



# Agile manufacturing systems in the automotive industry

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## Abstract

In the automotive industry, it is thought that agile manufacturing systems will permit fast cost-effective responses to unpredictable and ever-changing product demand, and support rapid product launches for previously unplanned products tailored to meet changing customer desires. We discuss two simple decision models that provide initial insights and industry perspective into the business case for investment in agile manufacturing systems. The models are applied to study the hypothetical decision of whether to invest in a dedicated, agile, or flexible manufacturing system for engine and transmission parts machining. These decision models are a first step toward developing practical business case tools that help industry to assess the value of agile manufacturing systems.

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## 1. Introduction

Automotive companies must consider strategic initiatives such as agile manufacturing systems to compete globally and respond to dynamic customer demand. In this paper, we explore agile manufacturing systems for engine and transmission machining applications as a key enabler in an automotive agile manufacturing strategy. We describe two simple decision models that help distinguish agile systems from dedicated or flexible machining systems (FMSs).

Gunasekaran (1998, 1999a) describes agile manufacturing as “the capability to survive and prosper in a competitive environment of continuous and unexpected change by reacting quickly and effectively to changing markets, driven by customer-designed products and services.” Goldman et al. (1995) have a slightly different definition, with agile manufacturing allowing companies to be capable of operating profitably in a competitive environment of continually and unpredictably changing customer opportunities. Both definitions apply to the automotive industry’s goals of operating profitably, and sensing and responding effectively to changing demand trends. Conceptually, an agile manufacturing system allows an automotive company to re-allocate production line capacity to products that are in

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higher than expected demand, rapidly launch new products (not previously conceived when the manufacturing system was designed), and yet retain production ability for other products with lower than expected demand.

Automotive companies are attracted to agile manufacturing systems, because of the potential for equipment reuse and equipment investment cost reductions over time. The promise of equipment reusability has also been associated with flexible manufacturing systems (FMSs). For example, Goranson (1998) defines a flexible system as a production system capable of dealing effectively with a specific (or predictable) scope of product variation. A FMS, as defined by Askin and Standridge (1993), refers to a set of computer numerically controlled (CNC) machine tools and supporting workstations that are connected by an automated material handling system and are controlled by a central computer. Shim and Siegel (1999) characterize a FMS as a computer-controlled process technology suitable for producing a moderate variety of products in a moderate flexible volume. More recently, Hallmann (2003) describes the implementation of an FMS for automotive parts machining that promises cost and time effective implementation of engineering change orders (ECOs), and thus continual process improvement. Agile systems differ from flexible systems in a critical way: the agile system has capability to adapt *rapidly and cost-effectively* within a predicted scope of product variation (out of scope is ideal but impractical) to allow future *unplanned* products to be manufactured. Automotive companies have previously experimented with and been disappointed by FMS for machining applications, because the promise of cost reductions for equipment reuse has not materialized as expected. In practice, to respond to changing demands, a FMS requires significant additional expenditures and a long time to convert or adapt to new “unplanned” products. Thus FMS do not meet the “agility criteria,” i.e., rapid and cost-effective reuse in response to changing product demands.

The remainder of the paper is organized as follows. In Section 2, we briefly review the technical literature on agile and FMSs. Section 3

summarizes how automotive engineers perceive the differences between dedicated, agile, and FMSs for engine and transmission machining applications. Two key terms, in-family flexibility and cross-family flexibility are introduced to help explain why automotive engineers are interested in agile and FMSs. We propose two simple decision models in Section 4 and use these models to provide insights into the business case for investment in agile manufacturing systems. Section 5 summarizes the insights gained and identifies opportunities for future research.

## 2. Related research

There is an extensive amount of research in the open literature discussing agile and flexible manufacturing philosophies. Industry has led the way in directing the research in this important area by collaborating to define the future needs of agile manufacturing. In particular, the Iacocca Institute Report on 21st Century Manufacturing Enterprise Strategy (Nagel et al., 1991) provides a valuable guide to the broad spectrum of applications for agile production systems. Authors have identified the drivers of agility (Yusuf et al., 1999), future research needs and opportunities (Gunasekaran, 1999b; DeVor et al., 1997), and strategic advantages of agility (Gunasekaran, 2001). Gupta and Goyal (1989) provide an extensive literature review on the different ways researchers have defined flexibility and attempted to measure it. Sanchez and Nagi (2001) also provide a thorough review and classification scheme for the open literature on agile manufacturing systems.

Several authors have proposed methods to measure flexibility in manufacturing systems (Kulatilaka, 1988; Chrystolouris and Lee, 1992; Das, 1996; Sieger et al., 2000; Giachetti et al., 2003). Others (Charles et al., 1999; Newman et al., 2000; Fernandez and Patrick, 2000) present best practices and lessons learned in designing agile and re-configurable manufacturing systems to support product flexibility, volume flexibility, and general equipment reusability. Shewchuk and Moodie (2000) investigate the effect of manufacturing system design on system flexibilities (product,

mix, production, and volume), and consider trade-offs between these flexibility types. Studies by Katayama and Bennett (1999), and Zukin and Dalcol (2000) on agility and flexibility in the Japanese and Brazilian manufacturing sectors respectively, reveal that agility and flexibility are of global manufacturing importance. Morgan and Daniels (2001) examine a portfolio approach to handling product mix and future technology decisions in the automobile industry. Xiaobo et al. (2000a, b) present a framework and optimization algorithms for reconfiguring a manufacturing system to handle production of several product families. Lee (1999) discusses generalized analytical methods to design FMSs at minimal cost, subject to performance, throughput, and capacity constraints. Fine and Freund (1990) and Rajagopalan (1999) explore optimal investment in flexible and dedicated capacity to handle product variety and volume uncertainty. Ordoobadi and Mulvane (2001) present a decision tool to analyze investment value in advanced manufacturing technologies. Similarly, Gupta and Buzacott (1993) offer some high level models for first-pass FMS investment analysis. Most closely related to our work, Ramasesh et al. (2001) describe a modeling framework and simulation that explores the financial value of agility.

Our paper focuses on the use of flexible and agile manufacturing systems in the automotive industry for engine and transmission machining applications. Next we examine how automotive engineers perceive the differences between dedicated, agile, and flexible manufacturing equipment for machining applications. The comparative characteristics are based on many discussions with machining system design engineers who must make recommendations about line design and equipment choices for engine and transmission machining applications. We introduce some terminology to clarify our discussion.

### 3. Dedicated, agile, and FMSs in the automotive industry

In this section, we discuss two industry terms that often arise in the discussion of agile and

FMSs, particularly for engine and transmission machining applications. These definitions are presented to help readers understand the automotive industry motivation for considering agile and flexible systems. Automotive engineers often use the generic term “product” to refer to both a product class and a product model. We are deliberate in our usage of the two terms to separate the concepts of product class versus product model. Following the explanation of product class and product model, we describe in-family and cross-family flexibility to stimulate our comparison of dedicated, agile and FMSs. Finally, we characterize the dedicated, agile and FMSs we shall consider in our decision models.

*Product class* is the general type of product being machined. For example, engines, transmissions, and axle rods are three distinct classes of products.

*Product models* are the specific variants within a general product class. For example, a V6-engine and an Inline-6 engine are two variants within the class of 6-cylinder engines.

#### 3.1. Two commonly used flexibility terms in the automotive industry

*In-family products* are closely related variants that have almost the same production envelope, and utilize similar (if not the same) manufacturing processes. A manufacturing system with in-family flexibility can produce in-family products. One example of in-family flexibility is a machining system that can make an engine cylinder head, whose design varies only in the number of cylinders (i.e., 6, 7, or 8 cylinders), cut consecutively along the length of the cylinder head block. Automobile manufacturers are beginning to design and build dedicated machining systems with some in-family flexibility to enable production of several similar models. Since the machining line is a dedicated line, it is very difficult and extremely costly (i.e., impossible) to make significant model changes, because much of the machining equipment cannot be reused if a new engine variant is introduced.

*Cross-family products* are distinct models in the same product class. A manufacturing system with

cross-family flexibility can produce cross-family products. One example of cross-family flexibility is a machining system that can make three distinctly different engine cylinder heads (not just a design variation in the number of cylinders being cut). Thus, the system could perhaps manufacture an Inline-6, a V-6 and a V-8 engine cylinder head. Both agile and FMSs have cross-family flexibility as a characteristic.

### 3.2. *Automotive industry characterizations of dedicated, flexible and agile machining systems*

*Dedicated machining system (transfer line)* can produce a single model of a product class. The automotive industry has traditionally purchased this type of machining system to produce a given product model efficiently, i.e., with low cost per unit and at high volume.

*Flexible machining system* is an adaptable and versatile machining system that can change quickly and easily to produce a planned range of product classes and product models within a designed machining envelope. CNC machine tools with flexible fixtures and flexible tooling are typically part of a FMS. In practice, FMS for automotive machining applications are typically designed to produce only one product class, with several models variants in the class, primarily because it is quite challenging just to design a system to process multiple models in a product class.

*Agile machining system* is a machining system that can change quickly and easily to produce a planned range of product models in a product class, and be rapidly and cost-effectively re-configured to respond to new model introductions.

### 3.3. *Similarities and differences between agile and FMSs*

The automotive industry is currently investigating agile systems because they desire the versatility of flexible systems, but also want lower system investment costs. In industry applications, agile and flexible systems both use CNC machines and tend to have short parallel line layouts, yielding higher system reliabilities compared to longer

serial lines of dedicated systems. The key difference between agile and flexible systems lies in the cost and utility of system tooling, fixtures, and material handling.

Agile systems allow fast introduction of new (unplanned) product models in the class, and require minimal additional investment cost to introduce new models. The tools, fixtures, and material handling support reconfigurations and modifications (within the product class), but have less utility for general purpose machining applications than those of a flexible system.

Flexible systems also permit introduction of new (unplanned) product models, but with a significant time and cost penalty incurred. Tools, fixtures, and material handling in a flexible system are more expensive, because they have more all-purpose utility for a variety of machining applications. Significant additional costs and time penalties are incurred in modifying the general-purpose tools, fixtures, and material handling to support the new model applications.

The main industry criticism of FMSs is that while the equipment is re-usable for *any* machining application, the throughput per investment dollar achieved is too low. Agile systems compromise on the re-usability, limiting tooling, fixtures, and material handling re-usability to a particular product class application to achieve lower investment costs and higher throughput rates. By developing machining systems focused on a particular class of product, system designers and equipment manufacturers are closer to achieving initial equipment costs that are competitive with high volume dedicated machining systems. Investment cost is the major determinant in deciding among machining system types. Dedicated systems are still the least expensive technology for machining applications. But as the name “dedicated” indicates, the equipment is specialized for one particular model of a general product class (e.g., one engine model). Dedicated systems are valuable for high volume production, and yield low investment per unit. Dedicated systems are preferable when the demand volume for a product is high and the life span of the product is relatively long (7–10 years). In comparison, agile machining systems allow several product models within a

Table 1  
Industry perception and comparison of dedicated, agile and flexible machining systems

Comparison factor	Dedicated	Agile	Flexible
Initial investment cost	Low	Medium	High
Cost to introduce new models	High	Low	Medium
Time to introduce new models	High	Low	Medium
Prod. volume capability	High	Medium	Low
Equipment reusability for other machining applications	Low	Medium	High
Capability to introduce new (unplanned) models	Low	High	Medium

product class to be made on the same line, with quick changeovers from model to model. By paying a higher initial cost for equipment, an agile manufacturing operation gains the option of hedging against uncertain future demand volumes and mix fluctuations. In trade for the ability to machine several product models, the volume per model is somewhat reduced due to lost production time during model changeovers. Agile systems are preferable when the demand volume for each model is relatively low and the life span of the product is comparatively short. Flexible systems are the most expensive among the three, but permit the most equipment, fixtures, tooling, and material handling re-use. Our work does not pursue flexible machining to a great extent, given the current industry trend away from flexibility. However, we do compare agile systems to both dedicated and flexible systems to “bound” results for agility between dedicated and flexible systems.

3.4. Summary comparison and industry perception of machining system types

Table 1 summarizes the automotive industry classification of dedicated, agile and flexible systems relative to their key characteristics. The three system types are compared visually using a “spider graph” in Fig. 1. The three system types are ranked relative to each comparison parameter. This type of graph proves quite valuable for stimulating dialogue among system designers and engineers to capture the system tradeoffs. These tradeoffs can be used to guide decision-making about the type of system to build. For example, a system designer may start by determining the number of product models that must be machined

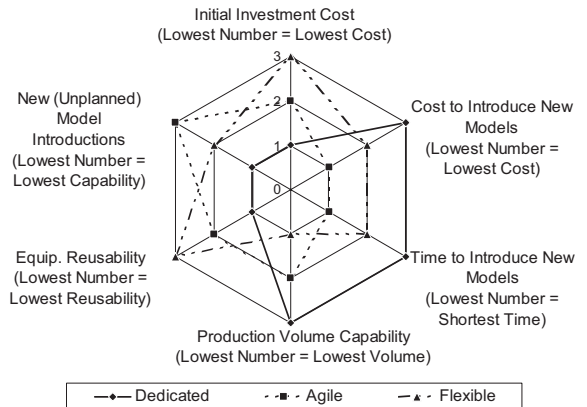


Fig. 1. Visual “spider graph” presenting industry perception and comparison among dedicated, agile and FMSs. Dedicated systems are perceived to have the lowest investment costs and highest production volume among the three system types. Agile systems have the lowest changeover costs and highest capability to introduce new (unplanned) products. Flexible systems have the highest equipment reusability, but highest investment cost.

at a particular plant location and the forecasted volume per model. If the volume for each model is high, then dedicated systems are the preferable choice. If low or medium volume is needed for several models, agile and flexible lines are considered. If the designer is exploring agile and flexible lines, the designer must consider the possibility of introducing new models for which the system was not originally designed.

4. Decision models to assess the value of agility

Two decision models are used to gain insights on the financial benefits of agility as part of a business case analysis for agile machining systems. The models are deliberately kept simple to permit

discussion with industry engineers not familiar or comfortable with more sophisticated approaches such as optimization or stochastic process modeling. At the same time, the models capture salient features of the economic decision of machining system selection. To facilitate modeling and comprehension of data relationships, an influence diagram is constructed (see Fig. 2) to identify the key information required to compare the different types of machining systems (i.e., dedicated, agile and flexible).

4.1. Spreadsheet model

Using the identified data and relationships as in Fig. 2, a spreadsheet based model is constructed to evaluate cumulative net present value (NPV) of profits for system purchase decisions made under high uncertainty of product volumes, system availability, and timing of new product introductions. The data values used are representative of the magnitudes of costs associated with the decisions made but are for illustrative purposes only. Given the demand for each month for each product model, the spreadsheet evaluates the net profit each month for each system type as the

revenue from product models made and sold during the month less system dependent operating costs, labor costs, tax, depreciation, and changeover costs. Monthly revenues are constrained by labor and production capacity, and may be negative to reflect a lost opportunity, when one system type is down for a changeover, while other system types are able to respond to the changeover more quickly. This lost opportunity cost is specifically included to help differentiate the systems during changeovers. Operating costs include fixed and variable costs for the months the system is in production and only fixed costs for the months a system is in changeover. Labor costs include any overtime costs if necessary to meet production goals. Taxes, assessed on revenues less operating and depreciation costs, may be either positive or negative, depending on whether or not the system makes a profit for the month. Changeover costs are the costs of additional equipment, tooling, and other system modifications, and are assessed during the first month of a system changeover. The cumulative NPV of profits over time for each system type is the main result, and is a running total of net profits discounted appropriately. Thus the cumulative NPV for a system

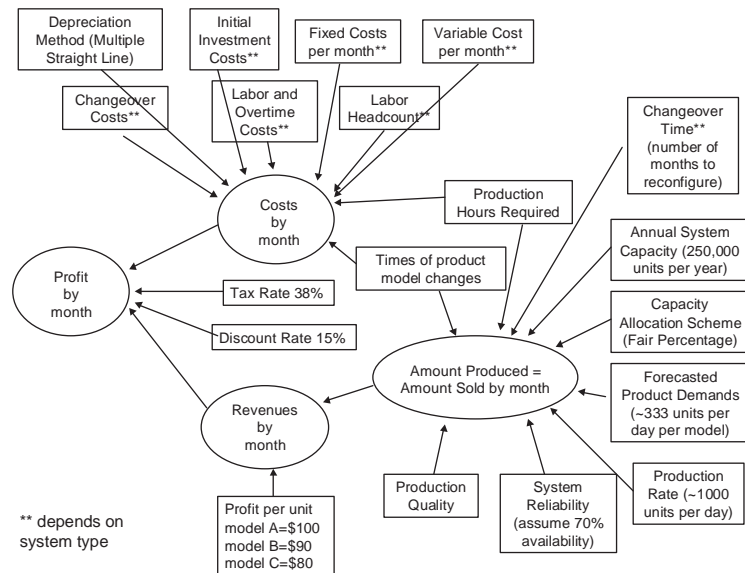


Fig. 2. Influence diagram illustrating the key data and relationships required to compare different machining systems.

type for month  $k$  ( $0 \leq k \leq 180$  months = 15 years) is given by

cumulative NPV(system type) at month  $k$

$$= \sum_{i=0}^k \text{netprofit}_i (1 + \text{discount rate/month})^{-i}.$$

The cumulative NPV is typically negative because total costs per month (equipment investment, labor, operations, materials, tax, etc.) exceed the revenue (value added) obtained from machining parts for an engine or transmission. The engine or transmission produced is a key competitive differentiator in vehicle manufacturing, and significant additional value is obtained upon sale of a vehicle, which must have an engine and transmission.

We employ a test data set to exercise the spreadsheet model and illustrate insights on the value of machining system agility. The model compares investment options among dedicated, agile and FMSs by evaluating the systems on cumulative NPV of profits over a 15-year time span. The 15-year time span may seem long for financial business case analysis, particularly in studying the impact of an uncertain future. To explore the systems' capabilities to respond to demand fluctuations for different product models, a shorter time period of 5 years may be more appropriate. However, our purpose is to examine the potential of an agile system to introduce new product models, not previously anticipated when the system was designed. In general, the types of

machining equipment we are considering has an industry lifespan of 15 years use, and further, it counts as assets on our financial balance sheet for 15 years. Thus, we will study the investment decision over a 15-year period.

An annual discount rate of 15% is used in the model to account for the time value of money. Taxes are assessed on net profits at a rate of 38%, to approximate both state and federal taxes. The initial investment cost for each system type is depreciated over the 15-year period using multiple straight-line depreciation. This depreciation strategy spreads 50% of the total investment cost over the first 5 years, 33.3% of total investment cost over the next 5 years and the final 16.67% of total investment cost over the final 5 years. This type of depreciation is used to "front-load" the depreciation over the early part of the equipment lifecycle.

Table 2 organizes the key data distinguishing the system types. While the agile and flexible systems have higher initial costs, they also can machine several product models in the current planned product generation, and potentially machine future product models. Flexible systems are more expensive than agile systems, but also have more equipment reusability for other machining applications. The dedicated system in comparison can only produce a single product model, but has lower initial investment costs. Costs to introduce a new product model reflect that the entire dedicated system is usually replaced, while a good portion of the equipment in the flexible and agile systems may

Table 2  
Test data for comparing dedicated, agile and flexible machining systems

	Dedicated system	Agile system	Flexible system
Initial investment costs	\$50,000,000	\$60,000,000	\$70,000,000
Changeover costs	\$50,000,000	\$10,000,000	\$20,000,000
Changeover times	12 months	0 months	3 months
Product classes	1	1	1
Product models	A	A, B, C	A, B, C
Profit per model	\$100	\$100, \$90, \$80	\$100, \$90, \$80
Capacity allocation to each model	100%	45%, 35%, 20%	45%, 35%, 20%
Annual fixed costs	\$5,000,000	\$6,000,000	\$6,000,000
Variable cost per unit	\$50	\$60	\$60
Hourly labor rate	\$100	\$120	\$120
Labor headcount	10	10	10

be reused. The zero month changeover time for the agile system reflects that only a few hours to a few days of changeover time is required to introduce new product models. Fixed and variable costs in agile and flexible systems are assumed to be 20% more expensive than dedicated system costs, reflecting the possibility of more maintenance and overhead costs to operate agile and flexible systems. The cost of labor is assumed to be 20% more for agile and flexible systems, because skilled trade workers will need more training and expertise to operate agile and flexible systems.

Demand per product model is 333 parts per day  $\pm 50\%$ , reflecting high uncertainty in demand for each planned product. This demand rate for a single product model is low for a dedicated system, which typically has production capacity to meet demand of 1000 parts per day. To compare systems fairly, all system types are designed and purchased so that production capacity is rated at 1000 parts per day assuming a standard workday of two 8-hour shifts. Total annual system capacity for each system is 250,000 parts per year operating at 70% availability. Each dedicated system can only produce one product model, which is typically the case in industry, when the model variants are distinct. Assuming the automotive company must manufacture all three-product models, then three dedicated systems must be purchased—one system per product model. The initial cost of the three dedicated systems increases to \$150 million, fixed costs increase to \$15 million, and labor head count increases to 30 workers to cover all three dedicated systems. In contrast, the agile and flexible systems are designed to produce several product models (models A, B, and C). No system is designed to produce more than one product class. Thus the additional capability of producing several product classes in a single flexible system is ignored for now. However, we note that the initial investment cost of the flexible system already reflects the limitation to one product class. The true investment cost for a flexible system is somewhat higher if multiple product classes or true re-usability for other machining applications are truly an option. Capacity is allocated by fair percentage across the models in the agile and flexible systems, with

capacity percentages of 45% for model A, 35% for model B, and 20% for model C. No product model changes are introduced over the 15-year time span. Net profit per model unit is \$100 for model A, \$90 for model B, and \$80 for model C. Net profit represents value added to the part by performing the machining.

#### 4.1.1. Base spreadsheet model results

The base model examines the value of being able to allocate capacity among the currently planned product models as needed, when higher than expected demand is observed. The decision model identifies the most profitable system type by comparing the three system types meeting dedicated system production targets. Each system starts at time 0 with the initial investment cost as a negative cash flow. It is clear that agile and flexible systems are much more attractive due to lower initial costs to produce all three product models and low demand for all models (see Fig. 3). Purchased capacity is more effectively utilized by agile and flexible systems compared to the three dedicated systems. The agile and flexible systems can share total system capacity (1000 parts per day) across the three models. In comparison, each dedicated system can produce 1000 parts per day, but only  $333 \pm 50\%$  parts per day are needed. While each dedicated system can handle much more expected demand volume per model, one system is purchased per model. In comparison, the agile and flexible systems can also handle higher

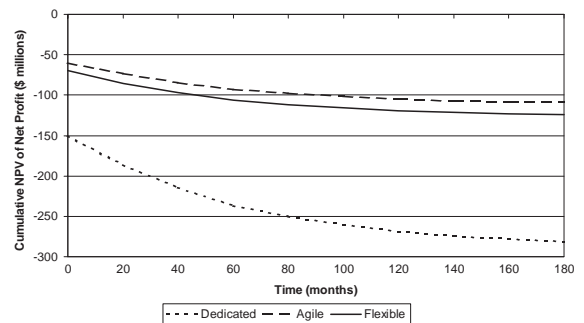


Fig. 3. Base case comparison of dedicated, agile, and flexible systems. The constraint that all the three product models must be manufactured is imposed, causing the complete dedicated system to be much more expensive and to have three times the total capacity that the agile and flexible systems have.

than expected demand for a model by reallocating unused capacity from the models that experience lower than expected demand. Note that the only difference between the agile and flexible system for the base case is the initial investment cost. The flexible system is more expensive because the machining equipment has more “reusability” for other machining applications. In practice in industry, machines are generally not “reused” for other machining applications, so the managers are hesitant to spend money on an equipment feature that is never used.

Some may argue it is unfair to compare the dedicated systems with so much capacity to agile and flexible systems with less capacity. However, all three models must be manufactured, regardless of system type chosen or amount of capacity purchased. Under the constraint that all three models must be produced, the company would rather manufacture the models at lowest total investment cost. From Fig. 3, we see that agile systems are most attractive when multiple product models must be manufactured at low volume per model. If the volume per model is significantly higher, perhaps dedicated systems would appear more attractive. For the machining application we are challenged to explore, the demand per product model is expected to be low. Our job is to make a business case recommendation on the type of system that should be purchased.

#### 4.1.2. Value of new (unplanned) product model introductions

Next, consider the value of making two new model introductions at points of time in the future. The models are not previously conceived or planned for when the manufacturing system is initially designed and purchased. Suppose that one model change occurs at 60 months (after 5 years), and the other at 120 months (after 10 years). All three-system types are compared at 70% availability, and must make all three-product models. The drop in the cumulative NPV of net profit lines at each of these new product launch times reflects the discounted additional cost to implement the changeover (see Fig. 4). The flexible and dedicated systems also lose production time during the required changeover period, which can be seen in

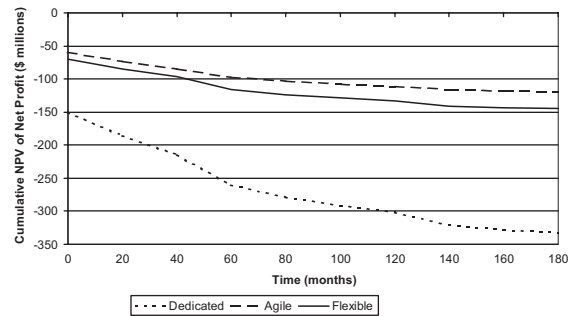


Fig. 4. Systems comparison if a new product model (not previously conceived and designed for) is introduced every 5 years. Agile systems are most effective in responding to new product model introductions.

the graph as the slight downward sloping lines at 60 and 120 months. Agile systems are most efficient in handling model changes and lose little or no production time in introducing the new model. Flexible systems are also preferable to dedicated systems if a product model change must be implemented, but not as attractive as agile systems due to the higher initial investment and new product model introduction costs.

#### 4.1.3. Spreadsheet model insights

The spreadsheet model graphs yield the following insights:

1. Agile and flexible systems are attractive financially and strategically compared to dedicated systems, because agile and flexible systems have lower initial investment costs when producing several product models simultaneously. The initial investment cost is a key driver differentiating system types. Agile systems have lower investment costs and lower new model launch costs than flexible systems, but do not have as much equipment reusability for other machining applications. The value of being able to reuse the flexible equipment for other machining applications has been ignored in this analysis (primarily because it is not done in practice in engine and transmission parts machining). This equipment reusability may merit future consideration if a company is willing to acknowledge the value of flexible machining for multiple applications.

2. Agile production systems best respond to new (unplanned) product model introductions with lowest cost and fastest launch compared to flexible or dedicated production systems.
3. Even one unplanned product model introduction causes a dramatic change in cumulative NPV of profits, making agile systems valuable as a tool for long-term strategic manufacturing.

The spreadsheet model, however, is cumbersome to use and requires significant data inputs. Further, the data, while seemingly clear in terms of relevance, is relatively hard to obtain and contains a large amount of uncertainty in the values. These modeling limitations lead to a second class of models that specifically address uncertainty in the cost and time data.

#### 4.2. Decision tree model

A simple decision tree model (see Fig. 5) and Monte Carlo simulation analysis are used to study the decision to buy a production system given the uncertain costs and the future opportunity to introduce a previously unplanned product model. The decision tree illustrates that once a system type is chosen, the system choice can be evaluated relative to the new opportunity. The decision tree focuses on minimizing costs of buying a system to produce the current and future generations of

product models. The decision tree model shows in the cost framework that agile capacity has a strategic future value and is competitive with the low cost dedicated lines, after considering the future option to change product models.

The decision tree modeling paradigm is appealing, for it visually captures the essential decision features and facilitates structured discussion of the decision. Less data is required to drive the model as compared to the spreadsheet model previously studied. The main criticism of decision tree models is how to obtain the subjective probabilities of the types of future changes. However, the subjective probabilities do allow managers to introduce “expert opinions” on future responses to new product model launch opportunities, given that a particular system type is selected. Finally, a bonus feature of this type of modeling and analysis is that risk of investment for each type of system purchase decision can be evaluated and compared.

The types of future change opportunities (all unplanned at time of initial system purchase) considered for this particular decision tree include no change, an in-family model change, a cross-family model change, and a completely new model introduction. The option of no change is specifically included because even though agile or flexible production systems may be purchased, the change-over feature may never be used. Subjective discrete probabilities are assigned to each type of change (see Fig. 5), and these probabilities are assumed system dependent. Thus a dedicated machining system has a much higher probability of a “no change” outcome when compared to an agile system due to significant cost and downtime penalties for conversion. Some readers may feel that it is unfair to use different probabilities for likelihood of change for dedicated systems, compared to agile or flexible systems, but it is the reality in industry that once the dedicated system is purchased, model changes are not very likely, because executives focus on the investment cost already spent.

Tables 3 and 4 provide the triangular distribution parameters for initial costs and changeover costs used in the model. These parameter estimates are used to demonstrate the utility of this decision model for agile business case assessment.

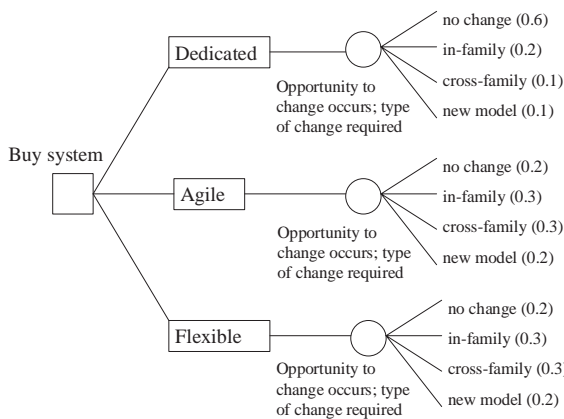


Fig. 5. Decision tree model for buying machining systems under future uncertainty of a product model change. The probability of each type of change occurring is indicated in parentheses and may depend on the system type purchased.

Table 3  
Initial investment costs for different machining system types

Initial costs	Minimum (\$ millions)	Most likely (\$ millions)	Maximum (\$ millions)	Calculated average (\$ millions)
Dedicated	57	60	63	60
Agile	55	65	70	63.33
Flexible	60	76	87	74.33

Table 4  
Changeover costs for different machining system types

Changeover costs	Minimum (\$ millions)	Most likely (\$ millions)	Maximum (\$ millions)	Calculated average (\$ millions)
Dedicated	57	60	63	60
Agile	8	10	15	11
Flexible	20	25	30	25

Triangular distributions are used for rough modeling primarily because they have parameters that are easy to obtain or estimate.

Note that the changeover cost for a dedicated system is the same as the initial cost for a dedicated system. Unless specifically designed to support in-family flexibility, dedicated systems are scrapped when moving to a new product model. In-family flexibility is still relatively uncommon in industry, so the model assumes that if an in-family change is required, the dedicated system is scrapped and a new system is purchased. Agile and flexible systems pay a conversion cost, with the difference in costs reflecting whether or not new tooling and fixtures must be purchased. However, the conversion cost is significantly less than purchasing a new system, because the majority of the equipment can be reused.

If a change is implemented, the production system type is penalized by the appropriate changeover cost. Further, if a change occurs and the system type is not designed to handle that type of change, the current system is replaced with a new system of the same type. For example, suppose that in year five a cross-family product model is a recognized market need. The dedicated system cannot support the model change, and thus a new dedicated system is purchased to support the shift to the new model. The agile and flexible systems can support the model change but pay the

associated changeover costs (sampled from the appropriate triangular distributions). Changeover times are omitted in this model, but help to differentiate agile and flexible systems if the investment costs are more competitive. For a preliminary analysis, it is sufficient to compare system types on costs alone. It may be possible to assess changeover costs that account for the changeover time indirectly, but this possible model extension is left for future work.

Monte Carlo simulation analysis of the decision tree is performed in Microsoft Excel using Palisade Decision Tools PrecisionTree and @Risk, which are Excel decision tree and simulation add-in packages, respectively. For each simulation iteration, the decision tree evaluates the expected NPV for each line type, where the expected NPV per line type is given by

$$\begin{aligned}
 & \text{NPV}(\text{line type}) \\
 &= \sum_{\text{all model change types}} [\text{initial cost} \\
 & \quad + \text{changeover cost}(1.15)^{-n}] \\
 & \quad \times P\{\text{model change type occurring}\}.
 \end{aligned}$$

The annual discount rate used is 15%, and  $n$  is the number of years into the future when the model change occurs. Note that  $n$  is a random variable, sampled from a triangular (1, 5, 10) distribution and rounded to the closest integer.

Table 5  
Simulation results for the decision tree model studying system purchase decisions

Decision expected cost (\$ millions)	Minimum (\$ millions)	Mean (\$ millions)	Maximum (\$ millions)
Dedicated system	63.54	71.78	83.60
Agile system	58.37	67.65	76.22
Flexible system	68.94	88.99	111.46
Overall decision (buy agile)	58.37	67.65	76.22

Similarly, the initial investment cost, type of changeover, and cost of changeover are sampled from the appropriate triangular distributions. While, this decision tree model only considers the value of making one model change, typically in the automotive industry, only one such change opportunity occurs during the life cycle of machinery. Thus, considering a single model change is appropriate to capture the value of the line investment decision.

For the machining system example presented, the expected NPV of each decision can be used to make recommendations on the types of systems to purchase. Table 5 summarizes an example of results of the simulation, and how they might be used to decide between different system types. The results indicate that the agile system is the best choice if the goal is to buy a machining system that can respond to a future product model change at minimal cost. Among the three system types considered, the agile system has the lowest expected investment and the smallest spread of possible costs. The risk profile for the different system types is presented in Fig. 6. The risk profile plots the expected costs of each system type and their associated probabilities of occurrence. The agile system is the least risky in terms of investment cost for it has the smallest spread of possible outcomes as compared to the dedicated and flexible system.

## 5. Summary and conclusions

In this paper, we have discussed agile manufacturing systems from an automotive industry perspective. A descriptive influence diagram, spreadsheet model and a decision tree model are

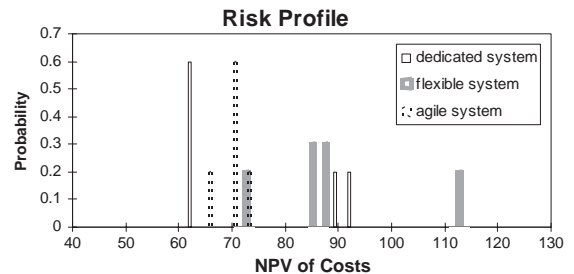


Fig. 6. The risk profile for the system design and purchase decision. A risk profile gives the expected costs and the corresponding probabilities of occurrence. The agile system is the least risky in terms of investment cost, for it has the smallest spread of possible outcomes.

studied to gain understanding about the value of system agility. From the limited study presented here, agile systems seem to meet the promise of rapid and cost-effective response to new (unplanned) product model introductions and dynamic capacity allocation to meet unpredictable demand. The two decision models developed are simple, capture the important features of economic decisions about manufacturing systems, and facilitate discussion with automotive industry engineers about agile and FMSs. However, there is a significant opportunity to extend research to more fully address the business case for agility. The preliminary analysis described here is localized to system selection for one manufacturing site. It could prove interesting to extend decisions to an enterprise perspective—where to use flexible, agile, and dedicated systems to build a most “robust and resilient” manufacturing enterprise. Portfolio analysis tools may be developed to determine the optimal mix of system types to meet fluctuating demand volumes and simultaneously address future model changes. Hybrid systems consisting

of both dedicated lines and agile lines should also be considered. Finally, we note that our results are based on the assumption that demand per product model is much less than available system capacity, which is generally the situation in industry. Business case analyses when demand is approximately equal to or greater than system capacity are also left for future research.

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