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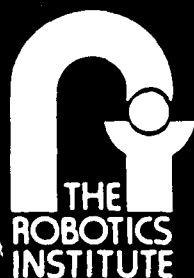
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**A Methodology to Assess the Strategic Benefits
of New Production Technologies**

Aydan Kutay and Susan Finger

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Carnegie Mellon University

The Robotics Institute

Technical Report

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Abstract

In this paper, we develop a formal methodology to enable firms to assess the economic benefits of new production technologies, particularly, the integrated design and manufacturing systems. The methodology accounts for the benefits of new technologies that are not captured or quantified using the current methods of capital investment. Many new production technologies have been developed to help meet long term strategic goals such as product quality, delivery speed, reliability, and rapidity of new product introduction. Traditional economic analysis, with its focus on reducing labor costs, does not capture these strategic advantages that make new technologies attractive. Our methodology integrates investments in new production technologies into the business strategy of a firm. By creating a formal description of the role of new technologies in improving a firm's competitive position, the economic benefits of new technology can be assessed systematically. The methodology stresses the connections between competitiveness of the firm and the limitations imposed by its existing technological capability.

1. Introduction

A consensus is growing among academicians, business leaders, and government officials that America's competitive problem rests on our failure to integrate new production technologies into our manufacturing systems. Although new design methodologies and manufacturing technologies are continuously being created in U.S. universities and research centers, American firms are slow to adopt these technologies. We contend that the reluctance of many firms to adopt new technologies partly reflects the inability of current capital investment justification methods to assess the long term strategic benefits of new engineering technologies. Firms that could achieve substantial benefits from new technologies may fail to use them simply because current methodologies do not quantify the strategic benefits, such as reduced lead times, faster response to market shifts, and increased flexibility in product differentiation.

In recent years, the difficulty in realizing the economic benefits of new technologies has received increasing attention from both academics and practitioners [Cohen 87, Hayes 88, Kaplan 89, Kutay 89a]. Prior studies on the evaluation of new manufacturing technologies have either assessed the system's profitability by traditional capital budgeting techniques such as discounted cash flow [Kaplan 86, Johnson 87, Johnson 88] or have emphasized the strategic aspects of new technology without providing a firm methodology to measure the strategic benefits [Primrose 84, Primrose 87, Williams 87]. The implicit assumption in these studies is that firms continue to produce the same product mix in deterministically known quantities in a status-quo market. These assumptions run counter to current market conditions. A major benefit of new technologies is the ability to respond rapidly to the variability of market conditions. By integrating design and manufacturing operations through new technologies, firms can effectively gain a competitive edge by attaining a faster response time to changing market conditions.

Our methodology will integrate investments in new production technologies into the business strategy of a firm. By creating a formal description of the role of new technologies in improving a firm's competitive position, the economic benefits of new technology can be assessed systematically. The methodology stresses the connections between competitiveness of the firm and the limitations imposed by its existing technological capability. In addition, we assume that the goal is to increase variety, quality, and reliability of new products as opposed to the prior goal of reducing labor costs.

The methodology will be tested using two competing technologies for the rapid production of tooling for injection molding; the two systems are the Rapid Tool Manufacturing (RTM) [Weiss 89] system and the Intelligent Machinist Workstation (IMW) [Bourne 89]. Both technologies are currently being integrated with a concurrent design system, Design Fusion [Finger 88], so that we can design a part and then automatically either produce a prototype of the part or produce its tooling for injection molding. All three systems are under active development at the Engineering Design Research Center (EDRC) and the Robotics Institute at Carnegie Mellon University.

One of the sponsors of the RTM project, the Aluminum Company of America (ALCOA) will work with us to supply economic data to assess the economic benefits of these systems. As a test case, we will use the design and manufacture of the tooling for injection-molded building products such as shutters and window trim. These products are well-suited for this study because rapid styling changes, and hence rapid redesign and tooling, are often needed to meet customer requirements.

2. The Nature of the Technology Assessment Problem

Typically, U.S. firms use a capital investment procedure to allocate current resources in the prospect of future returns when deciding whether to adopt a new technology. The principles of these techniques were laid down in 1934 when labor was the chief variable cost and when mass production propelled U.S. industry to world dominance. These techniques still shape and generate decisions in such a way that the required level of financial attractiveness is achieved by focusing on short term financial goals and responding to the implied needs of a forecasted future by reducing labor costs. However, over the last 20 years, direct labor costs have been reduced to about 10 to 12% of the total production costs, so the savings from further reductions in labor costs are too small to justify investments in new technology. Many of the new production technologies have been developed to help meet long term strategic goals such as product quality, delivery speed, reliability, and rapidity of new product introduction. Traditional economic analysis, with its focus on reducing labor costs, does not capture these strategic advantages that make new technologies attractive. In many cases, retaining the existing manufacturing equipment

performs as a more profitable alternative than investing in new technology. Firms that could achieve substantial benefits from new technologies may fail to use them because there is no acceptable methodology to quantify the return on investment.

2.1. Economies of Scope

The foundations of economic theory were developed at the same time that mass production was becoming predominant. In the system of mass production, the major production strategy to expand profits was to increase the size of the total target market. The major dilemma a firm faced to meet competition was, therefore, to lower unit costs to expand the size of the market for its products. The unit costs were lowered through economies of scale and by lowering labor and raw material costs through capital investments. Capital investments in new technology were justified by their potential to replace human labor with machines.

Once the world markets began to saturate during the 1960s and the 1970s, it became increasingly clear that mass production of standardized products was no longer profitable since the size of the total target market could not be expanded. With an increase in international competition, the number of manufacturers in the market multiplied, resulting in a large number of differentiated products on the market. The emphasis to gain the markets shifted from *economies of scale* to *economies of scope*. Using economies of scope, manufacturers produce a variety of products to satisfy a greater range of market needs by increasing the capacity to manufacture goods in small batches.

Economies of scope exist if a single plant can produce a variety of products at lower unit cost than a combination of separate plants each producing a single product at the given level of output [Kutay 89b]. By integrating new manufacturing technology with its operations, a firm can increase the probability of capturing different market segments representing different consumer tastes by increasing product differentiation without making the existing equipment obsolete and without the loss of marketing opportunities. Tailoring products to consumer tastes to increase the market share becomes not only possible but more economically feasible because the cost penalty for variety is substantially removed.

The economic foundations of the benefits derived from new technologies are fundamentally different from the benefits obtained from capital investments in the mass production system. The main benefits of many of the new technologies, particularly the integrated design and manufacturing technology, such as reduced lead times, faster response to market shifts, and increased flexibility in product differentiation, do not enter into the calculations of the conventional measures of capital investment procedures currently used by American firms to justify the adoption of new manufacturing and design technology. There is great need for the development of a methodology that takes into account the long term strategic benefits of new technologies. We believe that integrated design and manufacturing technology will improve the long term strategic position of a firm in the market by reducing the lead time to introduce new products to the market. It, therefore, serves as a relevant testbed for the development of a methodology to justify the return on investment by considering long term strategic factors.

2.2. Using Technology to Reduce Market Uncertainty

The conceptual basis of the economic assessment of new production technologies developed in this paper rests on the assertion that a firm competes based on economies of scope by introducing a high variety of products to the market in the shortest time period. Given the current trend of the rapid obsolescence of products the best strategy to compete in the market is to produce many new products rapidly. New integrated production technologies enable the firm to undertake the production of a large number of differentiated versions of similar products without being subject to increased costs commonly experienced with long design cycles and inflexible manufacturing technology.

A firm can reduce its uncertainty about the variability in the market conditions through timely introduction of new products to the market. To express the analytical foundation of the integration of uncertainty factors into the economic evaluation analysis, we use the Lancasterian method of viewing a product as an n -element vector [Lancaster 79]:

$$P = [p_1, p_2, p_3, \dots, p_n]$$

where p is the product characteristics vector and each of the n dimensions is a different characteristic sought after in the market. Similarly, a given user of the product has a user characteristics vector:

$$u = [u_1, u_2, u_3, \dots, u_n]$$

in the same n -dimensional space.

If $p = u$ for the case of a given user, the probability of the product being sold to a user would be 1; that is, the characteristics of the product would exactly match the desires of the consumer. The probability decreases as u and p diverge from each other. Thus, the probability of sale to a potential user can be expressed as a stochastic function:

$$P(S) = \psi$$

where

$$\psi = p_i - u_i$$

for every i th characteristic.

In a world of complete certainty about the users and zero cost to offer variety, the firm could capture the entire market by reducing ψ to zero. In the absence of this unlikely situation, the firm must minimize ψ subject to the constraint that the marginal revenue from an additional variety is greater than the marginal cost of offering that variety.

The ψ factor can be influenced by finding the average user characteristics vector. This vector can be obtained by dividing a population of potential users into subpopulations whose preferences are relatively close to each other. In this way, the firm tries to find the average user characteristics vector of each subpopulation and tries to design a product to fit that average. If subpopulation j has N_j users, then the average user characteristics vector would be:

$$\mu_i = \sum_{j=1}^N \frac{u_{ij}}{N_j}$$

for every characteristic i .

Given the above equation, and considering that user characteristics u_i are not mutually independent, a firm can maximize the certainty of sales to a subpopulation j by offering a variety such that $p = \mu$.

However, even when $p = \mu$, a firm still faces uncertainty in the magnitude of demand for its product. The larger the subpopulation of j , the greater will be the uncertainty, expressed in terms of the standard deviation vector σ :

$$\sigma = \left[\sum_{j=1}^N \frac{(u_{ij} - \mu_i)^2}{N_j} \right]^{0.5}$$

Thus, increasing the product variety offered by the firm to the market increases the number of subpopulations and reduces the number of users in each subpopulations, reducing the uncertainty of the firm in determining the magnitude of demand for its products.

The increase in the certainty that a firm has about the variability of market conditions obtained through product differentiation is integrated into our analysis in two ways: through the determination of market share in the goal state of the firm in the market, and through the finished goods inventory holding costs. These are discussed in detail in Appendix A.

3. A Methodology to Assess the Strategic Benefits of New Technology

Our methodology to assess the economic benefits of integrated design and manufacturing systems takes into account:

- A firm's competitive position in the market
- A firm's existing manufacturing operations
- The benefits of new design and production technologies such as
 - reduced lead times for design and manufacturing

- increased product and manufacturing flexibility
- improved quality
- increased reliability
- The time horizon over which the benefits of new technologies are realized

An overview of the assessment process is illustrated in Figure 1.

The model's overall structure is shown in Figure 2. This figure illustrates that the economic evaluation of new technology is composed of determining the benefits and costs in order to derive the profitability of investment in new technology. Appendix A gives a detailed explanation of the computation of costs and benefits of new technologies, and the links between the firm's competitive position, its market, and technology.

3.1. Competitive Position in a Market

To develop performance measures of the firm's competitive position in the market first requires a characterization of the market in which a firm competes. We use the following three measures to characterize the firm's market:

1. *Size of demand* to measure the magnitude of the market
2. *Market growth rate* to measure the strength of the market
3. *Frequency of new product introduction* to measure variability in the market

A firm's competitive position in the market is an important factor in assessing the benefits of new production technologies. The technological requirements of a firm operating in a stable market with a substantial share of market demand are different from a firm with a small share of a volatile market with a high frequency of new product introduction. A firm's current competitive position is expressed by its market share, the growth rate of its market share, and the weight of that particular market in its total activity.

Four measures are used to characterize the firm's goal for its competitive position in the market.

1. *Product differentiation*: Frequency of new product introduction required for the firm to capture the market growth during the investment period
2. *Response time*: Time required for the firm to respond to changing market conditions by introducing new products into the market. This value is exogenously determined in the market and represents the time necessary for the firm to introduce a new product from the time of its conceptualization to actual manufacturing. This value is constrained by the firm's existing technological capability.
3. *Market share*: The desired share of the market.
4. *Technological capability*: Required technological capability to undertake product differentiation to achieve the new goal state in the market.

Through product differentiation, a firm can reduce the uncertainty in market demand for its products. The new competitive state achieved through greater frequency of product differentiation in turn influences the firm's market share and together with market growth, determines distribution of demand for the firm's products.

We determine the extent of product differentiation required of the firm to improve its competitive position in the market by considering market characteristics and the firm's current competitive position in the market. We assume that firms can produce variants of a product and that the product variants can be formed into groups that share design and manufacturing characteristics. To expand its market share for products of group g , a firm can increase its product variety to achieve a closer match between the consumer requirements vector and the product characteristics vector. The extent of product differentiation necessary for the firm to expand its market share is determined by the frequency of new product introduction in the given market. The probability of a new product being introduced at time t by any firm in the market can be obtained from observations of the past market data:

$$D_g(t) = \text{random variable of the demand for products in group } g \text{ at time } t$$

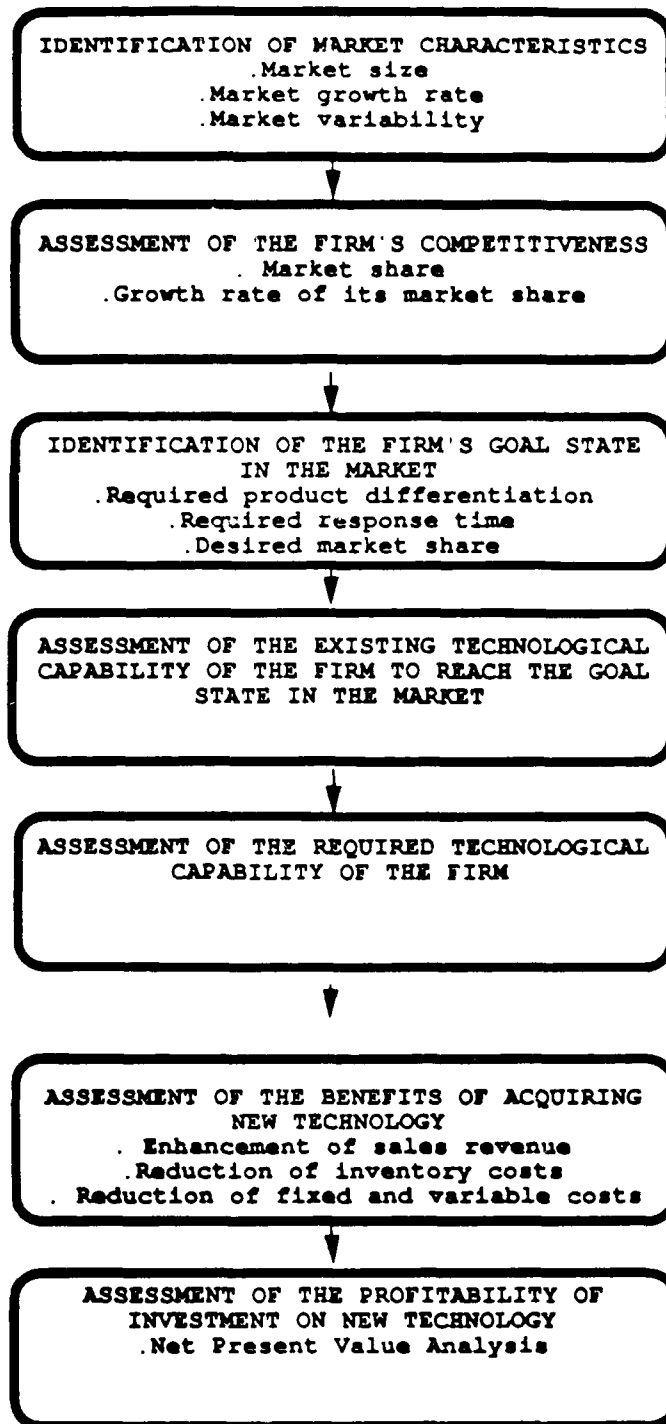


Figure 1: The steps of the economic evaluation of automation technology

Using $P_{gi}(t)$, probability that a new product of type ig is introduced to the market at time t , a realization for

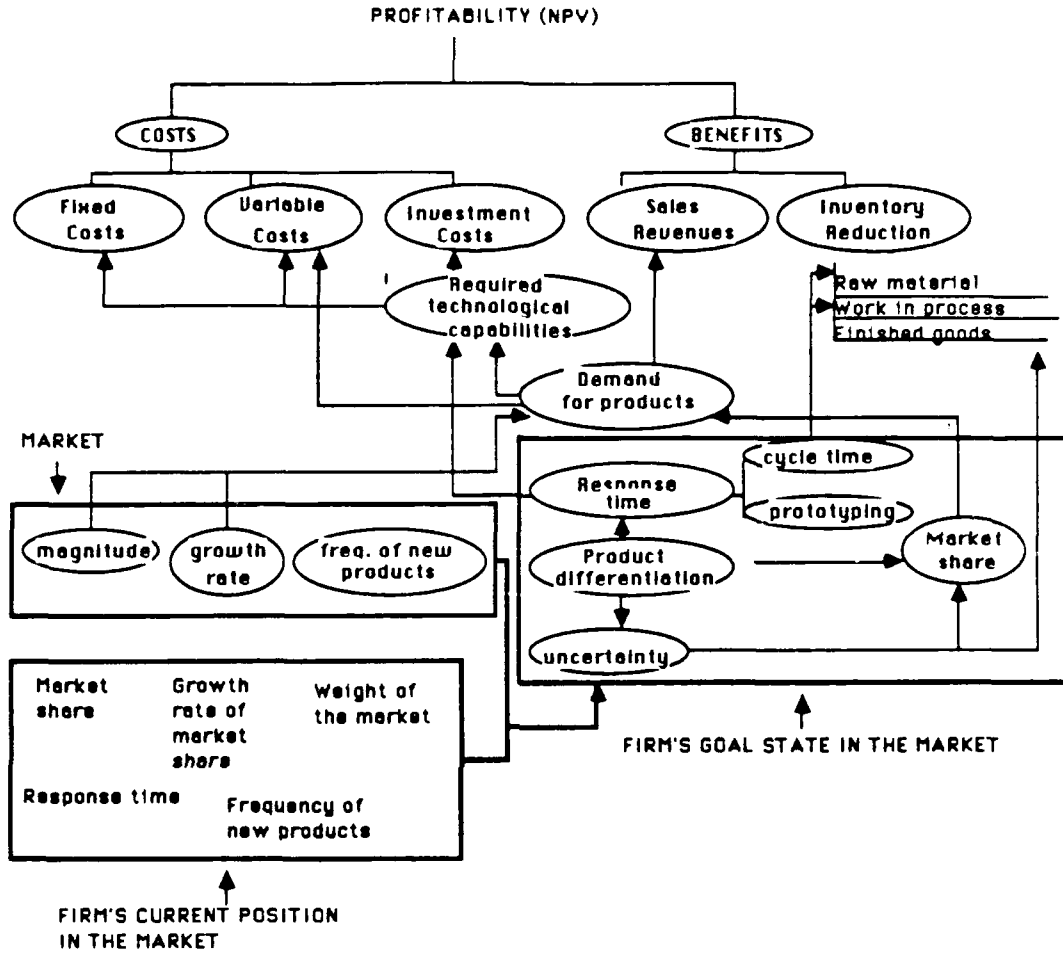


Figure 2: The structure of the economic evaluation of automation technology

the time at which a new product is introduced T_{gi} can be computed. If a new product is introduced to the market at time T_{gr} by introducing a new product at time T_{gi} or earlier, the firm captures the market growth for product group g during the period between the introduction of the last product version to the market and T_{gr} . Demand for the firm's products in group g at time t is then:

$$d_g(t) = W_g(t) D_g(t)$$

where $W_g(t)$ is the firm's share of the market at time t for products in group g .

$$W_g(t) = \kappa_g(t) W_g(t-\Delta t)$$

where $\kappa_g(t)$ is the market growth rate over time Δt for the firm.

Demand for products in group g during time period t is divided among the variants of the product subject to the conditions that the market share of each product w_{gi} is not greater than the maximum value of market share and that the sum of all market shares equals one. Finally, the statistical distribution of demand for each variant of a product group $d_{gi}(t)$ is given by considering the market share for variant i of group g at time t . The demand for the firm's products in group g is given by:

$$d_{gi}(t) = w_{gi}(t) d_g(t)$$

3.2. Technological Capability

The technological capability of a firm is critical in determining the time it takes a firm to introduce new products to the market. One can compute both the time it takes to introduce a new product using the existing technology, and one can compute the technological capability needed for the firm to introduce a new product before its competitors. We call this *the required technological capability*. The required technological capability of the firm is determined from the statistical distribution of product demands and the length of time the firm needs in order to introduce a new product in time. The firm's existing manufacturing operations must be taken into consideration before a decision is made to invest in new technology. Firms first consider increasing production capacity by acquiring new machines and equipment before acquiring new technology. To assess the ability of the existing technology to meet the firm's needs, we consider the following two variables: the probability that a new product in a particular product group uses the same prototyping and manufacturing processes required by the last product version in the same group, and the time available for work from each process in prototyping and in manufacturing. Examples of processes are design detailing, milling, and spraying.

The required technological capability is determined by considering the lead time for a new product. The lead time is composed of two parts: the prototyping time t_p , and the manufacturing time t_m . We first determine the time that a new product requires for each process in prototyping and manufacturing. Then, we determine the number of resources required given that each resource q can perform a set of processes L_q with a given reliability. Using optimization, we determine the number of resources, n_q , required in order to meet the response time.

3.3. Costs and Benefits of New Technologies

The costs of new technologies are composed of the fixed, variable, and investment costs. Variable costs are determined by the demand and by the available resources, while investment costs are determined by the required technological capability of the firm. From the computation of the number of resources of each type required to meet the demand, we can compute the number and type of new resources that must be acquired for the firm to meet the response time.

The benefits due to integrated design and manufacturing technology such as improved quality, reduced lead times, and increased flexibility, that are considered to be intangible and are not quantified in current practices of capital investment, must be an integral part of the economic analysis. We quantify these benefits by considering the firm's new competitive position in the market through two measures: potential enhancement of sales revenue and potential reduction in inventory costs. Sales revenue is determined by the demand for the firm's products. As can be seen in Figure 2, demand reflects the new market share of the firm as a result of the timely introduction of new products to the market.

Shorter product lead times reduce the raw material inventory because the firm has better control over the demand for its products, over the lead-time demand for raw material, and over the expected number of backorders per cycle. These factors enter into the quantification of benefits through the following equation:

$$C_R(\rho, Q) = \frac{A}{Q}k + \gamma \left[\frac{Q}{2} + \rho - \mu \right] + k \frac{A}{Q} B(\rho)$$

where A is average annual demand rate for raw material, Q is number of items ordered each time, k is cost per order, γ is inventory holding cost per unit (investment plus storage cost), ρ is reorder point, μ is average lead-time demand, and $B(\rho)$ is the expected number of backorders per cycle.

Shortening the product lead time also reduces the work-in-process inventory. In addition, if the new technology is more reliable and controllable than the previous technology, then these differences must also be taken into account. These factors enter into the calculation of the benefits due to changes in WIP inventory as follows:

$$C_W = \int_0^T r c W dt + n_f \int_{W/a}^{\Delta T} k(a t - W) dt$$

where W is inventory level of WIP inventory, a is the production rate in units per unit time, c is the material cost of an item in WIP, k is the penalty per unit per unit time for late delivery to the next stage in the manufacturing process, r is the interest rate, ΔT is the repair duration, and n_f is the number of times a failure occurs during the planning horizon T .

Improved control of the firm over the demand for its products reduces the finished goods inventory level through the change in expected number of shortages during the investment horizon. Again reducing the lead time reduces the finished goods inventory because the time to fill a shortage is substantially lower. These factors enter into the calculation of benefits as follows:

$$C_{FG} = \int_0^T \zeta FG(t) dt + N_s \int_{FG/d_s}^{\Delta T} k [d_s(t) - FG(t)] dt$$

where ζ is the material plus storage cost per unit of material, k is the penalty per unit time for a shortage, ΔT is the time to fill a shortage, and N_s is the expected number of shortages during time horizon T .

Other benefits of new technology are measured by reduction in fixed and variable costs.

3.4. Profitability of Investment In New Technology

Because most of the benefits of new technologies are realized over a period of time, determination of the timing of cash flows is an important tool to monitor progress in the firm's competitive position in the markets. Economic analysis techniques based upon the time value of money, such as discounted cash flow analysis, is a rational choice. We will use net present value (NPV) analysis to assess the profitability of investment on new technology.

4. The Case Technologies

This section gives the background for the design and manufacturing systems that we plan to use in this study. We have omitted much of the discussion of the research issues and the relation of our approach to others working in the same area. Instead, we present an overview of how each of the systems works and how the economic analysis will be integrated into the design and manufacturing systems.

Until recently, design and manufacturing functions have not been closely coupled and many iterations have been required to arrive at production-ready tooling. Often the part designer does not have specific knowledge of manufacturing methods, resulting in multiple design change iterations. Both the RTM and the IMW systems have the potential to resolve this problem by creating an integrated design and manufacturing environment that includes design evaluation tools for manufacturing. The representational and physical models used in design, prototyping, and manufacturing are often incompatible with one another, so transitions between the stages are time-consuming and error-prone. Products often make several complete cycles through design, prototyping, and fabrication before reaching production. Thus, new product development or product modification implies a series of iterative changes for both product manufacturers and toolmakers. Embedding tool design knowledge within the part design function greatly reduces the overall new product development time. Therefore, the greatest potential of integrated design and manufacturing systems is a rapid and smooth transition from product concept to production.

The level of integration and the number of different models in these systems requires geometric representations that can be abstracted at several levels and that can be manipulated over several dimensions. Rather than using several different modeling environments customized for the demands of each subsystem, the models in our framework for design, analysis, and fabrication share a single common *unifying* geometric representation implemented in the software modeling system NOODLES [Gursoz 89]. With this approach, model manipulation capability is robust and models need not be transformed between subsystems.

4.1. The Design Fusion Project

Traditionally, designers have been perceived as being concerned primarily with function and fit. Other issues were of lesser concern. In particular, the design implications of manufacturing, that is, ease of manufacture, process planning, and inspectability as well as and other life-cycle issues such as serviceability and disposability were considered only after important design decisions and commitments were made. This practice has led to many less than optimal designs when the entire life of a product, from conception to disposal, is considered. Awareness of the economic cost associated with this practice motivates our research in concurrent design systems.

- Current design checkers work only after the design is completed. To avoid unnecessary iterations in the design stage, critiques of incomplete designs are necessary.
- Manufacturing is not the only process that determines whether a design is realizable: for example, the requirements from manufacturing, assembly, and maintenance may be in conflict. The designer must be able to make informed tradeoffs among conflicting constraints.
- A design may be manufacturable using one process, but infeasible using an alternative process. Thus, two parts can have different manufacturing processes and different forms, but still fulfill the same behavioral requirements. Because current CAD systems are driven by form, exploring alternative manufacturing processes requires complete redesign of the part.

The goal for the Design Fusion Project is to create a system in which a designer can compose a design using high-level entities, called features, that have behavioral and geometrical attributes. As the design evolves, the designer receives feedback from automated experts representing the concerns of manufacturing, analysis, inspection, maintenance, etc. We call the different downstream concerns *perspectives*. When the design is complete, it can be transmitted directly to the manufacturing system where it will be rapidly produced and inspected.

One motivation for creating feature-based design systems is that a product design is viewed differently as the design evolves and as viewed by different experts, such as the SLA expert, the machining expert, the molding expert, or the inspection expert. If such expertise is to be given automatically to the designer, it is essential that each expert be able to interpret the design and generate comments about the design using the important features in that domain.

A key idea in this approach is the use of a central, neutral representation of the design. In our system, the design is stored in the representation of the NOODLES geometric model [Gursoz 89]. We describe features using graph grammars [Pinilla 89]. Because the designed object is an element in the language generated by this grammar, the features can be recognized by parsing the feature against the graph of the object. Using the neutral, graph-based representation of the design, we are developing a system in which each life-cycle perspective can define its own set of features with which to view the design.

A prototype system for providing designers with early feedback during the design of turbine blades has been created as part of the DARPA-funded DICE program. We have funding from DARPA to integrate this system with the RTM system and from McDonnell-Douglas to integrate it with the IMW system. For more details on the Design Fusion project, see [Finger 88, Pinilla 89, Navinchandra 89, Safier 89].

4.2. The Rapid Tool Manufacturing System

In the RTM system, a part and its tooling is first created and represented in a geometric model in the design system. To produce the tooling for the part, the geometric model of the tooling is translated into the path to drive a laser through a liquid photopolymer in the stereolithography apparatus (SLA). As the laser scans the photopolymer, a solid plastic prototype corresponding to the geometric model is produced. This plastic model, in turn, is sprayed incrementally with metal deposits to build the tooling. In this application, we are looking at producing the tooling for injection molding.

The RTM system is based upon the integration of shaping deposition processes into a unified system. Shaping deposition processes build three-dimensional shapes by incremental material build-up of thin layers, and can make geometrically complex parts with little difficulty. The RTM system incorporates commercially available technologies: SLA and arc spray equipment. Stereolithography¹ is a new process

¹Stereolithography has been commercialized by 3D Systems, Inc. (Valencia, California)

that creates plastic prototype models directly from a vat of liquid photocurable polymer by selectively solidifying it with a scanning laser beam. In arc spraying, metal wire is melted in an electric arc, atomized, and sprayed onto a substrate surface. On contact, the sprayed material solidifies and forms a surface coating. Another step in this integrated approach is to automate the thermal spray process with robotics. Tooling manufacture by thermal spraying is currently a labor intensive manual art-form. Shifting emphasis to robotic spraying, driven by an off-line trajectory and process planner, will improve tooling quality by achieving consistent and predictable performance of the sprayed metal shell.

Spray coatings can be built up by depositing multiple fused layers which, when separated from the substrate, form a free-standing shell with the shape of the substrate surface. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tooling can be fabricated including injection molds, forming dies, and EDM electrodes. For example, the cavities of injection molds can be fabricated by direct deposition of metal onto plastic SLA models of the desired part and backing the framed shell with epoxy resins.

Relative to conventional machining methods, the sprayed metal tooling approach has the potential to produce tools more quickly and less expensively, particularly for those parts with complex shapes or with large dimensions. Thus, with stereolithography, an initial part shape or prototype can be created quickly. Thermal spraying is then used to make tools based on the part shapes produced by stereolithography. For more details on the RTM process, see [Weiss 89].

4.3. The Intelligent Machinist Workstation

The goal of the IMW is the automated machining of high-quality parts in one-off batches. We are building a manufacturing environment that is completely observable and controllable so that corrective actions can be taken as conditions and errors are detected. The result is a machine that is as flexible as a general purpose computer but which manufacturing operations instead of mathematical operations.

An advanced system has been built for planning the production of machined parts from a feature-based description. Its special characteristics are that it can design some new fixtures and can balance tradeoffs between different machining strategies. A prototype system has been built for planning fixture configurations and assembly sequences. A theoretical system has been developed for planning computer vision inspection tasks. Its experimental tasks include tool wear, surface finish inspection, and volumetric inspection.

Traditional planning models assemble a sequential plan from a set of predefined operators. However, in fact, human planners often invent or design new planning operators if they feel that the set of actions available to them will not do the job, or if they feel they can create an operator that will do the job better. We are investigating when planning can use the available operators and when it is necessary to design a new operator. For example, in the domain of part fixturing, the individual fixtures and fixture subplates can be thought of as operators. The planner considers the part shape, the features to be cut, the available fixtures and tools and starts piecing together the plan for manufacture. However, at some point, a fixed set of resources may not be adequate or efficient to make the part. Our system is able to invent new designs for subplates, that is, plates onto which a part and/or fixtures can be directly bolted.

After planning is finished, the plan must be executed to get the desired part. Because the real world rarely cooperates with even the best of plans, it is necessary to have a general strategy for reacting to these deviations. We have a two-tiered approach to this problem. The plan is dispatched to the manufacturing components and the sensing components that verify that the actions are being properly carried out. The sensing and manufacturing systems then report back as various manufacturing milestones are reached. The dispatcher in turn looks for a consensus between these two systems, so that it can verify by sensing that satisfactory manufacturing actions are being executed.

Along with the function of dispatching, this control unit also has a general concept of how the process should be progressing. This concept is represented by equations about machining that have been derived from several expert sources on machine cutting. The control unit does not try to solve these equations directly, rather it reasons about the relationships between the key variables. For example, if the quality of a part's surface finish is equated with the division of two variables and the denominator is decreasing, then the system should take action to either reverse this trend or directly increase the value

of the numerator to keep up with the effect of the decreasing denominator.

A production quality scheduling system for factory floor manufacturing cells has been built and is in daily use. Its special features include a graphic programming language (in the Cell Management Language) and the automated protection of critical regions for collision avoidance. An experimental system has been built to automate the assembly of setups in machining, as well as to automate cutting in 3-axis machining.

The IMW uses several novel manipulators that are loaded into the machine tool's spindle and transform the milling machine into an assembly station, a robot, and a coordinate measuring machine. Two experimental modular fixturing systems have been built for holding parts during machining. For a 3 axis machine tool we have created a gripper for manipulating fixtures, a two axis expanding finger for manipulating parts and fixtures with holes, a torque wrench for fastening fixtures, and 2 axis CCD camera. The IMW also uses several manufacturing hands to handle difficult part geometries. For more information on the IMW, see [Bourne 89].

5. Future Research

A critical part of the development of the methodology for assessing the economic benefits of integrated design and manufacturing systems is the collection and verification of the economic data. We will compile our database on market characteristics, the firm's current position in the market, the existing technology, the inventory costs, sales revenue, and fixed and variable costs based on information we will obtain from ALCOA's subsidiary the Stolle Corporation's Building Products operations which are located in South Carolina.

Based on the results of our preliminary data collection, we will determine the extent of product differentiation, required technological capability, the desired market share, and the required response time for new products. We will then assess whether the required response time is attainable by increasing capacity without changing the existing technology or by integrating IMW or RTM technologies to design and manufacturing operations. We will also compare the costs of three alternatives, that is, using existing technology, using IMW technology, and using RTM technology. A prototype model will be built and tested by using continuous feedback from Stolle Corporation and the scientists developing the IMW and RTM technologies at Carnegie Mellon University.

The methodology will be generalized and encoded into a software system that will be applicable to a variety of integrated design and manufacturing technologies. We will also explore the generality of the model for firms operating in different markets with different product requirements. As a testbed and as a proof of concept, we will integrate our software with the existing software for Design Fusion, the IMW and the RTM. The software will serve as a tool in further developing the methodology and to demonstrate its utility.

6. Concluding Comments

Through our research, we hope to establish a formal methodology for the assessment of the economic benefits of integrated design and manufacturing technology. We believe that such a methodology will accelerate the pace of technology transfer from universities to industry. The methodology will at the same time provide an invaluable tool to realize the benefits of integrated design and manufacturing technology that are not quantifiable using the current methods of capital investment.

A major goal of our study is to enable the transfer of technologies into industrial systems. Our goal is not only to transfer a new strategic planning methodology, but through this methodology to enhance the transfer of new design and manufacturing systems. Variations of the RTM and IMW technologies ultimately will be used by several Alcoa manufacturing operations. Alcoa-TRE, a supplier of high temperature component assemblies to airframe and aircraft engine companies, would fabricate tooling for hot creep forming titanium components using the rapid tool manufacturing process. The Stolle Corporation is a broad based manufacturer of components and assemblies for the automotive, appliance, computer and building products industries. In 1987 Stolle produced two million stamped automobile bumpers and has contracts for complete bumper systems extending into the early 90's. A large percentage of U.S.

appliance panels are stamped annually at Stolle. These along with Stolle's continually growing injection molding capability can realize significant reductions in tooling lead times and manufacturing costs using the RTM and the IMW technology. The economic assessment and integrated product design systems we will further develop will aid in realizing the benefits of these new technologies.

Appendix A. Costs and Benefits of New Technologies

This Appendix gives a more detailed discussion of the methodology for computing the costs and benefits of new technologies. The methodology accounts for the costs and benefits of increasing product variability to match the market demands. Using this methodology, a firm can determine the required technological capability needed to introduce new products as demanded by the market.

Through product differentiation, a firm can reduce the uncertainty in meeting the consumer demand. The new competitive state achieved through greater frequency of product differentiation in turn influences the firm's market share and together with market growth, determines distribution of demand for the firm's products.

Finally, the costs for new technologies are composed of the fixed, variable, and investment costs. Variable costs are determined by the demand, while investment costs are determined by selected technologies and the magnitude of demand for firm's products. The benefits of new technologies arise from sales revenue and from reductions in inventory costs.

A.1. Determination of the Extent of Product Differentiation

We assume that firms can produce variants of a product and that the product variants can be formed into groups, g , which share design and manufacturing characteristics. We also assume that at the time a new technology is considered for introduction, the firm has a fixed group of products, g . The subscript, gi , denotes the i^{th} product of group g .

The overall market demand D_g for each product group g is known stochastically over the investment horizon. The demand for the firm's products in group g , d_g , is given by:

$$d_g = w_g D_g$$

where w_g = the firm's share of the market for products in group g . The market share for variant i of group g , w_{gi} , is zero when a new variant product is first introduced. Its share of the market is assumed to grow according to a linearized life cycle curve.

To expand its market share for products of group g , a firm can increase its product variety to achieve a closer match between the consumer requirements vector and the product characteristics vector. The extent of product differentiation necessary for the firm to expand its market share is determined by the frequency of new product introduction in the given market. The probability of a new product being introduced at time t by any firm in the market, can be obtained from observations of the past market data.

Let

$P_{gi}(t)$ = probability that a new product of type gi is introduced to the market at time t

$D_g(t)$ = random variable of the demand for products in group g at time t

Demand for the firm's products in group g at time t is given by:

$$W_g(t) = \kappa_g(t) W_g(t - \Delta t)$$

$$d_g(t) = W_g(t) D_g(t)$$

where

$\kappa_g(t)$ = the market growth rate over time Δt for the firm.

$W_g(t)$ = firm's share of the market for products in group g at time t

From the distribution for new product introductions, $P_{gi}(t)$, a realization for the time at which a new product is introduced can be computed. That is,

T_{gi} = realization for the time at which a new product in group gi is introduced to the market

If a new product is introduced to the market at time T_{gi} by introducing a new product at time T_{gi} or earlier, the firm captures the market growth for product group g during the time period between T_{gi} and the time that another firm introduces a competing product. The length of time that a firm has to respond in to introduce a new product is called the *response time*. If t is the current time, then the response time is

given by:

$$R_t = T_{gi} - t$$

Demand for products in group g at time t is divided among the variants of the products subject to the conditions that the market share of each product w_{gi} is not greater than its maximum potential share and that the sum of all market shares equals one:

$$0 \leq w_{gi}(t) \leq \frac{t - T_{gi}}{LC_g}$$

$$w_{gi}(t) + \sum_{k=1}^n w_{gk}(t) \leq 1$$

where LC_g = the total product life for products in group g .

Finally, the statistical distribution of demand for each variant of a product group is given as:

$$d_{gi}(t) = w_{gi}(t) d_g(t)$$

A.2. Required Technological Capability of the Firm

The technological capability of the firm is critical in determining the time it takes a firm to introduce new products to the market. One can compute both the time it takes to introduce a new product using the existing technology, or one can compute the technological capability needed for the firm to introduce a new product before its competitors. The required technological capability of the firm is determined from the statistical distribution of product demands and the length of time the firm needs in order to introduce a new product in time. The firm's existing manufacturing operations must be taken into consideration before a decision is made to invest in new technology. Firms first consider increasing production capacity by acquiring new machines and equipment before acquiring new technology.

We assume that the firm starts with an initial mix of products, each in a different group g . The products are being produced using a set of resources q , and each resource can perform a set of processes L_q . An example of a process, l , is design detailing, milling, or spraying. We assume that the following are known at the beginning of the time horizon:

g = the product groups being produced by the firm

q = the firm's resources (e. g. designers, machinists, machines)

l_q = a process l performed by the resource q (e.g. detailing, cutting, spraying)

At the beginning of the time horizon there are g products being produced. For simplicity, we assume that each of the g products is an archetype for all new product designs; that is, all new products will be variants of one of the initial products. At the beginning of the time period, we also assume that there are N_q resources of type q .

The lead time for a new product is the time required for designing, prototyping, and producing the tooling, as well as time to manufacture the part itself. We assume that the prototyping and manufacturing processes and processing times are known for the products that are being produced in the initial mix. For simplicity, we also assume that a process takes the same length of time for all products in a group. The lead time for a new product is composed of two parts: the time to produce the design and manufacturing plan and the time to manufacture the part. To compute the prototyping time, we define the following variables:

P_{gql}^p = time for products in group g to complete process l using resource q in prototyping

P_{igl}^p = probability that a new product i in group g requires the process l in prototyping

Using the probability that a new product requires a particular resource, we can obtain a realization for the processes that a particular product i requires during prototyping. Let

$\delta_{igl} = 1$, if product ig requires process l during prototyping

$\delta_{igl} = 0$, otherwise

We assume that

$$t_{igt}^p = t_{gqt}^p$$

That is, we assume that the processing time for a variant is the same as for the archetype of the group. (This is a pessimistic assumption since variants are likely to be redesigns whereas archetypes are more likely to have been new designs.) Then the prototyping time for product i is calculated:

$$t_i^p = \sum_{l=1}^{N_l} t_{ilq}^p \delta_{igl}$$

In addition, for the prototype stage of product ig , we can compute the time required for each process, l :

$$t_l^p = \sum_{i=1}^{N_i} t_{ilq}^p \delta_{igl}$$

Computing the manufacturing time is similar to computing the prototyping time except that manufacturing time must account for the number of products to be produced to meet the initial demand.

t_{gqt}^m = time for products in group g to complete process l using resource q in manufacturing

P_{igl}^m = probability that a new product i in group g requires the process l in manufacturing

We again use the probability that a new product requires a particular resource to obtain a realization for the processes that a particular product i requires during manufacturing. We also assume that the process time for a variant is the same as for the archetype. Then the manufacturing time for product i is calculated:

$$t_i^m = \sum_{l=1}^{N_l} t_{ilq}^m \delta_{igl}$$

And, for the manufacturing stage of product ig , we can compute the time required for each process, l :

$$t_l^m = \sum_{i=1}^{N_i} t_{ilq}^m \delta_{igl}$$

Finally, using optimization, we find the number and type of resources required for prototyping and manufacturing based on the amount of time required for each process and by the set of processes that each resource can provide. That is, we construct an integer program to compute n_q , subject to the constraints that each resource q can provide a set of processes l , that together the resources must provide the total time required for each process l , that the resources have availability factors and failure rates, and that the sum of the prototyping and manufacturing processes times be less than the response time. We consider only total capacity and do not consider scheduling constraints in this optimization.

A.3. Derivation of Costs

The costs for new technologies are composed of the fixed, variable, and investment costs. Variable costs are determined by the demand, while investment costs are determined by the required technological capability of the firm. The total fixed and variable costs of the manufacturing system are expressed by:

$$C_T(t) = C_F + \sum_{q=1}^{n_q} c_{Fq} + \sum_{g=1}^N d_{ig}(t) c_{vg}$$

where

C_F = fixed costs, independent of products or operations

c_{Fq} = fixed costs for resource q

c_{vg} = variable cost of products in group g

The *investment costs* include the costs of investment in new equipment.

$$C_{IV}(t) = \sum_{q=1}^{n_q - E_q(t)} c_q(t)$$

where

$c_q(t)$ = cost of obtaining resource q at time t

$E_q(t)$ = existing capacity for resource q at time t

A.4. Derivation of Benefits

The benefits of new technologies arise from sales revenue and from reductions in inventory costs. Sales revenue is determined from the distribution of demand for the firm's products. Reduction in inventory costs occurs in three areas: reduction in raw materials inventory, reduction in work-in-process (WIP) inventory, and reduction in finished goods (FG) inventory. The product lead time influences the raw material and WIP inventory, the certainty in market demand influences the FG inventory. Labor costs are influenced by the technology and by the new state of inventory. Labor costs are computed as a part of the variable costs.

The sales revenues are expressed as:

$$R = \sum_{i=1}^N p_g d_g(t)$$

where:

$d_g(t)$ = demand for products of group g in time t

p_g = unit price of products of group g .

The inventory holding costs arise from out-of-pocket losses such as inventory taxes, insurance, damage, deterioration, handling, storage, and space requirements. In addition, there are opportunity losses associated with the funds tied to inventory. Also working capital is required to finance inventories.

The raw material inventory holding costs, C_R , are computed as follows:

$$C_R(\rho, Q) = \frac{A}{Q}k + \gamma\left[\frac{Q}{2} + \rho - \mu\right] + k\frac{A}{Q}B(\rho)$$

where:

A = Mean annual demand rate for raw material

Q = number of items ordered each time

k = cost per order

γ = inventory holding cost per unit (investment plus storage cost)

ρ = reorder point

μ = mean lead-time demand

$B(\rho)$ = the expected number of backorders per cycle

The total cost of work-in-process inventory, C_W , over investment horizon T can be expressed as a function of inventory holding cost and shortage cost during the lead-time.

$$C_W = \int_0^T r c W dt + n_f \int_{W/a}^{\Delta T} b(a t - W) dt$$

where

W = inventory level of WIP at any point in time between production stages

a = production rate in units per unit time, assumed to be equal for all stages of production

c = material cost of an item in WIP

b = penalty per unit per unit time for late delivery to the next stage in the process

r = interest rate

ΔT = repair duration

n_f = number of times a failure occurs during the planning horizon T

Solving for C_W :

$$C_W = rcWT + mb \left[\frac{1}{2} a \Delta T^2 - W \Delta T + \frac{1}{2} \frac{W^2}{a} \right]$$

Let

$$n_f \approx \frac{T}{t_f} \text{ and } \alpha = \frac{W}{a \Delta T}, \text{ then}$$

$$C_W = rc \alpha (a \Delta T) T + b a T \frac{(\Delta T)^2}{2 t_f} (1 - \alpha)^2$$

where

t_f = time interval between successive machine failures

In this formulation, α defines the relationship between the level of WIP and the maximum possible shortage. If the firm is operating at the optimum production schedule, then α should be:

$$\alpha^* = 1 - \frac{rc t_f}{b \Delta T}$$

The optimum WIP inventory level is therefore:

$$W^* = \left[1 - \frac{rc t_f}{b \Delta T} \right] a \Delta T$$

The corresponding value of C_W^*

$$C_W^* = rc (a \Delta T) T - \frac{a T (rc)^2 t_f}{2b}$$

The total cost of the *finished goods (FG) inventory*, over the investment horizon T including shortage costs, is given by:

$$C_{FG} = \int_0^T \zeta FG(t) dt + N_s \int_{FG/d_{gi}}^{\Delta T} \epsilon (d_{gi}(t) - FG(t)) dt$$

where:

ζ = material plus storage cost per unit of material

ϵ = penalty per unit time for a shortage.

ΔT = time to fill a shortage

n_s = expected number of shortages during the investment horizon T .

Solving for C_{FG} :

$$C_{FG} = \zeta FG(t) + n_s \epsilon \left[\frac{1}{2} d_{gi}(t) \Delta T^2 - FG(t) \Delta T + \frac{1}{2} \frac{FG(t)^2}{d_{gi}(t)} \right]$$

The expected number of shortages, n_s , is computed as:

$$n_s = \sigma_{gi} L \frac{FG(t) - d_{gi}(t)}{\sigma_{gi}}$$

where

L = inventory loss function due to shrinkage and waste.

σ_{gi} = standard deviation in demand for product gi .

A.5. The Profitability of Investment in New Technology

The analytical method of Discounted Cash Flow (DCF) analysis is used to determine the profitability of investment in new technology. DCF analysis is based on the concept of discounting cash inflows and outflows to their present values. Because most of the benefits of automation technology are realized over a period of time, determination of the timing of cash flows is an important tool to monitor progress in the firm's competitive position in the markets.

There are four types of DCF analysis which fully consider the time value of money: net present value (NPV), profitability index (PI), internal rate of return (IRR), and equivalent annual charge. When a firm is evaluating a single project, the NPV, PI, and IRR methods always agree on the attractiveness of the project. In this paper, we will use the NPV analysis. For more detail on DCF methods, see [Kutay 89a].

The NPV criterion for evaluating proposed investments involves summing the present values of cash outflows required to support an investment project with the present values of cash inflows resulting from operations of the project. The outflows and inflows are discounted to present value using the firm's required rate of return (the hurdle rate). The *net present value* is the difference in the present value of the inflows and outflows:

$$NPV = \sum_{t=0}^T \frac{S_t}{(1+r)^t} - A_0$$

where:

A_0 = present value of the after tax cost of the project

S_t = cash inflow to be received in period t

r = rate of return

If the project cost is incurred over a period of time, then A_0 represents the present value of those cash outflows and may be expressed as:

$$A_0 = \sum_{t=0}^n \frac{A_t}{(1+k)^t}$$

where

A_t is the cash outflow in period t

n = useful life

If the NPV is positive, the project is expected to yield a return in excess of the required rate; if the NPV is zero, the yield is expected to exactly equal the required rate; and if the NPV is negative, the yield is expected to be less than the required rate.

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