots of machine utilization as a function of new product throughput; and for each product, the manufacturing cycle time as a function of new product throughput. In addition it plots the relative utilization of the different resources in the form of a bar graph for the specified new product throughput. The following algorithm gives the operating procedure for the tool. Note that Fig. 1 corresponds to Steps 1a, 1c, and 2g through 2k.

Algorithm:

1. Inputs:
   (a) The factory file, which describes the resource set $\mathcal{F}$ present in the manufacturing system
   (b) For the set $\mathcal{P}_{old}$ of existing products, a design file containing the set $\mathcal{D}_{old}$ of critical design information and an operations file containing the set $\mathcal{O}_{old}$ of operations sequences
   (c) The set $\mathcal{P}_{new}$ contains the products in $\mathcal{P}_{old}$ and the new product x. For $\mathcal{P}_{new}$, a design file containing the set $\mathcal{D}_{new}$ of critical design information and an operations file containing the set $\mathcal{O}_{new}$ of operations sequences
2. Program Execution:
   (a) For each product in $\mathcal{P}_{old}$, calculate the necessary processing times based on the critical design information in $\mathcal{D}_{old}$. Save the set $\mathcal{T}_{old}$ of times in the processing times file
   (b) From $\mathcal{O}_{old}$ identify the set $\mathcal{R}_{old}$ of required resources, and save in required machines file
   (c) If $\exists\ o \in \mathcal{O}_{old}$ such that o requires a resource r where $r \notin \mathcal{F}$, advise user. Exit
   (d) Create the set $\mathcal{Q}_{old}$ of process plans $\forall\ p \in \mathcal{P}_{old}$ using information from $\mathcal{R}_{old}$ and $\mathcal{T}_{old}$
   (e) Using $\mathcal{Q}_{old}$, calculate the utilization u_r, $\forall\ r \in \mathcal{R}_{old}$. If $u_r \geq 1$ for any $r \in \mathcal{R}_{old}$, advise user of insufficient capacity. Exit
   (f) Calculate the cycle times $CT_r^* \ \forall\ r \in \mathcal{R}_{old}$ and $CT_p \ \forall\ p \in \mathcal{P}_{old}$. Create output files for each resource and product
   (g) Repeat Steps 2a through 2d for $\mathcal{P}_{new}$ using $\mathcal{D}_{new}$ and $\mathcal{O}_{new}$ to create $\mathcal{Q}_{new}$
   (h) Using $\mathcal{Q}_{new}$, calculate the utilization u_r, $\forall\ r \in \mathcal{R}_{new}$.
   (i) Calculate the cycle times $CT_r^* \ \forall\ r \in \mathcal{R}_{new}$ and $CT_p \ \forall\ p \in \mathcal{P}_{new}$. Create output files for each resource and product
   (j) If $u_r < 1 \ \forall\ r \in \mathcal{R}_{new}$, then increase the throughput of x, the new product, by a predetermined amount and return to Step 2h
   (k) Plot results. Exit

The manufacturing cycle time for a product is the sum of the cycle times at each resource that it will visit. The cycle time at each resource and for each product may be calculated as,

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

$$CT_i = \sum_{j \in R_i} CT_j^* \quad (2)$$

where,

CT_j^* = the average cycle time at station j
CT_i = the average cycle time of jobs of product i
u_j = the average resource utilization at station j
c_j^a = SCV of interarrival times at station j
c_j^* = SCV of the modified aggregate process time
n_j = the number of resources at station j
t_j^* = modified aggregate process time at station j
R_i = the sequence of stations that product i must visit

Herrmann and Chincholkar [6] give a detailed explanation and formulation of the model. Although the DFP tool described here uses the same queuing network model, it is a much more general method and performs a larger range of analyses.

4.2 Example

This section describes a manufacturing system producing microwave modules (MWM) as an illustrative example. 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.

Microwave modules are electro-mechanical devices comprising an aluminum substrate with a Teflon dielectric layer and an artwork layer that includes many functional components of the circuit. The substrate supports the electronic circuit and its components, connects to the ground plane where it is mounted, and serves as a heat sink. Figure 2 shows the schematic of the microwave module and features

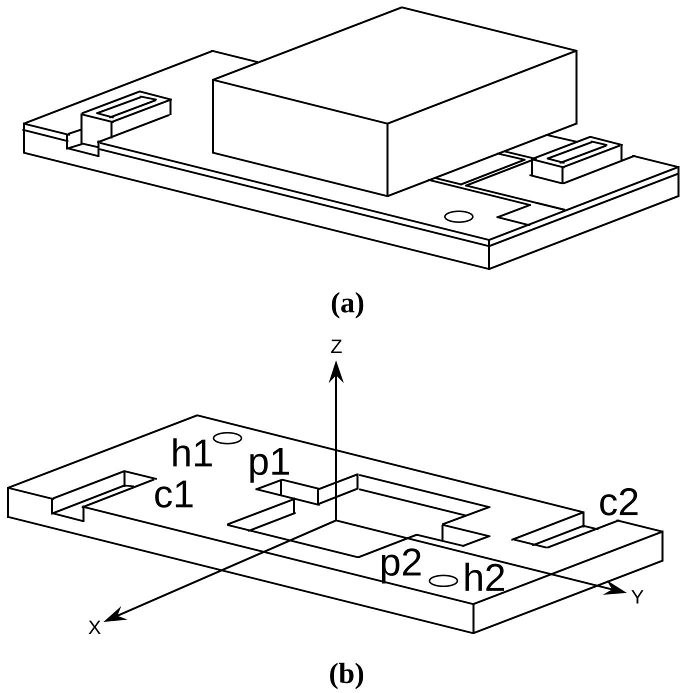

Figure 2: Microwave Module

No.	MWM Product_1	MWM Product_2	Improved MWM
1.	Grinding	Milling	Milling
2.	Drilling	Grinding	Grinding
3.	Etching	Drilling	Drilling
4.	Plating	Etching	Coating
5.	Automatic_ Assembly	Plating	Etching
6.	Manual_ Assembly	Automatic_ Assembly	Plating
7.	Testing	Testing	Automatic_ Assembly
8.			Manual_ Assembly
9.			Testing

Table 1: MWM Process Plans

of the substrate. The company purchases aluminum substrates that already have the dielectric layer. The processing includes machining the substrate, creating the artwork, assembling the electronic components on the substrate, and testing. More details about this domain can be found in Minis *et al.* [7].

Consider the following hypothetical scenario: the current product set for the manufacturer comprises *MWM_Product_1* and *MWM_Product_2*, two variants that are similar but have different process plans. The operations sequences for these products are shown in Table 1. The manufacturer intends to introduce a new product *Improved_MWM* into the market while maintaining the original set. The portion of the substrate where there is no artwork is insulated in the improved product. The aim is to prevent conduction between any extraneous electronic components which may come in contact with the aluminum substrate. This insulation requires a coating operation on a coating machine. The process plan for the new product is also shown in Table 1. Note that the new product has a different number and sequence of operations than either of the existing products. The specified throughput of the new product is 3.5 parts per min.

We present the detailed inputs for the tool in the form of relevant product design and manufacturing system information in an earlier paper [6]. The DFP tool determines how the new product will affect the utilization of the resources and estimates the manufacturing cycle time of the

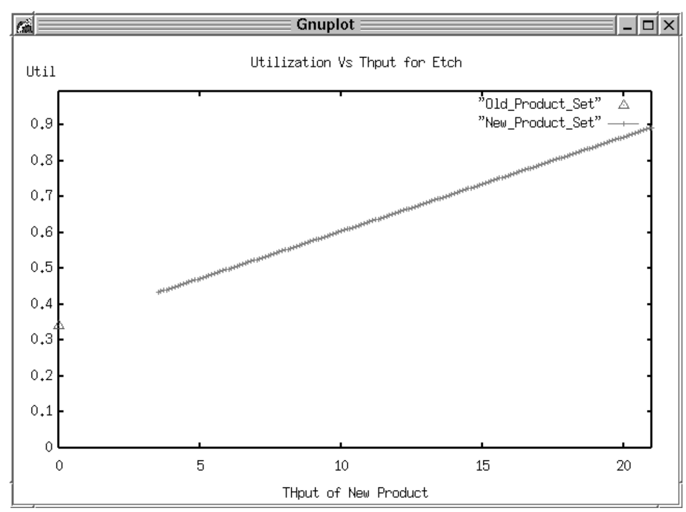

Figure 3: Machine Utilization as a function of New Product Throughput

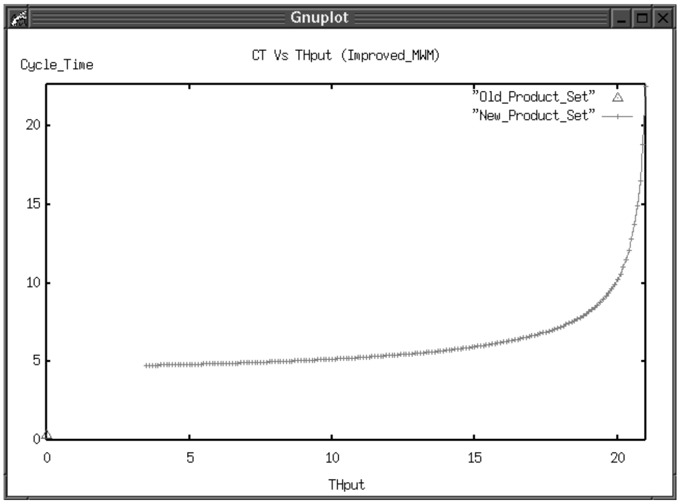

Figure 4: CT as a function of Throughput for New Product

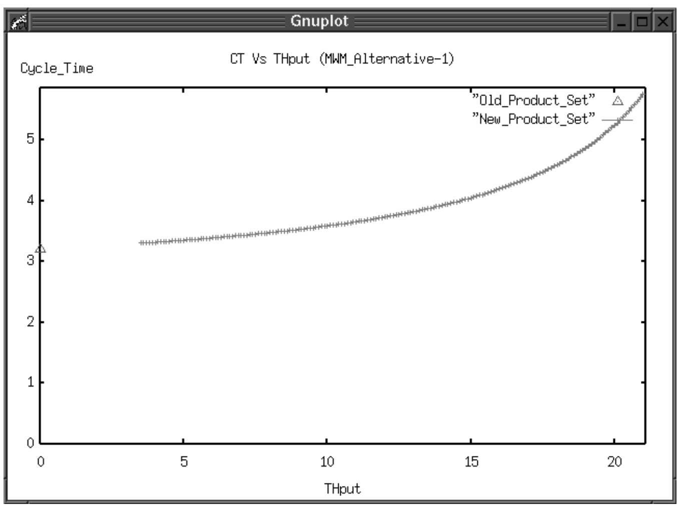

Figure 5: Old Product CT as a function of New Product Throughput

products. Some of the outputs from the DFP tool for the microwave module example are presented here. Figure 3 shows the utilization of the etching machine as a function of the new product throughput. Figure 4 shows the plot of manufacturing cycle time for *Improved_MWM* as a function of its throughput. Figure 5 shows the manufacturing cycle time for one of the existing products, *MWM_Product_1* as a function of the throughput of *Improved_MWM*. The manufacturing cycle time for the existing product increases as the throughput of the new product increases. Finally, Fig. 6 shows a bar graph indicating the utilizations of the various resources used at the specified throughput of new product.

The graphs of product cycle times versus new product throughput indicate the effect that introducing the new product has on each of the products in the current product set. As expected, the cycle times of the existing products that share resources with the new product also increase as the new product throughput goes up due to larger queue times at the shared resources, which have a higher utilization. Since the resource utilization plot is drawn for the user defined initial new product throughput, it indicates the performance of the manufacturing system at new product introduction.

5 Relating Manufacturing Cycle Time to Economic Gain

The product design has considerable influence on the manufacturing cycle time for the product. Changing the manufacturing cycle time has multiple impacts. This section discusses these impacts. To help us describe these impacts, we developed Fig. 7, which maps how reducing manufacturing cycle time increases the economic returns. In the figure, ovals represent product performance improvement opportunities, and rectangles indicate the end effects of such improvements. This section proceeds by explaining this map, along with the significance of the edges in the graph.

Ultimately we seek to model the economic impact quantitatively. Discussing the impact of a change in manufacturing cycle time is a type of sensitivity analysis that helps identify the important issues. Statements about the benefits of reducing manufacturing cycle time also implicitly indicate the negative impacts of increasing it.

Manufacturing cycle time for a product is composed of processing times and non-processing times. The processing times depend on the manufacturing operations involved. These operations are governed by the type and properties of the materials and the type of resources used. Considerable work towards reducing processing times has been conducted in DFM research. Minimizing setup times has also been the focus of many researchers. However, reducing the non-processing components such as queue times and move times also significantly reduces total manufacturing cycle time. This would have a significant positive impact on the economic returns from new product introduction, including reduced product costs, increased product sales and increased revenue. These benefits, in turn, increase profits. In this section we explain the links and components in Fig. 7. Taken together, these links and components show how reducing manufacturing cycle time increases product profitability.

Edge aa indicates that reducing the manufacturing cycle time reduces the work-in-process inventory. This is substantiated by Little's Law [16]. This reduction in work-in-process inventory also means that whenever a new product is introduced and production of an old product is sus-

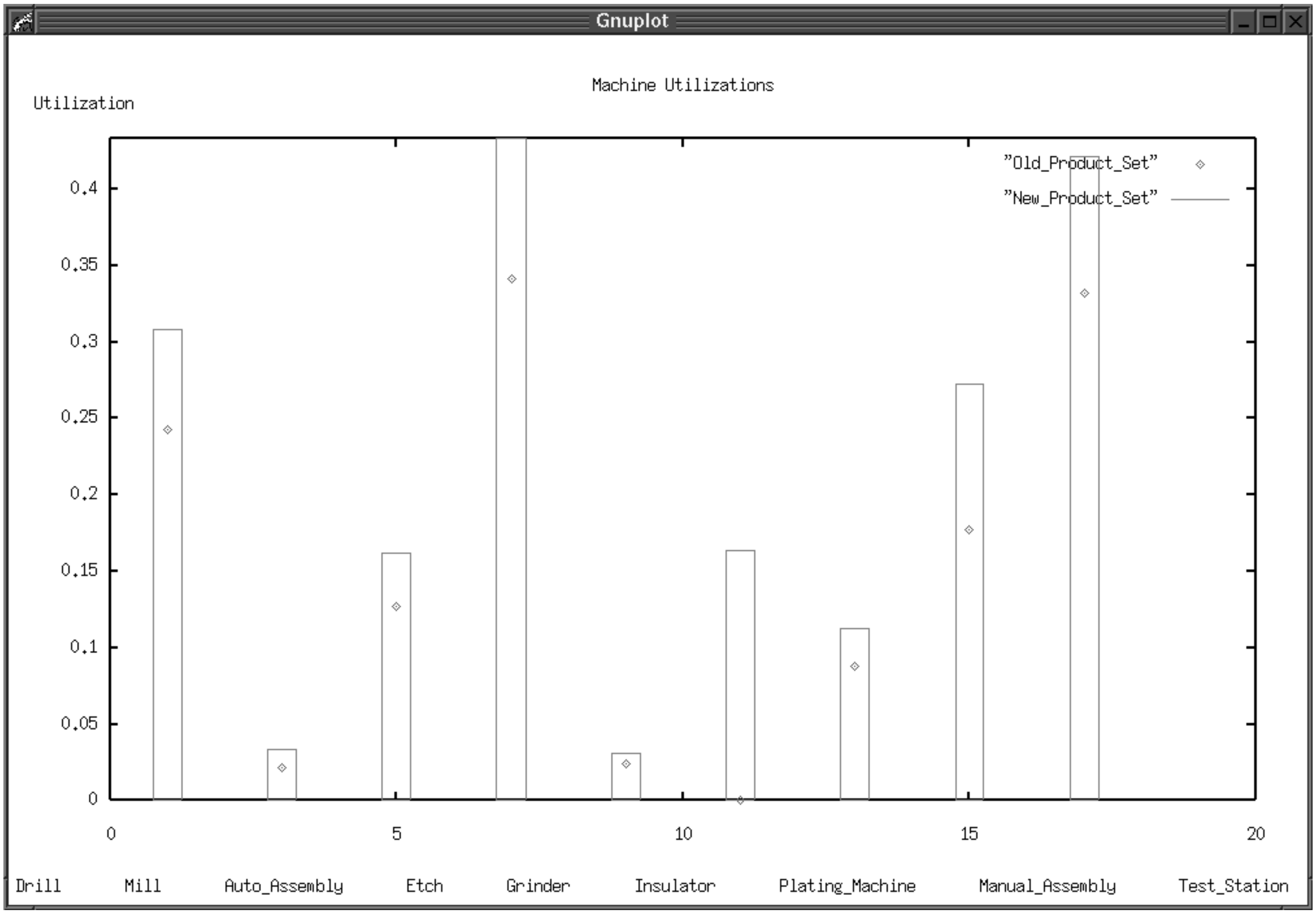

Figure 6: Utilizations of various resources

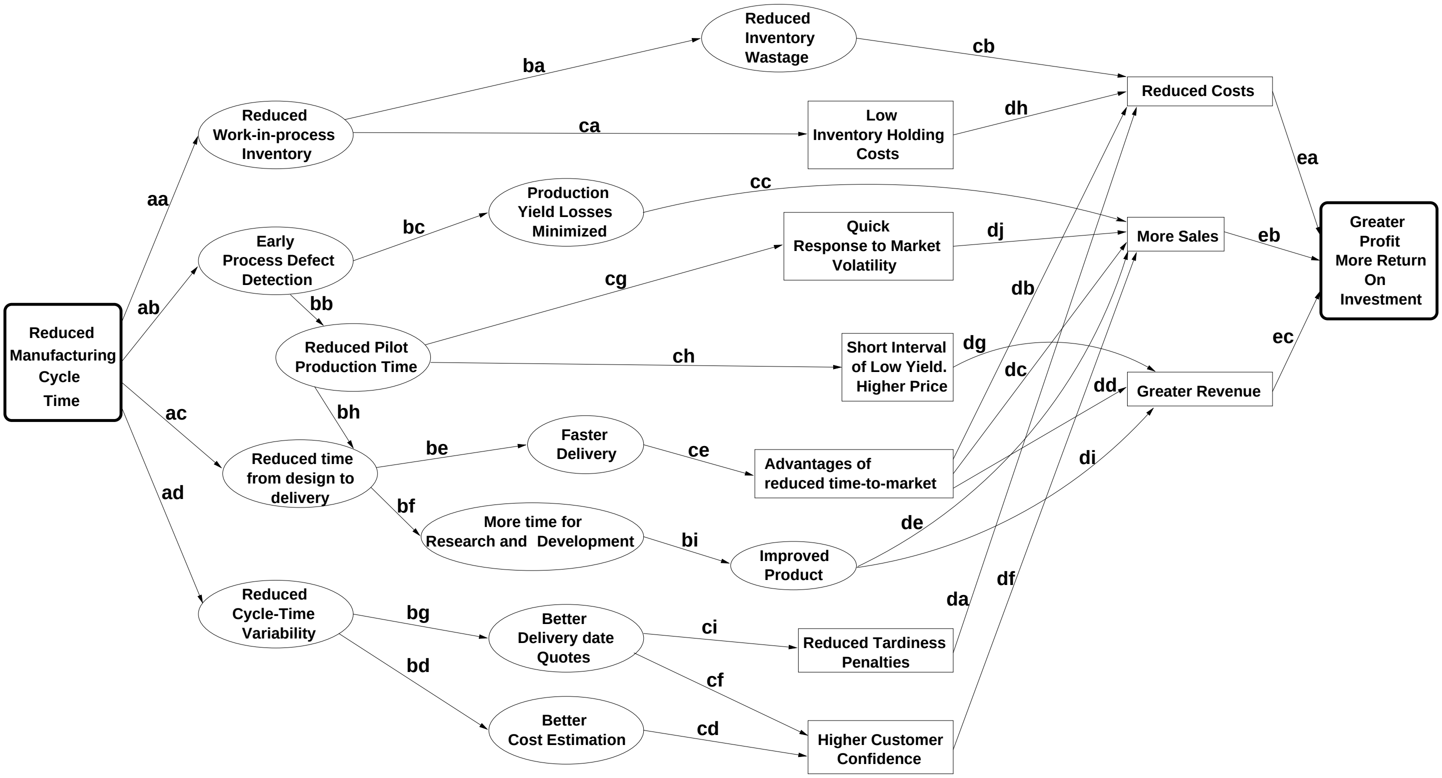

Figure 7: Map between reduced manufacturing cycle time and economic gains

pended, there is less waste from the incomplete jobs (of the earlier product) that are undergoing processing but are now useless [17]. This relationship is represented by *edge ba* in the figure. *Edge ca* shows the economic effect of this reduction in work-in-process inventory, which is to reduce the costs associated with holding this inventory [18]. Reducing the inventory waste reduces the cost associated with the material and processing of these products, as shown by *edge cb*, thus lowering the losses to the manufacturer and reducing a contributor to the product cost [17]. Since inventory holding costs contribute to the total cost of the product, *edge dh* indicates that reducing in these costs will reduce the overall product cost.

A reduced manufacturing cycle time allows for earlier detection of any problems that might be present in the manufacturing process (*edge ab*). This means that the process is rectified before damage is done to a large number of jobs. This in turn means that the yield losses are minimized because fewer products become defective, as indicated by *edge bc*. Benefits of early rectification also include a quicker ramp-up of production during the pilot production phase as well as faster process feedback which is very critical, as shown by *edge bb*. Products like semiconductor wafers have very volatile markets wherein not only does the product type change at frequent intervals but also the demand fluctuates considerably. The nature of the product market is such that the selling price decreases rapidly over time. Hence, the product returns are maximum closest to the launch and it is necessary to be able to supply as much of the product immediately after launch as possible. Nemoto *et al.* [19] provide substantial evidence to these facts. As indicated by *edge cc*, lower yield losses reduce the number of faulty parts, and hence a larger number of products are available for sale. Similarly, reduced manufacturing and hence development cycle time means that the manufacturer is able to cope with this market volatility effectively, as shown by *edge cg*. *Edge ch* shows that the reduced pilot production time allows for a shorter interval of low yield. An added advantage for the manufacturer is the possibility of charging a higher price during this period due to a lack of competent competition. Thus, increased production with higher prices during the early phases of product introduction could result in higher revenues (*edge dg*). As shown by *edge dj*, a quicker response to changes in the market demand means that the changing requirements of the market can be met more easily and earlier resulting in higher sales [20].

Reducing manufacturing cycle time means that the product completes manufacturing faster. Manufacturing cycle time is a component of the total product development

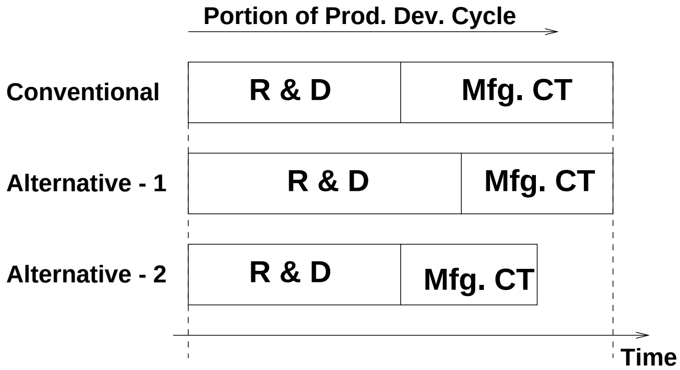

Figure 8: Lower manufacturing cycle time allows more time for research and development

time. Hence reducing this time reduces the total development time (from conceptualization to actual delivery to the customer) as shown by *edge ac*. The total product development time is also reduced by reducing the time for pilot production runs (*edge bh*) [20, 19]. *Edge be* shows the effect of this reduction, which is that the product can now be delivered earlier [21, 22]. Another interesting aspect of an efficient development cycle, as indicated by *edge bf*, is that the reduced manufacturing cycle time provides more time for research and development while maintaining the same product introduction time. Cohen *et al.* [20] stress that product improvement is more valuable than unnecessarily early introduction into the market. Figure 8 illustrates these two benefits of reduced manufacturing cycle time. As a result of the additional time available for research, an improved product can now be introduced in the market (*edge bi*). Faster product development brings with it all the advantages inherent to short time-to-market indicated by *edge ce* and documented widely in literature [21, 8, 9, 23], including but not limited to reduced costs, more sales, and higher revenue. In addition, for a domain such as wafer fabrication, time-to-market assumes a different dimension since there exists some scope of dictating the price of the product for some period after launch till the competition enters the market. *Edges db, dc* and *dd* represent the benefits of reduced time-to-market while *edges de* and *di* show that an improved product introduction yields higher sales. Also important is the possibility that the manufacturer can expect to charge a higher price, with an improved product, depending on its quality relative to that of competitive products. All these advantages result in increased revenue [20, 19].

The manufacturing cycle time depends on a number of manufacturing system and product variables, some of which are random in nature. As the cycle time for the product increases, the probability of occurrence of failure increases (*edge ad*). Thus the probability of completing an order on time decreases and the variance of the manufacturing cycle time increases [16]. This is clearly seen in the case of a manufacturing system approximated by a M/M/1 queue wherein the processing and interarrival times for the jobs are exponentially distributed. For an exponential distribution, the mean and variance are both functions of the scale parameter only. Hence a low mean means a low variance as well. Similar arguments can be presented for other distributions including the gamma (Erlang), Poisson, and Weibull distributions. *Edge bd* indicates that the reducing the variability of the cycle time allows for a more robust estimation of the costs involved. This results because the time-related costs such as operator hours needed per part can be more accurately estimated [16]. If the cost estimations are accurate in the beginning, the manufacturer does not need to update the price at a later date. This increases customer confidence and minimizes losses that the manufacturer may need to bear due to low price quotes (*edge cd*). Concurrently, increasing the variability of the manufacturing cycle time increases the error in estimating the lead time for product delivery, making it harder to quote an accurate lead time to the customer. Thus, by reducing this variability, an accurate lead time can be quoted [16] (*edge bg*). Delivering goods on the date promised (accurate lead time quotes) increases the confidence of the customer (*edge cf*) and also helps maintain customer loyalty [24]. Also, delivering the product to the customer on time avoids tardiness penalties (*edge ci*). The economic implications of these benefits are indicated by *edges da* and *df*. The tardiness penalties translate into direct costs to the manufacturer. Hence, avoiding or minimizing these penalties results in a reduction in cost. Higher customer confidence leads to an increase in sales. Also customer loyalty ensures steady product sales and a better market for any new product.

The product profit or return on investment is usually defined to be the difference between the total revenue and the total costs. Reducing costs and increasing sales and revenue yields increased profits and returns on investment for the manufacturer (*edges ea, eb* and *ec*). Thus, reducing manufacturing cycle time has a considerable influence on increasing the revenue from the product.

6 Summary and Conclusions

This paper presents an application of the DFP approach and describes a tool developed for estimating the manufacturing cycle time of a new product introduced into an existing manufacturing system. An example illustrates the use of the tool in the domain of microwave module manufacturing. Plots of manufacturing cycle time for the products and resource utilization describe the impact of the new product on the manufacturing system and the existing product set.

This paper also describes the economic impact that results from reducing manufacturing cycle time. The impacts include lower costs, increased sales, and greater revenue. The paper presents a figure that helps understand the relationships.

Clearly, product development teams should estimate manufacturing cycle time and include the economic impact of manufacturing cycle time when evaluating product designs and deciding which alternatives to develop. The results in this paper indicate what these impacts will be. More work is needed and ongoing to model these relationships quantitatively. Such mathematical models could be used in design optimization or tradeoff analysis methods.

Acknowledgments: This research was supported by the National Science Foundation under grant DMI 97-13718.

References

[1] Ahmadi, R. and Wang, R.H., "Managing Development Risk in Product Design Process," Operations Research, **47**, no 2, pp 235-246, 1999.

[2] Balachandra, R., "Some Strategic Aspects of Faster New Product Introduction," *Engineering Management Conference*, pp 226-229, July, 1991.

[3] Bralla, J.G., *Design for Excellence*, McGraw-Hill Inc., USA, 1996.

[4] Burhanuddin S. and Randhawa, S.U., "A Framework for Integrating Manufacturing Process Design and Analysis," Computers and Industrial Engineering, **23**, nos 1-4, pp 27-30, 1992.

[5] Locasio, Angela, "Manufacturing Cost Modeling for Product Design," The International Journal of Flexible Manufacturing Systems, **12**, pp 207-217, 2000.

[6] Herrmann, J.W., and Chincholkar, M.M., "Design for production: A tool for reducing manufacturing cycle time," paper DETC2000/DFM-14002 in *CD-ROM Proceedings of DETC 2000, 2000 ASME Design Engineering Technical Conference*, pp 1-10, Baltimore, September 10-13, 2000.

[7] Minis, I., Herrmann, J.W., Lam, G., and Lin, E., "A generative approach for concurrent manufacturability evaluation and subcontractor selection," Journal of Manufacturing Systems, **18**, no. 6, pp 383-395, 1999.

[8] Govil, Manish, "Integrating product design and production : Designing for time-to-market," Ph.D. Thesis, University of Maryland, College Park, USA, 1999.

[9] Govil, M., and Magrab, E., "Incorporating production concerns in conceptual product design," International Journal of Production Research, **38**, no. 16, pp 3823-3843, 2000.

[10] Taylor, D.G., English, J.R., and Graves, R.J., "Designing new products: Compatibility with existing product facilities and anticipated product mix," Integrated Manufacturing Systems, **5**, no 4/5, pp 13-21, 1994.

[11] Lee, Hau L., Billington, C., and Carter, B., "Hewlett-Packard gains control of inventory and service through design for localization," Interfaces, **23**, no 4, pp 1-11, 1993.

[12] Nielsen, N., Heeser, P., and Holmstrom, J., "Design for speed: a supply chain perspective on design for manufacturability," Computer Integrated Manufacturing Systems, **8**, no 3, pp 223-228, 1995.

[13] Kusiak, A., and Weihua He, "Design of components for schedulability," European Journal of Operational Research, **76**, pp 49-59, 1994.

[14] Soundar, P., and Bao, Han P., "Concurrent design of products for manufacturing system performance," *Proceedings of the IEEE 1994 International Engineering Management Conference*, pp 233-240, Dayton, Ohio, October 17-19, 1994.

[15] Herrmann, J.W., and Chincholkar, M.M., "Models for estimating manufacturing cycle time during product design," *Proceedings of* 10^{th} *International Conference on Flexible Automation and Intelligent Manufacturing*, Vol 1, pp 576-585, College Park, Maryland, June 26-28, 2000.

[16] Hopp, Wallace J., and Spearman, Mark L., *Factory Physics*, Irwin/McGraw-Hill, Boston, 1996.

[17] Lu, S.C.H., Ramaswamy, D., and Kumar, P.R., "Efficient scheduling policies to reduce mean and variance of cycle-time in semiconductor manufacturing plants," IEEE Transactions on Semiconductor Manufacturing, **7**, no. 3, pp 374-388, August 1994.

[18] Vollmann, T.E., Berry, W.L., and Whybark, D. Clay, *Manufacturing Planning and Control Systems*, 4th edition, Irwin/McGraw-Hill, New York, 1997.

[19] Nemoto, K., Akcali,E., and Uzsoy, R.M., "Quantifying the Benefits of Cycle Time Reduction in Semiconductor Wafer Fabrication," IEEE Transactions on Electronics Packaging Manufacturing, **23**, no. 1, pp 39-47, Jan 2000.

[20] Cohen, M.A., Eliashberg, J., and Teck-Hua Ho, "New Product Development: The Performance and Time-to-Market Tradeoff," Management Science, **42**, no. 2, pp 173-186, February 1996.

[21] Datar, S., Jordan, C., Kekre, S., Rajiv, S., and Srinivasan, K., "New Product Development Structures and

Time-to-Market," Management Science, **43**, no. 4, pp 452-464, April 1997.

[22] Weng, Z.K., "Strategies for integrating lead time and customer-order decisions," IIE Transactions, **31**, pp 161-171, 1999.

[23] Smith, P.G., and Reinertsen, D.G., *Developing products in half the time: new rules, new tools*, Van Nostrand Reinhold (International Thomson Publishing Company), New York, 1998.

[24] Garg, Amit, "An application of designing products and processes for supply-chain management," IIE Transactions, **31**, pp 417-429, 1999.

