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Rouse, William; Verma, Dinesh; Lucero, D. Scott; Hanawalt, Edward

Monterey, California. Naval Postgraduate School

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Strategies for Addressing Uncertain Markets and Uncertain Technologies

William B. Rouse—Georgetown University [wr268@georgetown.edu]

Dinesh Verma—Stevens Institute of Technology [dverma@stevens.edu]

D. Scott Lucero—Office of the Secretary of Defense (Ret.) [dslucero@gmail.com]

Edward S. Hanawalt—General Motors [edward.hanawalt@gm.com]

Abstract

Engineering involves designing solutions to meet the needs of markets or missions. Organizations would like to have the flexibility and agility to address both uncertain needs and uncertain technologies for meeting these needs. This article presents and illustrates a decision framework that enables flexibility and agility and provides guidance on when to pursue optimal, highly integrated solutions. We consider how uncertainties arise, contrasting the automotive and defense domains. We propose an approach to managing uncertainties. We consider how to represent alternative solutions and project the value of each alternative, including how market or mission requirements can be translated into system requirements. Possible use cases for our framework are discussed. A detailed case study of autonomous vehicles for enhancing the mobility of disabled and older adults is presented.

Introduction

Much of engineering involves designing solutions to meet the needs of markets, or perhaps military missions or societal sector needs such as water, power, and transportation. These needs are often uncertain, especially if solutions are intended to operate far into the future.

There is also often uncertainty in how best to meet needs. New technologies may be needed, and their likely performance and cost may be uncertain. Budgets may be insufficient to achieve what is needed. Competitors or adversaries may be creating competing solutions that are similar or superior.

Organizations would like to have the flexibility and agility to address both uncertain needs and uncertain technologies due to performance challenges, organizational experience, supply chains, and so on. This is likely to require ways of thinking and allocating resources that are foreign to many organizations. This article outlines and illustrates these ways of thinking.

To illustrate how companies address uncertainties, consider two experiences at General Motors (GM). Both illustrations involved Ford surprising GM. The first led to a major failure and the second to a substantial success (Hanawalt & Rouse, 2010).

In 1981, General Motors began planning for a complete refresh of its intermediate-size vehicles: the front wheel drive A-cars and the older rear wheel drive G-cars. The GM10 program would yield vehicles badged as Chevrolets, Pontiacs, Oldsmobiles, and Buicks. This program was to be the biggest research and development (R&D) program in automotive history and, with a $5 billion budget, the most ambitious new car program in GM's 79-year history.

The introduction of the Ford Taurus in 1985 was a huge market and business success and a complete surprise to GM. It was one of the first projects in the United States to fully utilize the concept of cross-functional teams and concurrent engineering practices. The car and the process used to develop it were designed and engineered at the same time, ensuring higher quality and more efficient production. The revolutionary design of the Taurus, coupled with its outstanding quality, created a new trend in the U.S. automobile industry, and customers simply loved the car.

The Taurus forced GM to redesign the exterior sheet metal of the GM10 because senior executives thought the vehicles would look too similar. Many additional running changes were incorporated into the design in an attempt to increase customer appeal. The first vehicles reached the market in 1988, approximately $2 billion over budget and 2 years behind schedule.

All of the first GM10 entries were coupes, a GM tradition for the first year of any new platform. However, this market segment had moved overwhelmingly to a four-door sedan style. Two-door midsize family cars were useless to the largest group of customers in the segment; members of the Baby Boomer generation were now well into their child-rearing years and needed four-doors for their children. GM completely missed the target segment of the market. From 1985 to 1995, GM's share of new midsize cars tumbled from 51% to 36%.

The Lincoln Navigator is a full-size luxury SUV marketed and sold by the Lincoln brand of Ford Motor Company since the 1998 model year. Sold primarily in North America, the Navigator is the Lincoln counterpart of the Ford Expedition. While not the longest vehicle ever sold by the brand, it is the heaviest production Lincoln ever built. It is also the Lincoln with the greatest cargo capacity and the first non-limousine Lincoln to offer seating for more than six people.

GM was completely surprised by the Navigator. They had not imagined that customers would want luxurious large SUVs. GM responded with the Cadillac Escalade in 1999, intended to compete with the Navigator and other upscale SUVs. The Escalade went into production only 10 months after it was approved. The 1999 Escalade was nearly identical to the 1999 GMC Yukon Denali, except for the Cadillac badge and leather upholstery. It was redesigned for the 2002 model year to make its appearance and features fall more in line with Cadillac's image.

In 2019, 18,656 Navigators were sold, while 35,244 Escalades were sold. Escalade has outsold Navigator every year since 2002. GM had clearly adapted to the surprise of the Navigator. One can reasonably infer that the company learned from the GM10 debacle. Surprises happen. Be prepared.

We recently studied 12 cars withdrawn from the market in the 1930s, 1960s, and 2000s (Liu et al., 2015). We leveraged hundreds of historical accounts of these decisions, as well as production data for these cars and the market more broadly. We found that only one vehicle was withdrawn because of the nature of the car. People were unwilling to pay Packard prices for Studebaker quality, the two companies having merged in 1954.

The failure of the other 11 cars could be attributed to company decisions, market trends, and economic situations. For example, decisions by the Big Three companies to focus on cost reduction resulted in each manufacturer's car brands looking identical, effectively de-badging them. Mercury, Oldsmobile, Plymouth, and Pontiac were the casualties. Honda and Toyota were the beneficiaries.

This article presents and illustrates a framework for addressing such scenarios. We first consider how uncertainties arise, contrasting the automotive and defense domains. We then propose an approach to managing uncertainties. This leads to consideration of how to represent alternative solutions and to estimate the value of these alternative solutions. We discuss possible use cases for our framework and present a detailed case study of autonomous vehicles to enhance the mobility of disabled and older adults.

Sources of Uncertainties

Table 1 portrays two domains where addressing uncertainties are often central and important aspects of decision-making. The primary domain emphasized in this article is automotive. However, we also want to emphasize the relevance of our line of thinking to the defense domain. The parallels are reasonably self-explanatory, but a few differences are worth elaborating.

In the automotive domain, there are multiple providers of competing vehicles. In defense, there is typically one provider of each platform. Many customers make purchase decisions in the automotive domain while, in defense, there is one (primary) customer making the purchase decision. The lack of competitive forces can lead to requirements being locked in prematurely.

In the automotive domain, vehicles are used frequently. In defense, platforms are used when missions need them, which, beyond training, may never occur. Competitors' relative market positions in the automotive domain change with innovations, for example, in the powertrain. In defense, adversaries' positions change with strategic innovations, for instance, pursuits of asymmetric warfare. As former Defense Secretary James Mattis has said, "The enemy gets a vote on defense planning" (Mattis, 2019).

Automobiles have model year changes, usually 3-year refreshes, and life spans of up to 10 years, typically 6 to 7. The B-52 bomber has been in use for almost 70 years, and the F-15 fighter aircraft has been in use for almost 50 years. There are block upgrades of military aircraft every few years, typically for changes of avionics and weapon systems—rather than body style.

There are similarities that can be seen in Table 1. Uncertainties associated with market needs or mission requirements typically flow down In Table 1. Uncertainties associated with technology typically flow up, for example, when the engineering organization (at the company or vehicle level) is not sure of how to provide a function or whether performance or cost objectives can be met. New technologies enable new military capabilities. The most important weapons transforming warfare in the 20th century, such as airplanes, atomic weapons, the jet engine, and electronic computers, did not emerge as a response to doctrinal requirement of the military (Chambers, 1997, p. 791).

Table 1. Multilevel Comparison of Automotive and Defense Domains

Automotive Domain	**Defense Domain**
Economy	**Geopolitics**
- Geopolitics (e.g., Regulations, Tariffs, War)	- Military Conflict (i.e., Hot War)
- GDP & Inflation (e.g., Recession)	- Geopolitical Tension (e.g., Grey Zone Conflicts)
- Financial Markets (e.g., Interest Rates)	- Civil Wars (e.g., Migration)
- Energy Markets (e.g., Fuel Prices)	- Soft Power (e.g., Alliances)
Market	**Economics**
- Market Growth/Decline (e.g., Consumers)	- GDP Growth/Decline
- Segment Market Saturation (e.g., Sedans)	- Inflation/Deflation
- External Competitors (Companies)	- Domestic & Allies' Defense Budgets
- Internal Competitors (Brands)	- Congressional Priorities (e.g., Jobs)
Company Priorities	**Defense Priorities**
- Market Strategy (e.g., Positioning, Pricing)	- Engagement Strategies
- Product Management (e.g., Processes)	- Missions Envisioned
- Dealer Management (e.g., Incentives)	- Adversary Capabilities
- Financial Management (e.g., Investments)	- Capabilities Required
- Brand Management (e.g., Rebadging)	- Emerging Technologies
Vehicle	**Platform**
- Price	- Performance
- Design	- Schedule
- Quality	- Cost

Automobile companies are currently wrestling with pursuits of battery electric vehicles and the uncertain rate of market adoption (Liu et al., 2018). Just over the horizon is the opportunity to compete in the driverless car market (Liu et al., 2020), with significant uncertainties about the regulatory environment (Laris, 2020). The case study later in this article addresses this opportunity.

There are also uncertainties associated with where to manufacture vehicles (Hanawalt & Rouse, 2017). Labor costs used to dominate location decisions, but other economic, legal, and political factors are now being considered. Decisions to withdraw from manufacturing in Australia, Canada, and South Korea have resulted.

Product line or program managers in the two domains often have similar questions regarding common uncertainties. A comparison of these questions is shown in Table 2. It is often socially unacceptable to verbalize such questions. Unfortunately, uncertainties not verbalized are seldom well managed (Rouse, 1998).

Table 2. Comparison of Automotive and Defense Domains

Automotive Domain Uncertainties	Defense Domain Uncertainties
Customer future preferences	Mission plans will remain relevant
Customers' future purchases will favor our offerings versus competitors	Mission platforms will remain superior to adversaries' capabilities
Performance of our offerings after development	Performance of mission platforms after development
Affordability over the coming years	Affordability over the coming years
Budgets for our offerings across a range of future needs	Budgets for mission platforms across a range of future needs
Supply chains will be economical, efficient, and secure	Supply chains will be economical, efficient, and secure
Competitors' capabilities will not be perceived to be superior	Adversaries' capabilities will be inferior and certainly not superior
Our enterprise will continue to support our endeavors	Ensuring that sponsors (e.g., Congress) will continue to provide support

Managing Uncertainties

In both the automotive and defense domains there are usually uncertainties about market or mission requirements as well as uncertainties about technologies and abilities needed to meet these requirements. This section outlines an approach to thinking about managing these uncertainties.

Consider a couple of extremes. You are absolutely sure a function will be required, and you are absolutely sure of how to deliver it. In other words, you are not at all uncertain. You should invest to create a solution to meet this need, assuming that you are confident the necessary human and financial resources are available. At the other extreme, you are absolutely sure a function will not be required. Regardless of your ability to deliver this function, you should not invest in creating this solution. Between these two extremes, there are several strategies a company might adopt. The choice depends on enterprises' abilities to predict their futures, as well as their anticipated abilities to respond to these futures. What strategies might enterprise decision makers adopt to address alternative futures? As shown in Figure 1, we have found that there are four basic strategies that decision-makers can use: optimize, adapt, hedge, and accept.

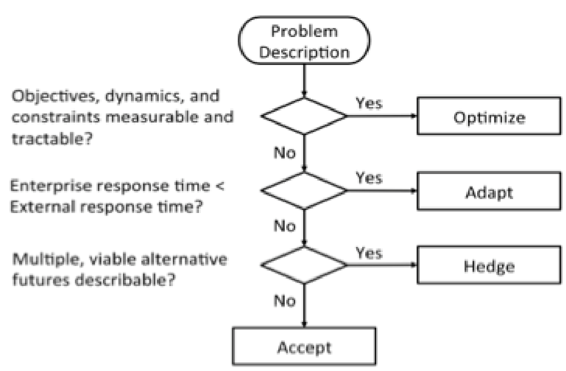

Figure 1. Strategy Framework for Enterprise Decision-Makers (Pennock & Rouse, 2016)

If the phenomena of interest are highly predictable, then there is little chance that the enterprise will be pushed into unanticipated territory. Consequently, it is in the best interest of the enterprise to optimize its products and services to be as efficient as possible. In other words, if the unexpected cannot happen, then there is no reason to expend resources beyond process refinement and improvement.

If the phenomena of interest are not highly predictable, but products and services can be appropriately adapted when necessary, it may be in the best interest for the enterprise to plan to adapt. For example, agile capacities can be designed to enable their use in multiple ways to adapt to changing demands—for example, the way Honda adjusted production capacity but other automakers could not in response to the Great Recession. Their planning was more efficient in the long run; even so, efficiency may have to be traded for the ability to adapt.

For this approach to work, the enterprise must be able to identify and respond to potential issues faster than the ecosystem changes. For example, consider unexpected increased customer demands that tax capacities beyond their designed limits. Design and building of new or expanded facilities can take considerable time. On the other hand, reconfiguration of agile capacities should be much faster, as Honda demonstrated. The value of this approach is widely known in the military. As renown fighter pilot Robert Boyd—inventor of the Observe, Orient, Design, Act (OODA) loop—noted, whoever can handle the quickest rate of change is the one who survives (Boyd, 2004). Similarly, Arie De Gues, head of Strategic Planning for Royal Dutch Shell, stated that the ability to learn faster than your competitors might be the only sustainable advantage (Senge, 1990).

If the phenomena of interest are not very predictable and the enterprise has a limited ability to adapt and respond, it may be in the best interest of the enterprise to hedge its position. In this case, it can explore scenarios where the enterprise may not be able to handle sudden changes without prior investment. For example, an enterprise concerned about potential obsolescence of existing products and services may choose to invest in multiple, potential new offerings. Such investments might be pilot projects that enable the enterprise to learn how to deliver products and services differently or perhaps deliver different products and services.

Over time, it will become clear which of these options makes most sense, and the enterprise can exercise the best option by scaling up these offerings based on what they have learned during the pilot projects. In contrast, if the enterprise were to take a wait-and-see approach, it might not be able to respond quickly enough, and it might lose out to its competitors.

If the phenomena of interest are totally unpredictable and there is no viable way to respond, then the enterprise has no choice but to accept the risk. Accept is not so much a strategy as a default condition. If one is attempting to address a strategic challenge where there is little ability to optimize the efficacy of offerings, limited ability to adapt offerings, and no viable hedges against the uncertainties associated with these offerings, the enterprise must accept the conditions that emerge.

There is another version of acceptance that deserves mention—stay with the status quo. Yu et al. (2011) developed a computational theory of enterprise transformation, elaborating on a qualitative theory developed earlier (Rouse, 2005). They employed this computational theory to assess when investing in change is attractive and unattractive. Investing in change is likely to be attractive when one is currently underperforming and the circumstances are such that investments will likely improve enterprise performance. In contrast, if one is already performing well, investments in change will be difficult to justify. Similarly, if performance cannot be predictably improved—due to noisy markets and/or highly discriminating customers—then investments may not be warranted despite current underperformance.

Lucero (2018) proposed that these four strategies would be differentially relevant for different areas of an uncertainty space with axes involving uncertainties around the requirements and the ability to meet those requirements. We extended his thinking to formulate Figure 2, focusing on uncertainties in developing technologies.

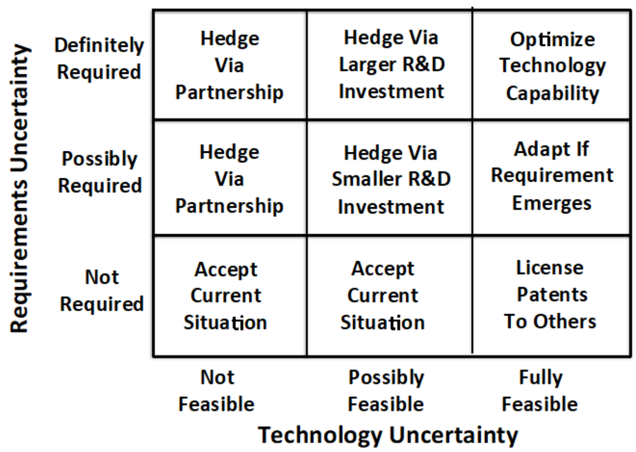

Figure 2. Strategies Versus Uncertainties

This figure depicts the space as having nine discrete cells, which makes it easier to explain, but there are unlikely to be crisp borders between areas where the different strategies are applicable.

There are three types of hedges in Figure 2. The upper two cells of the middle column represent company or agency investments in creating technology options to meet possible requirements. The upper two cells of the left column represent licensing, joint development, or other arrangements to buy technology options from partners. The lower cell of the right column represents selling options to others so they can hedge uncertainties.

The criteria on the left of Figure 1 constrain choices of strategies as well as positions in the uncertainty space. If, for example, the objectives, dynamics, and constraints are not measurable and tractable, then optimization may lead to an inappropriate or at least fragile solution (Carlson & Doyle, 2000).

At this point, we have strategies for addressing uncertainties. We now need to address the characteristics of the alternative solutions of interest and then the projected expected utility of each alternative.

Representing Solutions

Whose preferences should guide decisions? While there may be one ultimate decision-maker, success usually depends on understanding all stakeholders. Human-centered design addresses the concerns, values, and perceptions of all stakeholders in designing, developing, manufacturing, buying, and using products and systems. The basic idea is to delight primary stakeholders and gain the support of the secondary stakeholders.

The human-centered design construct and an associated methodology has been elaborated in a book, *Design for Success* (Rouse, 1991). Two other books soon followed (Rouse, 1992, 1993). The human-centered design methodology has been applied many times and continually refined (Rouse, 2007, 2015).

The premise of human-centered design is that the major stakeholders need to perceive products and services to be valid, acceptable, and viable. Valid products and services demonstrably help solve the problems for which they are intended. Acceptable products and services solve problems in ways that stakeholders prefer. Viable products and services provide benefits that are worth the costs of use. Costs here include the efforts needed to learn and use products and services, not just the purchase price.

Figure 3 embodies the principles of human-centered design, built around Set-Based Design (SBD; Sobek et al., 1999), Quality Function Deployment (Hauser & Clausing, 1988), and Design Structure Matrices (Eppinger & Browning, 2012). As later discussed, multi-stakeholder, multi-attribute utility theory (Keeney & Raiffa, 1993) is used to project the value of alternatives. Note that validity, acceptability, and viability in Figure 3 are defined in the above discussion of human-centered design.

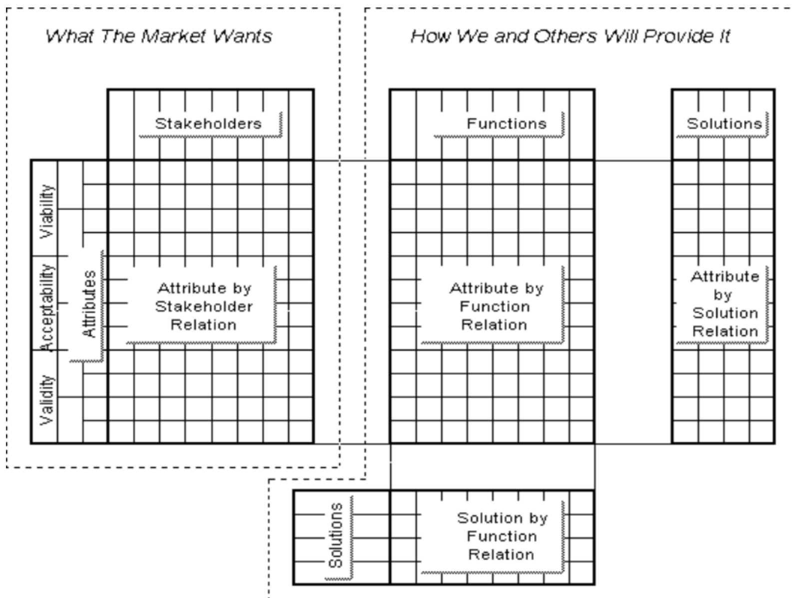

Figure 3. Model Structure for Attributes, Stakeholders, Functions, and Solutions

Sobek et al. (1999) contrast SBD with Point-Based Design. Developed by Toyota, SBD considers a broader range of possible designs and delays certain decisions longer. They argue that, “Taking time up front to explore and document feasible solutions from design and manufacturing perspectives leads to tremendous gains in efficiency and product integration later in the process and for subsequent development cycles.” Al-Ashaab et al. (2013) and Singer et al. (2017) report on interesting applications of SBD to helicopter engines and surface combatant ships, respectively.

SBD is reflected in Figure 3 in terms of defining and elaborating multiple solutions, including those of competitors or adversaries. Quality Function Deployment (QFD; Hauser & Clausing, 1988) translates the “voice of the customer” into engineering characteristics. For Figure 3, this translates into “voices of the stakeholders.” Design Structure Matrices (DSM; Eppinger & Browning, 2012) are used to model the structure of complex systems or processes. In Figure 3, multiple models are maintained to represent alternative offerings as well as current and anticipated competitors’ offerings.

The “What the Market Wants” section of Figure 3 characterizes the stakeholders in the product or service and their utility functions associated with context-specific attributes clustered in terms of validity, acceptability, and viability. The section of Figure 3 labeled "How We and Others Will Provide It" specifies, on the right, the attribute values associated with each solution. The functions associated with each solution are defined on the left of this section. Functions are things like steering, accelerating, and braking, as well as functions that may not be available in all solutions (e.g., backup camera).

Attribute to function relationships in Figure 3 are expressed on a somewhat arbitrary scale from −3 to +3. Positive numbers indicate that improving a function increases the attribute. Negative numbers indicate that improving a function decreases an attribute. For example, a backup camera may increase the price of the vehicle but decrease insurance costs.

Solutions on the bottom of Figure 3 are composed of functions, which are related to attributes of interest to stakeholders. In keeping with the principles of SBD, multiple solutions are pursued in parallel, including potential offerings by competitors. While it is typical for one solution to be selected for major investment, the representations of all solutions are retained, quite often being reused for subsequent opportunities.

There are additional considerations beyond SBD, QFD, and DSM. Uncertain or volatile requirements can be due to evolving performance targets (Ferreira et al., 2009) or surprises by competitors or adversaries (e.g., the Ford Taurus). Both causes tend to result in expensive rework. In the realm of defense, the end of the Cold War ended the need for a 70-ton self-propelled howitzer (Myers, 2001). Advances in anti-ship cruise missiles and a challenging performance envelope doomed the Expeditionary Fighting Vehicle (Feickert, 2009).

Decision-making may involve more than one epoch (Ross & Rhodes, 2008), including both near-term and later decisions. For example, at GM, Epoch 1 involved creating an Escalade as a rebadged GMC in 1999. Epoch 2 involved offering an Escalade as a unique upscale SUV in 2002.

Another issue is the costs of switching from one solution to another (Silver & de Weck, 2007). A surveillance and reconnaissance mission adopted an initial solution of a manned aircraft with an option to replace this solution with an unmanned air vehicle (UAV) several years later (Rouse, 2010). A deterrent to switching was the very expensive manned aircraft, which would no longer be needed. This problem was resolved by negotiating, in advance, the sale of the aircraft to another agency, effectively taking it "off the books." Thus, there can be significant value in flexibility. "A system is flexible to the extent that it can be cost-effectively modified to meet new needs or to capitalize on new opportunities" (Deshmukh et al., 2010).

Identifying options can be difficult (Mikaelian et al., 2012). What can you do when, and what will it cost? Rouse et al. (2000) discuss case studies from the semiconductor industry. Rouse and Boff (2004) summarize 14 case studies from automotive, computing, defense, materials, and semiconductor industries.

Projecting Value

Using the framework provided by Figure 3 and principles from SBD, QFD, DSM, and so on, one can create multi-attribute models of how alternatives address the concerns, values, and perceptions of all the stakeholders in designing, developing, manufacturing, buying, and using products and systems. The next issue of importance is the likely uncertainties associated with the attributes of the alternatives. These uncertainties involve what the market or mission needs—or will need—and how well solutions, in terms of functions and underlying technologies, will be able to meet these needs.

The expected value of an alternative can be defined as the value of the outcomes a solution provides times the probability that these outcomes will result. The probability may be discrete, or it may be represented as a probability density function. For the former, the calculation involves multiplication and summation; for the latter, the calculation involves integration.

Following Keeney and Raiffa (1993), we approach this problem using multi-stakeholder, multi-attribute utility theory. We can define the utility function of stakeholder i across the N attributes by

$$u_i = u\,(x_{1i}, x_{2i}, \ldots , x_{Ni}) = u(\mathbf{x}_i) \qquad (1)$$

where the bold **x** denotes the vector of attributes. The utility of an alternative across all M stakeholders is given by

$$U = U\,[u(\mathbf{x}_1), u(\mathbf{x}_2), \ldots, u(\mathbf{x}_M)] \qquad (2)$$

The appropriate forms of these functions vary by the assumptions one is willing to make. When there are many attributes, a weighted linear from is usually the most practical. The weights in Equation 1 reflect how much a particular stakeholder cares about the attribute being weighted. It is quite common for most stakeholders to only care about a small subset of the overall set of attributes. Those for which they do not care receive weights of zero.

The weights in Equation 2 reflect the extent to which the overall decision-maker or decision process cares about particular stakeholders. For example, is the customer the most important stakeholder, or do corporate finances drive the decision? These weights are usually subject to considerable sensitivity analyses.

Who are typically the stakeholders? We have found that the concerns, values, and perceptions of the following entities are typically of interest:

- Market/Mission
- Customers/Users/Warfighters
- Operators/Maintainers
- Technologists/R&D
- Finance/Budgets
- Current Competitors
- Possible Competitors
- Investors
- Governments (e.g., Regulatory Authorities)

For the case study presented in a later section, we focus on solely the investor stakeholder. Investors in driverless cars are interested in three primary attributes:

- **Competitive Advantage (CA):** To what extent will the investment of interest enable value-added pricing, reduce production costs, reduce operating costs, and leverage existing capacities?
- **Strategic Fit (SF):** To what extent will the investment of interest leverage technology competencies, exploit current delivery architectures, complement existing value propositions, exploit current partnerships and infrastructure, and provide other opportunities for exploitation?
- **Return on Investment (ROI):** What capital expenditures, technology acquisition costs, and labor expenses will be needed? What revenue and profits will likely result?

We will return to these attributes in the case study.

Use Cases

What types of decisions are amenable to the approach just outlined? We have applied this line of reasoning to 20+ projects involving science and technology investment decisions—in particular, investments in R&D, licensing technologies, and capacity expansion. The case study discussed in the next section is an example of this use case.

Another use case involves exploring tipping points in market/mission analysis, where small investments result in sizable performance gains, either for you or for your competitors or adversaries. A good example is when Motorola found that offering pagers in colors substantially increased sales (Henkoff, 1994). Another example is the aforementioned repurposing of a military aircraft. Getting it "off the books" greatly enhanced the UAV investment value and secured the needed resources (Rouse, 2010).

Another use case involves understanding when disaggregated architectures provide higher value than integrated architectures. A good example involves investments in system infrastructure to support modularity and decrease future switching costs. Tight integration may help the current generation of a technology perform better but may undermine the flexibility of the next generation.

A classic use case involves understanding where key points of uncertainty could be resolved with more information. For example, business intelligence that enables determining competitors' or adversaries' actual investments versus advertised intentions can enable avoiding investing in competitions that inherently will not happen. This is an important reason for modeling solutions of competitors or adversaries as indicated in Figure 3.

To address these use cases, we need to be able to predict impacts on outcomes (e.g., attributes):

- Impacts of investments on outcomes (e.g., performance, costs)
- Impacts of particular investments on outcomes (e.g., color on pagers)
- Impacts of architectures on outcomes (e.g., performance, costs)
- Impacts of uncertainties on decisions (e.g., strategies, investments)

Performance can include many things:

- Mission performance (e.g., sorties, targets hit)
- Market performance (e.g., sales, profits, earnings per share, share price)
- Platform performance (e.g., speed, quality)
- Platform acceptance (e.g., consumer ratings)
- Platform availability (reliability and maintainability)
- Time to deployment
- Time to market
- Acquisition and operating costs

Linking alternative investments to these types of metrics require models of how investments translate to capabilities, which then translate to platform, mission, and market performance.

Case Study

Assistive technologies (AT) hold enormous promise for the 100 million disabled and older adults in the United States (Rouse & McBride, 2019). Driverless cars have the potential to greatly enhance the mobility of this population with attractive pricing. Note that the platforms of interest are autonomous vehicles, while the market or mission is to provide enhanced mobility to disabled and older adults.

The Auto Alliance hosted a series of three workshops on “AVs & Increased Accessibility” (Auto Alliance, 2019). We focused on physical, sensory, and cognitive disabilities. Approximately 200 people participated in the three workshops from a wide range of advocacy groups, automobile manufacturers, and federal agencies. Workshop participants suggested a large number of needs as well as approaches to meeting these needs. We clustered these needs into 20 categories. Eight categories covered 70% of the suggestions. Definitions of these categories are as follows:

- ***Displays and controls*** concern information that users can see, hear, touch, and so on, and actions they can take.
- ***Locating and identifying vehicle*** concerns users knowing where their ride is waiting and recognizing the particular vehicle.
- ***Passenger profiles*** include secure access to information about passengers, in particular their specific needs.
- ***Emergencies*** concern events inside and outside the vehicle that may require off-normal operations and user support.
- ***Adaptation to passengers*** involves adjusting the human–machine interface (HMI) to best support particular users with specific needs.
- ***Easy and safe entry and egress*** concerns getting into and out of the vehicle, as well as safety relative to the vehicle’s external environment.
- ***Trip monitoring and progress*** relates to providing information as the trip proceeds, particularly regarding route and schedule disruptions.
- ***Onboard safety*** concerns what happens in the vehicle as the trip proceeds, assuring minimal passenger stress and injury avoidance.

An example mapping from needs to technologies is shown in Table 3. Technologies required include hardware, software, sensing, networks, and especially enhanced HMI. HMIs need to enable requesting vehicle services, locating and accessing vehicles, monitoring trip progress, and egressing at destinations to desired locations.

Table 3. Market Needs Versus Enabling Technologies (Auto Alliance, 2019)

Needs	Technologies				
	Hardware	Software	Sensors	Networks	HMI
Displays & Controls	Hardware for Displays & Controls	Tutoring System for HMI Use	Use and Misuse of Displays & Controls	Access to Device Failure Information	Auditory, Braille, Haptic, Tactile, Visual Displays
Locating & Identifying Vehicle	Vehicle-Mounted Sensors	Recognition Software	Integration of Sensed Information	Sensors of External Networks	Portrayal of Vehicle & Location
Passenger Profiles, Privacy	Phone or Smartphones, Tablets	App to Securely Provide Profile Information	Recognition of Passenger	Access to Baseline Info. on Disabilities	Portrayal to Assure Recognition
Emergencies	Controls to Stop Vehicle & Move to Safe Space	Recognition & Prediction of Situation	Surrounding Vehicles, People, Built Environ.	External Services—Police, Fire, Health	Portrayal of Vehicle Situation
Adaptation to Passengers	Adjusting Entry, Egress, Seating	Learning Passenger Preferences	Sensing Reactions to Adaptations	Access to Baseline Info. on Adaptations	Portrayal to Enable Change Confirmations
Easy & Safe Entry & Egress	Sufficient Space to Maneuver	Capturing Data on Space Conflicts	Surrounding Vehicles, People, Built Environ.	Networked Access to (e.g., Bldg. Directions)	Portrayal of Surrounding Objects
Trip Monitoring & Progress	Speedometer, GPS, Maps	Predictions of Progress, Points of Interest	Surrounding Vehicles, People, Built Environ.	Access to Traffic Information (e.g., Accidents)	Portrayal of Trip & Progress
Onboard Safety	Securement of Wheelchairs & Occupants	Capturing Data on Securement Conflicts	Sensing & Recording Safety Risks	Access to Best Practices on Safety Risks	Portrayal of Securement Status

The wealth of assistive technology (AT) and supporting technologies in Table 3 suggest a substantial need for seamless technology integration to avoid overwhelming disabled and older adults, or indeed anybody. We expect that artificial intelligence (AI)–based cognitive assistants may be central to such integration. The question of who might provide which pieces of an overall integrated solution is addressed in this case study.

The question of interest in this case study concerns how an automotive original equipment manufacturer (OEM) should position itself relative to this immense market opportunity. We begin with SBD. The hypothetical OEM wants to consider five alternative solutions, indicated as scenarios in Table 4 because each includes a market strategy as well as a solution.

Predominant uncertainties include competitors' strategies, technologies (particularly software), abilities to execute, and time. The third scenario, ally with advocacy groups, merits elaboration. The key idea is an American Association of Retired Persons (AARP)–branded vehicle—for example, similar to the Eddie Bauer branding of the Ford Explorer—with better paint job, leather seats, heated seats optional, and interior accents. This co-branding alliance with Ford lasted 20 years.

The next step in applying the methodology outlined in this article is characterization of Competitive Advantage (CA), Strategic Fit (SF), and Return on Investment (ROI) for the set of five scenarios. We then want to consider uncertainties associated with each scenario, which for this case study will be characterized using discrete probabilities.

The expected utility of each scenario $E[U_S]$ can then be calculated using

$$E[U_S] = W_{CA} \times P_{CA} \times U_{CA} + W_{SF} \times P_{SF} \times U_{SF} + W_{ROI} \times P_{ROI} \times U_{ROI} \quad (3)$$

where $W_{CA} + W_{SF} + W_{ROI} = 1$ and P_{CA} , P_{SF} , and P_{ROI} are the probabilities of achieving U_{CA} , U_{SF} , and U_{ROI} , respectively. As noted earlier, in many situations, probability density functions are needed rather than discrete probabilities. The calculation then involves integration rather than multiplication and summation.

Once we have the scenarios ranked by $E[U_S]$ we will return to consideration of the optimize, adapt, hedge, and accept strategies from Figure 1.

Table 4. Set of Solutions Considered

Scenario	Examples	Uncertainties	Confidence in Requirements	Ability to Respond
Provide total vehicle package	OEM itself or acquisition of autonomous vehicle player	Can OEM really compete against the technology companies?	Hardware is high; software has some unknowns	Strength in integration; easier when OEM controls
Provide vehicle platform to host intelligent software	Alliance with Amazon, Apple, Google, Microsoft, or Uber	Why will intelligent platform players source OEM's vehicles?	Basic vehicle platform design is known, but can OEM do this at lowest cost?	Time to integrate software, which will evolve faster than hardware
Provide vehicle platform to host user-centered HMI	Alliance with advocacy groups for disabled & older adults	Why will user-centered HMI players source OEM's vehicles?	How will HMI requirements impact vehicle design?	Time to integrate software, which will evolve faster than hardware
Provide vehicle platform without alliance	OEM will manufacture desired platforms	Why will major players source OEM's vehicles?	Basic vehicle platform design is known; can OEM do this at the lowest cost?	Time to integrate software; design in modularity
Provide integrated mobility services	OEM will provide total mobility experiences	Can OEM competitively manage an end-to-end service?	Auto OEMs do not really understand business model, but does anyone?	Longer time to build out entire ecosystem

Table 5 summarizes assumed probabilities and utilities for the five scenarios. The risk associated with CA is primarily a requirements risk (i.e., the market risk of not having the right offering or best offering). The risk associated with SF is primarily a technology risk (i.e., the risk of not creating, or being able to create, a competitive technology platform). The risk associated with ROI includes both requirements and technology risks.

The reasoning underlying the assumptions in Table 5 is as follows:

- **Competitive Advantage:** U_{CA} is high if providing total solution, moderate if only providing vehicle; P_{CA} is low without strong partners, not just branding partners
- **Strategic Fit:** U_{SF} is high if only providing vehicle, moderate if also providing intelligent software; P_{SF} is high if only providing vehicle, moderate if integrating partners' intelligent software
- **Return on Investment:** U_{ROI} is high if providing total solution, moderate if partnering, low if only providing vehicle; P_{ROI} is low if providing total solution, moderate if partnering or only providing vehicle

The scenarios differ significantly in terms of probabilities of success and utilities if successful. The scenarios also differ significantly in terms of costs of success. Scenarios 1 and 5 represent total up-front commitments and the net present value (NPV) of financial projections would underlie ROI calculations. Scenarios 2 and 3 represent hedges against the risks of not being a player. For these scenarios, net option value (NOV) would be the metric in ROI calculations. Scenario 4 represents an accept strategy, as it exploits existing capabilities and will require the least investment.

Table 5. Assumed Probabilities and Utilities for the Five Scenarios

Scenario	**Competitive Advantage**		**Strategic Fit**		**Return on Investment**	
	P_{CA}	U_{CA}	P_{SF}	U_{SF}	P_{ROI}	U_{ROI}
Provide total vehicle package	Low (P = 0.1)	High (U = 0.9)	Moderate (P = 0.7)	Moderate (U = 0.5)	Low (P = 0.1)	High (U = 0.9)
Provide vehicle platform as host	Moderate (P = 0.3)	High (U = 0.9)	Moderate (P = 0.7)	High (U = 0.9)	Moderate (P = 0.3)	Moderate (U = 0.5)
Provide vehicle platform to host HMI	Low (P = 0.1)	High (U = 0.9)	Moderate (P = 0.7)	High (U = 0.9)	Moderate (P = 0.3)	Moderate (U = 0.5)
Provide vehicle platform only	Low (P = 0.1)	Moderate (U = 0.5)	High (P = 0.9)	High (U = 0.9)	Moderate (P = 0.3)	Low (U = 0.1)
Provide integrated mobility services	Low (P = 0.1)	High (U = 0.9)	Moderate (P = 0.7)	Moderate (U = 0.5)	Low (P = 0.1)	High (U = 0.9)

Boer (2008) suggests how to value a portfolio that includes some investments characterized by NPV and others by NOV. He argues for strategic value (SV), which is given by

$SV = NPV + NOV$ (4)

The NPV component represents the value associated with commitments already made, while the NOV component represents contingent opportunities for further investments should the options be "in the money" at a later time.

Figure 4 provides results for $E[U_S]$ with varying assumptions regarding the relative importance (weighting) of CA, SF, and ROI. The overall results are as follows:

- Scenario 2 has the highest $E[U_S]$ unless SF dominates
- Scenarios 2 and 3 have the highest $E[U_S]$ if ROI and/or CA dominate
- Scenario 4, followed by 2 and 3, has the highest $E[U_S]$ if SF dominates
- Scenarios 1 and 5 have the lowest $E[U_S]$ across all weighting assumptions

Discussion

These results reflect, of course, the assumptions in Table 5. These assumptions could be varied to assess their impact, but given that W × P × U occurs in all the underlying equations, the variations of W in Figure 4 reasonably reflect the range of possibilities.

Scenario 1 embodies a significant technology risk in a very competitive market, while Scenario 5 involves a significant requirements risk in attempting to provide services not typical for an OEM. Both of these risks could be hedged with acquisitions of a software company (Scenario 1) or a service company (Scenario 5). This might be difficult, as the market capitalizations of the automotive OEMs are much lower than the capitalizations of likely and attractive acquisition targets.

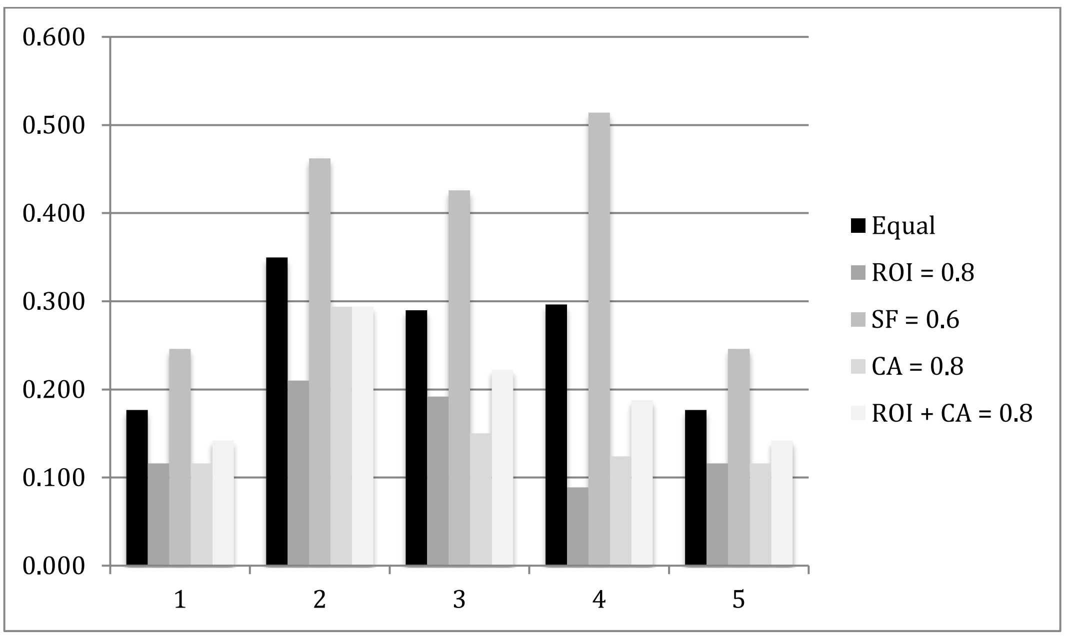

Figure 4. Expected Utilities for the Five Scenarios With Varying Weights

Scenarios 2 and 3 represent hedges against these risks as well but result in dividing the share of the vehicle that the OEM will provide and, hence, its revenues and profits. Nevertheless, they are attractive because they decrease the competition and provide key technologies. These scenarios also allow the freedom to pursue other strategies as uncertainties resolve themselves.

Scenario 4 focuses on leveraging SF. It represents acceptance by the OEM of whatever leverage is provided by its core competencies. This also involves acceptance that they will have to compete with the other automotive OEMs that want to provide the vehicle platform. They are quite familiar with this type of competition.

The resulting overall strategy involves a portfolio of three investments:

- Substantial investment in Scenario 2—a hedge against market and technology risks
- Moderate investment in Scenario 3—a hedge against Scenario 2 not resulting in a partner
- Baseline investment in Scenario 4—acceptance of a traditional role in the automotive marketplace

With the strategies decided, one is ready to apply the QFD and DSM aspects of Figure 3 to the functionality in Table 3. This requires that the set of stakeholders be expanded to include:

- OEM
- Partners
- Suppliers
- Car Service Providers
- Car Service Customers

It also requires characterizing competing offerings, whose likely functions, features, and pricing will have been sleuthed via business intelligence.

This illustrates the multilevel nature of the methodology. The first question is which of the business scenarios make sense and, for those that make sense, determining the appropriate strategy for pursuing each scenario. The idea is to iteratively refine the chosen scenarios and strategies, which will influence the nature of investments—for example, whether one makes a total commitment up front (NPV), hedges uncertainties with smaller investments (NOV), or simply accepts one's current position and waits to see how the market develops.

Conclusions

Engineering involves designing solutions to meet the needs of markets or missions. Organizations would like to have the flexibility and agility to address both uncertain needs and uncertain technologies for meeting these needs. This article has presented and illustrated a framework that provides this flexibility and agility. We considered how uncertainties arise, contrasting the automotive and defense domains. We proposed an approach to managing uncertainties. We considered how to represent alternative solutions and project the value of each alternative. Possible use cases for our framework were discussed. A detailed case study of autonomous vehicles to enhance the mobility of disabled and older adults was presented.

We did not consider but need to acknowledge broader risks. It is quite imaginable that driverless car technologies, once deployed, will lead to inadvertent failures with substantial consequences (Danzig, 2018). It is also possible that sweeping organizational and societal trends will substantially disrupt this seemingly immense market opportunity (Rouse, 2019, 2020). The current pandemic is a case in point. The impacts of climate change are on the horizon.

Understanding and managing uncertainties need to be core competencies in companies, agencies, and institutions. As this article has argued, uncertainties need to be rigorously and systematically addressed. Managing for success must also include forecasting and managing potential failures.

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Acquisition Research Program
Graduate School of Defense Management
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

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