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A Framework for Flexible Systems and Its Implementation in Multiattribute Decision Making

In this paper, a framework for the concept of flexibility in complex system design is presented. This is one of the first of many steps toward developing new design methods for designers that will aid them in the development of customizable systems that meet the requirements of multiple customers and multiple tasks. The hope is that this paper will provide both a starting point from which academia and industry can move forward in developing new design methods for flexible systems and a basis for establishing a standard lexicon for use when referring to flexible system design. [DOI: 10.1115/1.1701874]

1 Introduction

In this section, the key issues and motivation for this research topic are discussed. They serve to set up the remainder of this paper in which the flexible system concept is defined and some preliminary results from a hypothetical design problem are generated and discussed.

1.1 Key Research Issues. Flexible systems, in this work, are defined to be systems designed to maintain a high level of performance when operating conditions or requirements change in a predictable or unpredictable way. A flexible system may have robustness designed into the system [1] and/or it may physically change in order to adapt to new conditions or requirements. In order to develop methods to promote flexible systems design, there is a need to:

- Develop metric(s) for flexibility that can be used during a design process.
- Distinguish between flexible, adaptive, open, and robust systems and the tools necessary to design each.
- Develop methods to model flexibility and explore the inherent tradeoffs in flexible systems, while maintaining a sense of optimality in a multiobjective sense.

In this paper, a framework for these developments is established, some preliminary results are provided, and insights into future needs are presented. In the next subsection, the importance of flexible systems as the next revolution in design history is discussed.

1.2 Flexible Systems in Engineering Design. There are numerous current applications of flexible systems. Milliken Research Company, a consultant to automotive racing teams, is interested in designing flexible cars that are able to adapt to the curves and turns in a Formula One racetrack [2]. Praxair, a manufacturer of air separation plants, strives to implement flexibility into their family of air separation plants that operate on all seven continents [3]. NASA strives to design cost effective aircraft and space systems that are flexible enough to perform a number of duties, usually reserved for multiple systems [4,5]. Researchers at Xerox's Palo Alto Research Center (PARC) are developing a new breed of robots that are flexible enough to adapt to their changing surroundings or applications [6]. Mayflower Corporation is currently testing a variable motion engine, in which the compression ratio and the stroke of the engine may be varied through alterations of the lever-arm pivot-point. By modifying these two variables, compression ratio and the capacity, it is possible to optimize the engine to meet a particular running condition. [7].

These are only a few of the important applications of flexible systems and flexible design processes. The motivation for exploring and handling flexibility in design can be traced back to Henry Ford and his assembly line. Figure 1 shows a brief history of the trends in product design. Although Ford's process brought accuracy into manufacturing design it offered no choices to the customer [8]. The next evolution was to improve efficiency, while maintaining accuracy, in order to mass-produce products at lower cost. Today, manufactured product design is involving the customer more. A primary measure of success is *flexibility* in product design to create customized orders while maintaining accuracy and efficiency. The internet and information revolution have also contributed to flexible systems design being an iterative social-technical process [9]. Each new measure of success relies on the old measures to improve the process. Although the measure is unknown, the next logical step is a largely automated process. While it may be difficult if not impossible to replace the values, preferences, and judgments of designers, many steps of capturing customer preferences and converting them into function and form could be automated. Before this can happen, an understanding of flexibility and its impact on product design must be developed and integrated into the design process. Motivation for continuing in this vein is presented in the next subsection.

1.3 Motivation for Flexible Systems. The motivation for developing methods to achieve flexible systems has many facets. The first stems from the idea that tradeoffs may not always be

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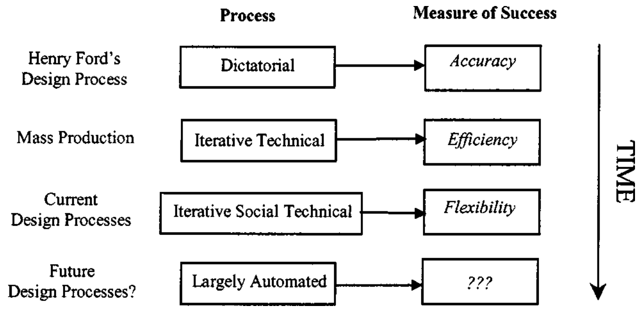


Fig. 1 Trends in product design

necessary in a well designed system. For example one may be able to achieve low cost and high quality [10]. Flexible systems have the ability to limit and potentially eliminate performance tradeoffs within systems that are capable of adapting to give optimal performance in predictable situations.

In the design of a racecar the difference between winning a race and not winning comes down to the ability of a driver to get the most out of his or her racecar. The core vehicle design (how it is set-up and tuned by a race team) is aimed at an optimal compromise that allows the driver to repeatedly turn fast lap times at a particular racetrack. Vehicle simulations are now used not only prior to and during a race weekend to guide tuning of the racecar, but also in the design phase where parameters, which are not adjustable, must be set and optimized. The basic configuration of the car (e.g., center of gravity, suspension systems, steering stiffness, roll stiffness) remains constant. Formula One racetracks are not constant radius tracks and do not consist of only a few turns. A layout of the Indianapolis Motor Speedway, site of the 2000 US Grand Prix, is shown in Fig. 2. This course, as typical with Formula One racetracks consists of a number of turns, ranging in radius sizes from 114 ft. to 840 ft. The optimal racecar configuration for each turn is also different [11]. However, the team must choose one configuration come race day. In addition, it may rain on race day, it may be humid, or it may be hotter than expected. All these uncontrollable conditions create a difficult job for racecar designers.

However, consider a *flexible* racecar design that is able to optimize its performance as a function of the current track conditions (ignoring racing restrictions for the time being). Whether on a straightaway, a big turn, or a small hairpin turn, the car could adjust variables such as the center of gravity, roll stiffness, and aerodynamic downforce (via wings and aerofoils). This adjustment could be more automated through an active control system, or less automated and a result of a driver adjustment. The ability of a racecar to dynamically change is a practical illustration of one aspect of flexible systems, *adaptability*, being presented in this paper.

While the racetrack layout provides a highly predictable aspect of a racecar's operating environment, there is a multitude of equally important factors that cannot be predicted (e.g. temperature, wind, rain, etc.). Such unknown factors are largely the focus of another aspect of flexible design, *robustness*, which strives to minimize the effect of unforeseeable changes in the operating environment on the performance of the system without eliminating the cause of the changes themselves [1]. The effect is to create a system that is less sensitive to variation in uncontrollable design parameters than the traditional optimal design point [12]. Though methods to incorporate robustness into the design process already exist [13–23], incorporation of these methods into a flexible design framework may require revision.

Robustness is similar to adaptability, but there is an important distinction between these various modes of flexibility. The key issue is the nature of the changes in operating conditions or requirements. *Adaptable design parameters* are capable of accommodating *predictable* changes in operating environment, while *robust design parameters* are capable of accommodating *unforeseeable* changes in the operating environment.

A final motivation for examining flexible design methods is the improvement of methods already developed. Incorporation of flexibility and adaptability into the design process has seen some application more recently, especially in the area of robust design. Combining robust design approaches and game theory was used by Chen and Lewis [14] to provide a range of solutions to designers, in effect giving more freedom to the designers and harnessing flexibility. Messac provides a Physical Programming based Robust Design Optimization method [15] which provides flexibility through incorporation of designer preferences. According to Roser, ''flexible design has the ability to change performance while requiring only minor time and costs to change the design parameters'' [24]. Flexible design under this context has been used to improve product design and reduce the economic cost associated with making changes to design parameters through a flexible design methodology [25]. In addition, Parkinson calls for the adoption of adaptive robust design approaches into the conceptual design stage [26]. Adaptive robust design is the addition of features to a design to ''control or absorb variability.'' Parkinson points out that adaptive robust design has been used in an ad hoc manner for some time and that incorporation of this ideology in the conceptual design stage would be beneficial. Finally, achievement of ''flexible'' systems has been proposed via product platforms and product families by Simpson [27] and Finch [28]. To this point however, ''flexibility'' has only been an abstract concept in system design. In the research presented here, flexibility is viewed as a tangible physicality achieved through adaptability and robustness.

Integration of these and other methods first requires that the fundamental concepts of the flexible design framework presented in the next section be well established. The development of metric(s) for and the modeling of flexibility could also lead to improvements or new extensions in these and other methods. Extending these approaches under the fundamental concepts proposed in this paper is viewed as an important step in providing dynamic design methods for the creation of truly flexible systems.

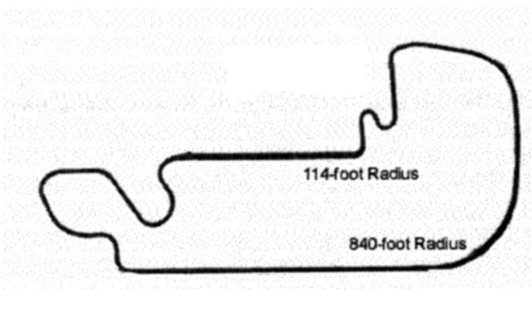


Fig. 2 Indianapolis Motor Speedway configuration

2 Conceptual Understanding of Flexible Systems

In this section, flexible systems are presented as a new type of open system and formal definitions are presented. These definitions should provide a consistent lexicon from which the design community can base future research in flexible system design.

2.1 Flexible Systems as Open Systems. Summarizing these concepts of flexible systems, a hierarchical organization for the design of flexible systems is proposed and shown in Fig. 3. In this organization, flexible systems are actually a subset of *open systems*, or systems that are capable of indefinite change, growth, and development over time [29], much like modular systems.

Modular architectures are a subset of open systems in much the

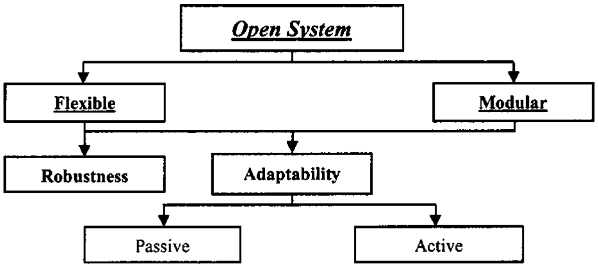


Fig. 3 Organization of open engineering systems

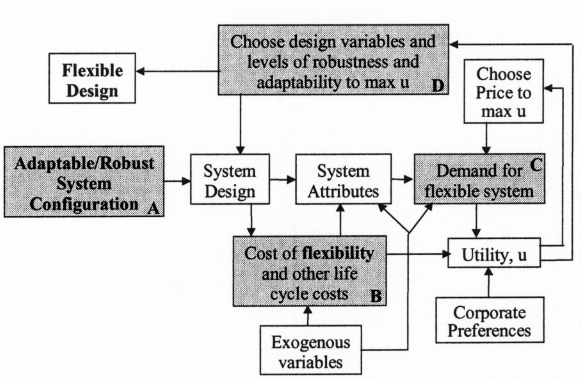


Fig. 4 Framework for flexible systems design

same vein as the flexible design framework proposed here. A modular architecture, according to Ulrich, has the following two properties [30]:

1. Chunks implement one or a few functional elements in their entirety.
2. The interactions between chunks are well defined and are generally fundamental to the primary functions of the product.

A truly modular architecture is one in which each ''chunk'' of the overall system accomplishes one specific function and the interface between chunks is well defined [30]. The advantage in such an architecture is that a change to one ''chunk'' can be made without requiring a change to the other ''chunks,'' in effect offering some amount of flexibility to designers [31]. However, it should be pointed out that if a design is too modular (needs different chunks for each situation) it may not be flexible enough. The approach to product family design by Simpson [27], is an example of a method based on a modular architecture.

The design of modular systems provides an effective way to design open systems. A modular design can be used to change or develop a system over time without having to redesign the entire system. Single or multiple modules can be effectively replaced and updated. A flexible design also supports open systems design in a different manner by allowing a system to adapt or remain robust over time due to changes in requirements or operating conditions. In this paper, the focus is on the flexible portion of Fig. 3, although there are similarities between flexible and modular systems. To facilitate understanding of what a flexible system truly is and to create a consistent lexicon, formal definitions are introduced here for flexible systems, robustness and adaptability.

2.2 Formal Definitions for Flexible Systems. From the motivation and conceptual discussion of flexible systems in previous sections, one gets a general understanding of the aspects of flexible design. In this research, the following definitions are used to describe flexible systems and its modes:

- **Flexible systems**—Systems designed to maintain a high level of performance through real time adaptations in their configuration and/or through robust parameter settings when operating conditions or requirements change in a predictable or unpredictable way. This definition implies that flexibility can be obtained through two modes: adaptability and robustness.
- **Adaptability**—Mode of achieving flexible systems where system parameters (design variables) that can be changed and their range of change are identified to enhance performance of the system in *predictable* changes in the operating environment; they can be changed when the system is not in use (passive) or in real time (active).
- **Robustness**—Mode of achieving flexible systems where system parameters (design variables) are set constant to minimize the effect of *unpredictable* changes in the operating environment on the performance of the system without eliminating the cause of the changes themselves [1].

Clearly, modular and flexible systems have a lot in common. Both system types utilize robustness to deal with unforeseeable changes in operating environment. Both systems also offer adaptability to improve performance in predictable situations. The major difference between modular and flexible systems is the type of adaptability utilized. Modular systems would more frequently use passive adaptability to achieve a new set of performance criteria while the system is offline. Flexible systems, on the other hand, use active adaptability in order to enhance performance while the system is in use. It is certainly possible to have a combination of active and passive components in a flexible system, similar to the integrated approaches to active and passive control of structures [32].

With a conceptual understanding and formal definitions of flexible systems in mind, a framework for achieving flexibility in design is presented in the next subsection. This framework provides a starting point for a formal methodology for designing flexible systems.

2.3 Framework for Flexible System Design. A design framework for flexible systems is proposed, aimed at providing effective decision support. This framework is shown in Fig. 4. This framework is an adaptation of the decision-based design framework given by Hazelrigg [33]. The focus in this paper is on the highlighted boxes where the concepts of flexibility, adaptability, and robustness have direct impact. The original framework provides a comprehensive approach to designing a system by iteratively changing design variables to maximize the assessed utility of the design. This utility is generated using corporate preferences, market demand, and selling price. The demand and price are determined using the system attributes, including life cycle costs. A set of exogenous variables, external variables influencing the system, also play a role in determining attributes and demand. See [33] for a detailed description of the generic framework. In this discussion, the focus is on the necessary changes in the framework for flexible systems.

The system configuration of interest can now be viewed as an adaptable/robust configuration (Box A), as shown in Fig. 4. The costs (Box B) now include the additional costs of flexibility (discussed in Section 3.2). The demand function (Box C) is also of interest, as demand for a flexible system would change, if the price were acceptable. This demand function would be a function of how flexible a system is, which creates a need to be able to *measure and quantify flexibility*. Lastly, the design variable values must be chosen to maximize the utility in Box D (which usually reflects profit). With flexible systems, the choice of design variable values also involves determining which variables should be made changeable (adaptive mode) and which should be made constant (robust mode), allowing for flexibility in a system's operation. The highlighted areas of the framework, A, B, C, and D are the focus of discussion in this paper.

Being flexible enough to accomplish a number of tasks does not come without a price. A tradeoff of flexibility versus performance versus cost versus potential net profit is absolutely necessary. For instance, in the racecar example, it would cost more to have an active control system. Is this added cost worth the potentially valuable few hundredths of a second per lap? This depends upon the potential future net profit of using the flexible system, which will dictate the demand for the product. When flexibility is important it may be beneficial to actually increase costs in order to increase the potential of increasing profit at a later date. In order to make this kind of tradeoff, *flexibility must be measured and quantified* so that designers can make rational tradeoff decisions. While there are a number of metrics for robustness, there are none for adaptability or flexibility in general. Therefore, the difference between the terms must be distinguished from a lexicon standpoint, and also from an implementation standpoint. For instance, certain measures of robustness may not work well with certain measures of adaptability.

Therefore, the decision-making environment is one that includes multiple performance measures, which translate into flexibility measures. In a multiattribute design problem there are typically an infinite number of ''optimal'' solutions, based on the preferences and risk assessments of the designer(s). In the next section, the issues required to address some of the primary challenges in designing flexible systems are discussed, including the technical background required for each task.

3 Issues in Designing Flexible Systems

In this section, a set of fundamental research issues that represent the foundation of flexible systems design are presented. Also some of the technical background necessary to address the issues is presented, including some initial studies.

The fundamental need for flexible systems stems from the presence of multiple requirements, operating conditions, or customers. These various states of operation for a system are typically represented by a system objective. For instance, in the racecar example of Fig. 2, possible objectives would be ''to minimize time around the 114/ft radius,'' ''to minimize time around the 840/ft radius,'' and every turning radius in between. If all these times can be minimized, and the driver performs well, then potentially many more races could be won and more profit could be realized. From a decision making perspective, satisfying all of these objectives simultaneously becomes a multiobjective decision problem.

When multiple competing objectives exist, the optimum is no longer a single design point but an entire set of non-dominated design points. This set is commonly referred to as the Pareto set [34]. The Pareto set is composed of Pareto optimal solutions. A feasible design variable vector, $\overline{x}'$, is Pareto optimal if and only if there is no feasible design variable vector, $\overline{x}$, with the characteristics,

$$f_i(\overline{x}) \leq f_i(\overline{x}') \quad \text{for all } i, \; i=1,n$$

$$f_i(\overline{x}) < f_i(\overline{x}') \quad \text{for at least one } i, \; 1 \leq i \leq n$$

where n is the number of objectives. The inherent problem with multiobjective situations is the lack of a single best, or optimal point. However, with flexible systems, it may be possible to design a system that could satisfy optimality conditions for multiple f's. This implies that some objectives could be unimportant at one time. Therefore, a system can adjust itself over some measurable time frame to concentrate on more important objectives at the sacrifice of other, less important objectives. If a flexible system must adjust during its operation it may be important to remain Pareto optimal (so that the performance follows the Pareto front) through changes in the system parameters. However, if a flexible system can adjust instantaneously or off-line, then it may not be important or even meaningful to follow the Pareto front. Regardless of how and when a flexible system adjusts, in order for this to become a reality, a paramount step is to be able to measure flexibility.

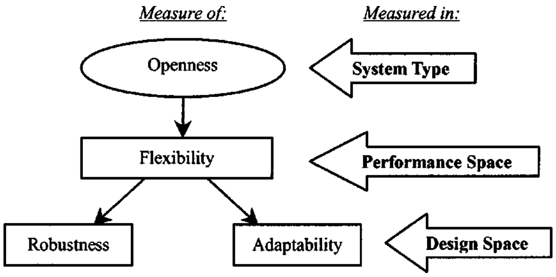


Fig. 5 Relation of concepts to design process

3.1 Creating Appropriate Metrics for Flexible Systems. One of the most important research issues to address in flexible systems design is to establish proper methods of measuring flexibility under certain conditions and assumptions. This will affect boxes C and D in Fig. 4, as the amount of flexibility in a system will influence the demand (by also affecting the price). The amount of flexibility will also influence the choice of the design variable values in order to achieve the necessary levels of flexibility. It is proposed to measure flexibility in the *performance space*, or the space defined by $f_i, \ldots, f_n$. The performance space allows a designer to understand how well a system meets performance requirements (technical and economic performance).

While flexibility can be achieved in the performance space, a system's ability to adapt or remain robust is achieved in the *design space*, or the space defined by the vector of design variables, $\overline{x}$. Designers must be able to understand how certain performance flexibility translates to adaptability and robustness in system configurations. Further, robustness will most likely be associated with design variables that are too expensive or impossible to make adaptable.

Beyond providing measures for flexibility, adaptability, and robustness, it is necessary to determine the relationship between a flexible system and its adaptable and robust modes. This primarily becomes a cost benefit issue and is presented in the next section.

3.2 Mapping Between Performance and Design Spaces. Finding a relationship between the concepts of flexibility, robustness, adaptability and openness is difficult. Initial work has lead to the development of a hierarchical organization as shown in Fig. 5. This figure is a combination of two branches from Fig. 3. Starting from the top, openness is a measure used to predict the system type that should be selected for product design, i.e., flexible or modular. Flexibility is a type of measurement related to the performance of the system being designed while adaptability and robustness require metrics that are measured in the design space. Given a measure of flexibility, the relationship to design variables can be made and lead to robust and/or adaptable designs. Again, Fig. 5 is merely a possibility. Further research and exploration of the concepts could lead to a change or additions to the ideas covered in this paper.

One of the significant research issues in Fig. 5 is the mapping between the conceptual levels. For instance, how does a particular measure of system openness (capability to change, growth, and development over time) map to a choice of flexibility or modularity? Further, how does a measure of flexibility map to a particular implementation of a robust and/or adaptable system configuration? While both issues are significant, the focus is on the latter in this section. This issue affects boxes B and D in Fig. 4, as the relationship between flexibility and adaptability, for instance, will influence what design variables are chosen to change or adapt. This mapping also affects the costs of system production, through additional costs to achieve flexibility.

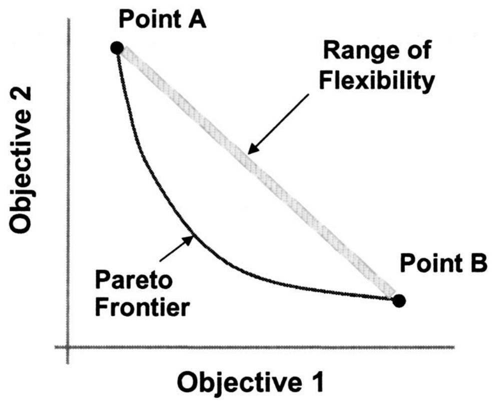


Fig. 6 Flexible design in performance space

While modeling demand and profit are necessary steps as part of the framework in Fig. 4, it is believed that before demand and profit can be modeled, the scientific foundations of flexible systems need to be explored and understood. Current work is being done on understanding the dynamics of demand, price, and profit within flexible systems, but this paper focuses on the foundations of flexible systems.

As a starting point, consider Fig. 6. In the figure, a generic performance space for a design problem with two objectives is shown. A representative Pareto frontier is also shown. At one end of the Pareto frontier, point A, objective 1 is optimized (minimized), while at the other end, point B, objective 2 is optimized (minimized). All points in between the endpoints represent where some tradeoff is made between the objectives. The opportunity with a flexible system is to design the system such that it can change its performance between points A and B, depending upon the current operating conditions. Therefore, the distance between points A and B could represent a region of flexibility for a given system. Of course, for 2 objectives, it is easy to visualize. However, parallel work is being done to allow the visualization of multidimensional spaces, as a way to understand flexibility [35].

While moving from point A to point B may be feasible from an engineering standpoint, it may be too costly to implement. For example, if a designer determines that it is physically possible to design a flexible racecar that is able to change its design variables (e.g., center of gravity, roll stiffness, and aerodynamics downforce) by a large amount, it may cost too much to make these variables adaptable. However, if a designer can achieve a certain level of flexibility by making a small change to the center of gravity for example, then this may be an effective decision to make. Another representative example is the Mayflower Corporation's flexible engine [7] which uses adaptive configuration changes to deal with competing objectives of power and fuel consumption. Making these types of tradeoff decisions is where mapping from flexibility to adaptability becomes critical.

Currently, there are three major decisions being addressed:

- How flexible the design can and should be?
- What design variables to make adaptable?
- What range of adaptability is required for each of these variables to meet the desired level of flexibility?

The method outlined here is built upon the assumptions that there are several costs associated with making a design flexible and it is desirable to minimize these costs.

4 Method Discussion

The method presented here addresses to some extent boxes A, B, and D in Fig. 4. The method attempts to determine an adaptable system configuration (Box A) based on a set of costs due to increased flexibility and other operating issues (Box B). The method involves utilizing optimization to select design variable ranges that produce flexible performance (Box D). While product demand is not being modeled here (Box C), a performance cost penalty is being used to penalize poor flexibility performance in an attempt to model lost profit.

Initially, a *target range of flexibility* is specified by the designer and indicated by the two design points representing its endpoints in the performance space. Figure 6 shows a representative performance space plot with a target range of flexibility defined by points A and B. With a target range of flexibility specified, the designer then must determine the penalty to deviate from this target range of flexibility. This penalty will reflect ''lost profit'' from not being able to achieve the target flexibility range. The designer must also determine the maximum allowable ranges of adaptability for each of the system design variables.

The general problem setup for the method is that of a standard optimization problem as shown in Fig. 7, with the objective being to *minimize a cost function* including three costs of flexibility that the designer must specify.

- The cost/penalty of deviating from the target range of flexibility (endpoints) for system performance,
- The one-time cost of making a design variable adaptable, and
- The operating cost of maintaining the required range of adaptability for each adaptable design variable.

This cost of flexibility function is by no means limited to the costs included here, and can easily be expanded to accommodate various problem specific cost issues. The optimization problem to minimize costs while achieving desired levels of flexibility is constrained by:

- a limit on the deviation from the target range of flexibility,
- a limit on which design variables can be made adaptable (because of costs limits), and
- a limit on the feasible range of adaptability of each design variable.

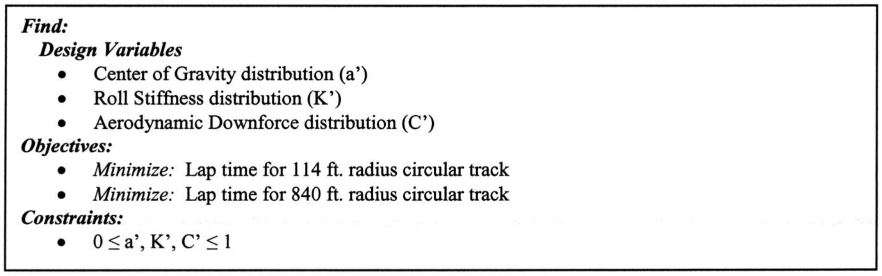
Find:
Design variables values that achieve the endpoints of the optimal range of flexibility (x_i)

Minimize:
F(x) = cost of adaptable variables + cost of deviation

Subject to:
Inequality constraints ($g_i(x) \leq 0$)
(Deviation from target flexibility range ≤ max allowable deviation)

Side constraints ($x_i^l \leq x_i \leq x_i^u$)
(Feasible range of adaptability for each design variable)

Fig. 7 General flexibility optimization problem setup



Find:

Design Variables

- Center of Gravity distribution (a')
- Roll Stiffness distribution (K')
- Aerodynamic Downforce distribution (C')

Objectives:

- *Minimize:* Lap time for 114 ft. radius circular track
- *Minimize:* Lap time for 840 ft. radius circular track

Constraints:

- $0 \le a', K', C' \le 1$

Fig. 8 Optimization problem statement for static racecar design

4.1 Case Study: Designing A Flexible Racecar. To illustrate the implementation and utility of this method it is applied to the design of a flexible Formula-One racecar. The motivation for implementing flexibility into a racecar stems from the fact that every unique turn radius in a road race results in a unique racecar setup to achieve optimal performance. By incorporating flexibility, the vehicle could reconfigure during a race to obtain optimal performance at each unique turn.

While the full details of the racecar model being used are not discussed (see [2] for model details), some background on the model is necessary. When attempting to capture the dynamics of an automobile in a computer-based simulation, the amount of detail available for inclusion is almost limitless. However, the three fundamental parameters of racing vehicle design, known as the ‘‘magic numbers’’ in racing are given to be weight distribution, aerodynamic downforce distribution, and roll stiffness distribution [36]. These three ‘‘magic numbers’’ are chosen as our three design variables, each normalized between the front and rear axle.

Weight distribution is the fore/aft distance of the vehicle’s center of gravity (CG) behind the front axle divided by the vehicle’s wheelbase. The potential exists to make this variable adaptable via movable ballast (or some other method) within the vehicle. Aerodynamic down force distribution is the division of aerodynamic downforce (created by overall vehicle shape and inverted airfoils) acting at the front axle and the rear axle. This distribution can be made adaptable by adjusting the front and rear spoilers. Roll stiffness distribution is the amount of resistance to vehicle roll the front axle provides relative to the total resistance provided by the front and rear axles. Roll stiffness can potentially be made adaptable through changes in the front and rear suspension.

The sole mechanism connecting racecars to the road surface is the four tires. The tire model used in conjunction with the vehicle model is based on empirical data taken on a tire-testing machine over a range of loads [37]. The detail included in the tire model is essential to the accuracy of the vehicle model. The vehicle must be designed to take best advantage of its tires, as they are the only means to generate control forces for maneuvering. The three design variables are the principal values influencing tire-operating conditions. Furthermore, the basic design is studied solely in the condition of steady state cornering. This is done by considering the performance of the vehicle on a constant radius circle known as a ‘‘skidpad.’’ Changing the radius of the circle changes the vehicle’s velocity, thereby allowing the entire speed range of the vehicle to be studied. Constant velocity at peak cornering (maximum lateral acceleration) is sought through iterative solution techniques. The skidpad and steady-state cornering design concepts are well founded and widely used in vehicle design and development.

The two conflicting objectives of interest in the case study are:

- Minimize lap time on a 114 ft radius skid pad
- Minimize lap time on a 840 ft radius skid pad

These objectives are indicative of the smallest and largest radii turns at the Indianapolis Motor Speedway (Fig. 2). The problem setup is shown in Fig. 8 (design variables are all normalized between 0 and 1).

4.2 Discussion of Results. To illustrate some characteristics of the method and its effective application to the design of flexible systems, the flexibility optimization problem for the racecar is solved for four different cost scenarios (CS1, CS2, CS3, CS4). In each of these scenarios, the costs for making the design variables adaptable and the unit costs for the range of adaptability for each of the design variables are changed and are hypothetical in nature to investigate the dynamics between system flexibility and costs of this flexibility. The costs for each scenario are shown in Table 1. The resulting range of adaptability for each design variable (a', K', C') and resulting lap times for each skid pad (F_{114}, F_{840}) were found using a fine grid search to ensure optimality and are shown in Table 2. In CS1 and CS4, each variable is made adaptable. However, in CS2 and CS3, the center of gravity, a', is kept constant, indicating that the cost of making the center of gravity adaptable was not worth the marginal increase in system flexibility. The corresponding ranges of flexibility are plotted in the racecar model’s performance space in Fig. 9. Also, in Fig. 9, the effective performance of each flexible racecar is shown for each cost scenario and for the ideal flexible racecar. The ideal racecar is one that achieves performance corresponding to optimal points A and B in Fig. 9, or whose effective performance is the utopia point (the point that combines the optimal performance of both objectives). Each of the flexible designs achieves a level of performance that exceeds the Pareto frontier. This is precisely one of the significant results of flexible systems; it is possible (and desirable) for flexible designs to exceed Pareto optimality (exist left and below of the Pareto frontier) as a result of the added flexibility. However, it is important to note that simply exceeding the set of Pareto optimal designs does not guarantee that the flexible racecar configuration will win a race against a single, static, Pareto optimal racecar design configuration. To illustrate this, a mock race is conducted in which each of the flexible racecar configurations compete with several static, Pareto optimal racecar configurations.

A mock race is conducted in which 11 different racecar configurations compete. Five of these racers are flexible (Target, CS1, CS2, CS3, and CS4) and it is assumed that their configurations

Table 1 Cost scenarios for racecar design variables

DV	Initial Cost	Unit Cost	Initial Cost	Unit Cost
	CSI		CS2	
a'	2000	1000	20000	10000
K'	20000	10000	2000	1000
C'	20000	10000	20000	10000
	CS3		CS4	
a'	20000	10000	5000	1000
K'	20000	10000	5000	1000
C'	2000	1000	5000	1000

Table 2 Results of flexibility optimization for racecar design

Cost Scenario 1	Adaptable Range
a'	0.329–0.350
K'	0.284–0.210
C'	0.508–0.430
(F_{114},F_{840})	(10.075, 16.578) sec
Cost Scenario 2	**Adaptable Range**
a'	0.350–0.350
K'	0.210–0.250
C'	0.430–0.480
(F_{114},F_{840})	(10.116, 16.578) sec
Cost Scenario 3	**Adaptable Range**
a'	0.350–0.350
K'	0.210–0.250
C'	0.430–0.480
(F_{114},F_{840})	(10.116, 16.578) sec
Cost Scenario 4	**Adaptable Range**
a'	0.329–0.520
K'	0.284–0.670
C'	0.310–0.508
(F_{114},F_{840})	(10.075, 16.437) sec

change instantaneously to achieve flexible performance. The other six racecars are non-flexible (static), Pareto optimal configurations (R1-R6). The Pareto configurations are chosen evenly from along the Pareto set, including the two endpoints (R1-endpoint A and R6-endpoint B). The race is composed of 100 laps of the 840 ft radius skid pad, and 400 laps of the 114 ft radius skid pad. The mock race is conducted via numerical simulation (multiply time for one lap on a skid pad by number of laps). The race results are shown in Fig. 10, where the bars represent each racer's time, with the shorter bars more desirable.

From the results presented in Fig. 10, it is determined that a flexible racecar configuration does exist that has the ability to beat any non-flexible competitor. While this may seem an obvious conclusion, it is important to realize that economic constraints may keep flexible car designs from achieving performance superior to static car designs. Such is the case under two of the cost scenarios evaluated (CS2 and CS3). Although CS2 and CS3 are flexible, the nature of the race—100 laps on 840 ft radius skid pad + 400 laps on 114 ft radius skid pad—and the economic constraints of these scenarios make these flexible designs inferior to the fastest static design. The remaining two cost scenarios (CS1 and CS4) do result in optimally flexible configurations that are effective (i.e. faster than any of the nonflexible racecars). While the details of the cost scenarios are not critical, it is significant to recognize the dynamics between the various costs and the capability of a system to be flexible. An effective flexible configuration for a design problem may exist, but the "best" flexible configuration for that design problem may, in fact, not be effective (i.e. not perform any better than a non-flexible configuration). If this is the case the designer may revert to a static design, or accept a higher cost of flexibility allowing for an effective flexible design.

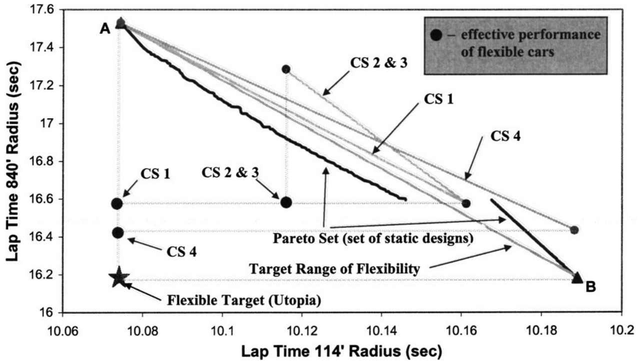


Fig. 9 Performance space plot for racecar model with ranges of flexibility

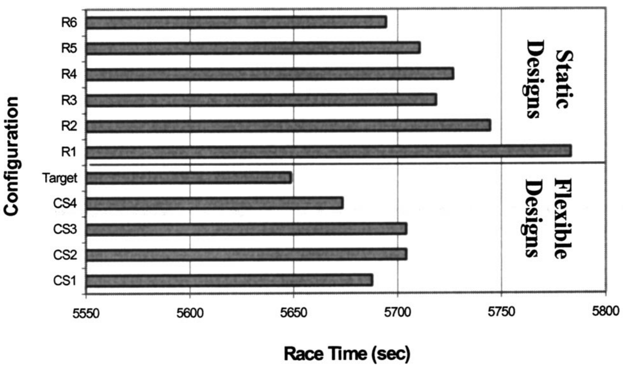


Fig. 10 Race results for various static and flexible racecar design configurations

In design problems with many more variables and objectives, it will become necessary to use advanced techniques to map between performance and design spaces. This is not a trivial problem. For a given set of design variable values there is one set of performance values. However, the converse is not true. For one set of performance values, there may be many designs that provide the given performance. This one-to-many mapping problem represents a significant challenge. Developments from other work could be used to facilitate solving this mapping problem [38].

5 Closing Remarks

The concepts and example presented in this paper, though simple, serve to show the potential benefits that a flexible design framework can provide. The method used in the case study provides the designer(s) an approach to bring flexibility into the design process while considering the cost of such flexibility. The method also gives an indication of the adaptable range of certain design variables that change over time to provide the system's performance flexibility.

Though the potential benefits are well suited for the future of flexible system design, answering the questions presented here (and those that will inevitably arise in the future) will prove challenging. The major concerns to be considered in developing the flexible system framework and answering the questions posed here are:

- Profit of being flexible: will the additional cost of flexible systems be offset by increases in demand and profit? This is an important question that requires a comprehensive decision support framework.
- Applicability of system measures: what measures of flexibility and adaptability can be used for certain types of systems?
- Interface relationships: what are the relationships between openness and flexibility/modularity, and flexibility and adaptability/robustness?
- Search techniques: how can the best combination of adaptable and/or robust variables be found? The cost of making design variables adaptable may not be worth the added value of flexibility or the profit generated from the added flexibility. Therefore, finding the combination of adaptable (changing) and robust (constant) variables that gives the desired flexibility for a maximum profit is the objective in flexible systems design.

Finally, this paper is intended to provide both, a starting point from which academia and industry can move forward in developing new decision support tools and as a basis for establishing a standard lexicon for use when referring to flexible system design. It may also be viewed as an invitation to help take flexibility from an abstract concept to a tangible reality in product and systems design.

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