ART-005: METHODS FOR INTEGRATING DYNAMIC REQUIREMENTS

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Executive Summary

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 report presents and illustrates a decision framework that enables flexibility and agility, and provides guidance on when to pursue optimal, highly integrated solutions, and when to hedge investments. 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. Three detailed case studies are reported. The first focuses on designing a portfolio of autonomous vehicle platforms for enhancing the mobility of disabled and older adults. The second addresses designing a portfolio of policies for mitigating global warming as well as the impacts of global warming. The third case study is concerned with designing a portfolio of policies to enhance the STEM talent pipeline. An appendix of the report provides a software development plan for a software tool capable of supporting all three case studies.

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, etc. This is likely to require ways of thinking and allocating resources that are foreign to many organizations. This report 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 R&D Program in automotive history and with a $5 billion dollar budget, the most ambitious new car program in GM's 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 U.S. 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, ~$ 2 billion over budget and two 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 ten 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, Rouse & Yu, 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 debadging them. Mercury, Oldsmobile, Plymouth, and Pontiac were the casualties. Honda and Toyota were the beneficiaries.

This report 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 three detailed case studies of applying this framework and methodology.

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 the first case study 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.

Table 1. Multi-Level 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

In the auto 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 auto 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 auto 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 auto 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 three-year refreshes, and lifespans of up to ten years, typically 6-7. 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 airplane, atomic weapons, the jet engine, electronic computers, did not emerge as a response to doctrinal requirement of the military (Chambers, 1997).

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

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.

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 vs. 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 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

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.

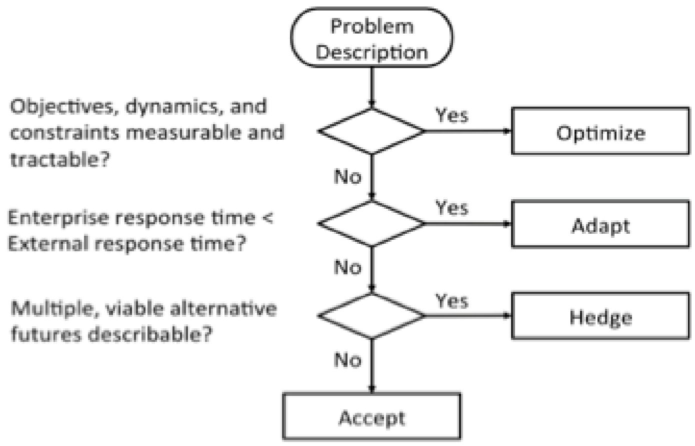

Figure 1. Strategy Framework for Enterprise Decision Makers (Pennock & Rouse, 2016)

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, e.g., 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 OODA (observe–orient–decide–act) loop, noted that whoever can handle the quickest rate of change is the one who survives (Coram, 2002). 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, Rouse and Serban (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. 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 their uncertainties.

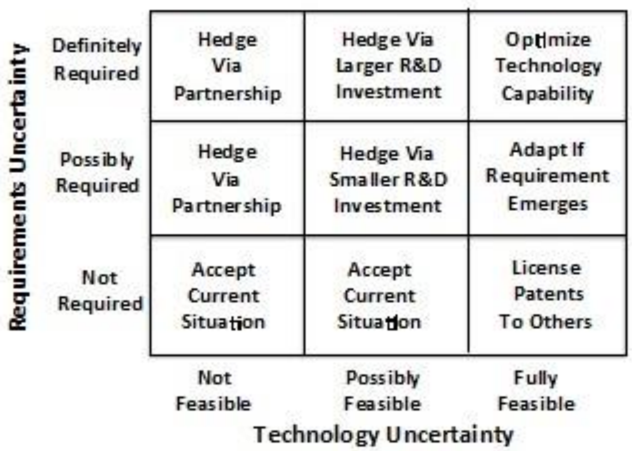

Figure 2. Strategies Versus Uncertainties

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, operating, and maintaining 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.

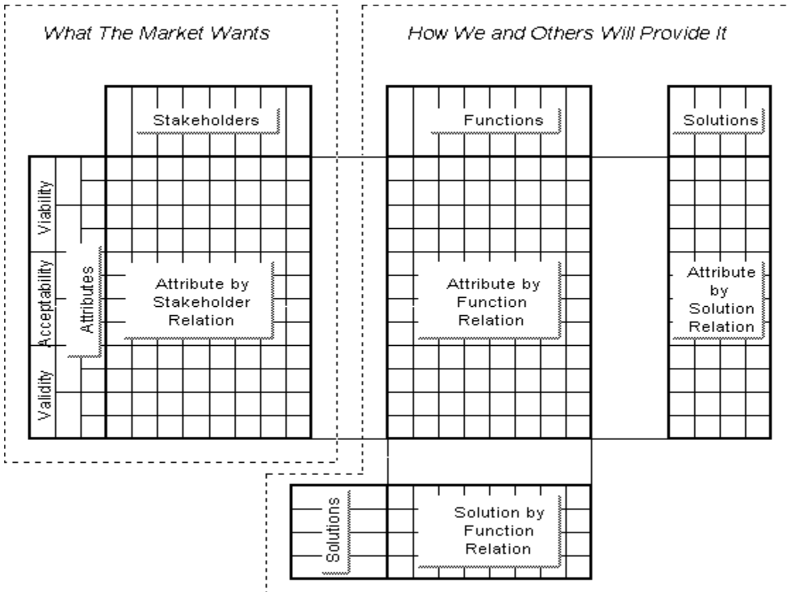

Figure 3. Model Structure for Technology Platforms

Figure 3 embodies the principles of human-centered design, built around Set-Based Design (Sobek, Ward & Liker, 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.

Sobek, Ward and Liker (1999) contrast Set-Based Design (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 and colleagues (2013) and Singer and colleagues (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 (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 (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 Set-Based Design, multiple solutions are pursued in parallel, including potential offerings by competitors. While it is typical for one solution to eventually 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, e.g., (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 and colleagues (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, etc., 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 will 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 attributed 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
- Competitors – Current
- Competitors – Possible
- Investors
- Governments, e.g., Regulatory Authorities

For the first 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 first 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 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 vs. 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 & maintainability)
- Time to deployment
- Time to market
- Acquisition & operating costs

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

Case Study 1: Driverless Cars for Disabled and Older Adults

Background

Assistive technologies (AT) hold enormous promise for the 100 million disabled and older adults in the US (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, etc. 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 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 with regard to 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 human-machine interfaces. Human-machine interfaces need to enable requesting vehicle services, locating and accessing vehicles, monitoring trip progress, and egressing at destinations to desired locations. The content of this table provides a starting point for filling in the framework in Figure 3.

The wealth of 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 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.

INVESTMENT SCENARIOS

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 (Rouse, et al., 2021). We begin with Set-Based Design. 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 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.

Table 3. Market Needs vs. 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 Smart Phones, 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

Table 4. Set of Scenarios 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 tech 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

MULTI-ATTRIBUTE UTILITY MODEL

The next step in applying the methodology outlined in this report 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

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

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 of optimize, adapt, hedge, and accept strategies from Figure 1.

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

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)

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.

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

$$SV = NPV + NOV \qquad (4)$$

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.

EXPECTED UTILITIES VS. WEIGHTINGS

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 x P x U occurs in all the underlying equations, the variations of W in Figure 4 reasonably reflects 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 auto OEMs are much lower than the capitalizations of likely and attractive acquisition targets.

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 Strategic Fit. 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 auto OEMs that want to provide the vehicle platform. They are quite familiar with this type of competition.

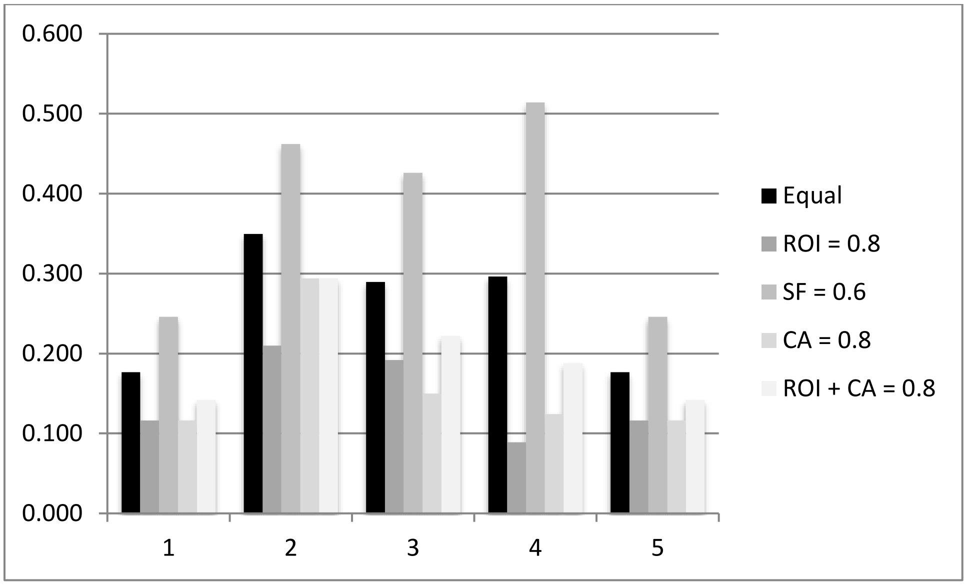

Figure 4. Expected Utilities for the Five Scenarios with Varying Weights

OVERALL INVESTMENT STRATEGY

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.

Discussion

This illustrates the multi-level 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, e.g., 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.

Case Study 2: Energy Policy for Global Warming

This case study addresses alternative policy interventions to address global warming, as well as the impacts of global warming (Rouse, 2022). We assert that a portfolio of interventions is needed rather than an integrated "solution" – there is no silver bullet, no vaccine for sea level rise. We consider a range of interventions, each with one or more potential implementation mechanisms. Each member of the portfolio has associated uncertainties in terms on the effectiveness of interventions and mechanisms, and required investments. Each member of the portfolio has preferred strategies for dealing with these uncertainties. This case study illustrates a systemic approach to designing this portfolio of policy interventions.

Background

Humanity has always exploited natural resources for food, shelter, energy, etc. This exploitation emerged on an industrial scale in the 19th century as the extraction and processing of raw materials blossomed during the Industrial Revolution. During the 20th century, energy consumption rapidly increased.

Today, the vast majority of the world's energy consumption is sustained by the extraction of fossil fuels, including oil, coal and gas. Intensive agriculture also exploits the natural environment via degradation of forests and water pollution. As the world population rises, the depletion of natural resources will become increasingly unsustainable.

New England's Wood Economy

New England was heavily forested when the colonists arrived in the 17^{th} century. It is heavily forested today, particularly in northern states. However, the forests one sees today are "new growth." The earlier forests were denuded to support the region's wood economy. Annie Proulx's novel ***Barkskins*** (2016) chronicles this era.

The colonists used wood for everything. They cut down trees to build homes, roads, bridges, and ships. Shipbuilding in New England was a major industry. The first author's great, great grandfather founded a shipyard and later was superintendent of construction for a steamship line, originally with wooden ships but later iron and then steel.

Ships were also built for fishing and hunting whales. This affected what goods people in New England could trade. There was much trade between New England and other regions or countries such as England. New England would export resources like fish and lumber. In return, unfortunately, New England would receive slaves that were sold to plantations in the south.

New England and the rest of the country moved from a wood economy to a fossil fuel economy. Coal, oil, and gas fueled industry. Private automobiles emerged in the early 20th century, enabling by mid-century vast suburbs and increasing traffic and congestion. This has resulted in vast amounts of carbon dioxide (CO2) emitted into the atmosphere.

CONSEQUENCES OF CO2

Almost 90% of all human-produced CO2 emissions come from the burning of fossil fuels like coal, natural gas and oil. Deforestation also increases CO2 in atmosphere by destroying trees that consume CO2.

The CO2 in the atmosphere increases greenhouse warming that results when atmosphere traps solar radiation. Consequently, the Earth's temperature increases. This leads to ice melting and sea level rise.

Beyond threatening coastal buildings, rising sea levels lead to salinization of groundwater and estuaries. This decreases the availability freshwater. Ocean acidification also affects sea life. Consequently, the food supply and human health are degraded.

REDUCING CO2 EMISSIONS

This report suggests a multi-faceted approach to CO2 reduction involving reducing, reusing, and recycling, elaborated in a later section. Using less heat and air conditioning, using less hot water, replacing incandescent light bulbs, and buying energy-efficient products are elements of this approach. Using the off switch on lights and appliances is also of value.

Transportation is a large producer of CO2. Compared to an average single-occupant car, the fuel efficiency of a fully occupied bus is six times greater and a fully occupied train car is 15 times greater. In general, we need to drive less and ride smarter. Increased migration to cities should help this, as the feasibility of mass transit increases with population density.

Urban living is, in general, more energy efficient than suburban or rural living. For example, apartment living involves more shared walls and fewer exposed walls, reducing energy consumption for heating and cooling. Green spaces in cities are also important both for people's well-being and the CO2 that trees consume.

PROGRESS AND PROBLEMS

We have known about these phenomena and the challenges for at least four decades (NAP, 1983). However, the recently published Production Gap Report (SEI, et al., 2019) provides a stark assessment of progress toward constraining temperature increases:

- "Governments are planning to produce about 50% more fossil fuels by 2030 than would be consistent with a 2ºC pathway and 120% more than would be consistent with a 1.5ºC pathway.
- The global production gap is even larger than the already-significant global emission gap, due to minimal policy attention on curbing fossil fuel production.
- The continued expansion of fossil fuel production – and the widening of the global production gap – is underpinned by a combination of ambitious national plans, government subsidies to producers, and other forms of public finance."

Lenton and colleagues (2019) argue that we are already at climate tipping points in terms of artic warming, ice collapses, and ocean heat waves. Waterman (2019) reports on emerging consequences for US national parks in terms of climate change and invasive species, as well as overcrowding and money woes. The consequences of global warming are no longer hypothetical.

Lightbody and colleagues (2019) consider flood mitigation efforts across the US and argue for the cost effectiveness of mitigation. Lempert and colleagues (2018) focus on climate restoration. As compelling as such proposals may be, they face fundamental economic hurdles.

Flavelle and Mazzei (2019) recently reported on efforts to estimate the costs of raising roads in the Florida Keys to escape rising ocean levels. Route 1 in the Keys is 113 miles long. Raising all of it by 1.3 feet by 2025 will cost $2.8 billion; elevating it by 2.2 feet by 2045 will cost $4.8 billion; and by 2060 the cost would be $6.8 billion. With 13,300 people living in the Keys, this amounts to a range of $215,000 to $523,000 per person. They conclude that, "As sea levels rise, some places can't be saved."

Prospective owners of coastal homes in the US will no longer be able to get 30-year mortgages, as the mortgage companies can no longer predict long-term risks (Flavelle, 2020). Similarly, owners will no longer be able to afford increasingly expensive flood insurance. The companies specializing in this type of insurance will go out of business.

Extreme heat has started to melt roads in states experiencing record level heat waves (Alderton, 2020). Applying an additional rubberized layer to roads helps with this, but the higher road levels result in trucks not being able to go under many bridges.

Warmer ocean waters have caused warm water fish to migrate to Northeast waters in the US, while resulting in cold water fish moving further north (Samenow & Freedman, 2020). The New England fishermen are catching fish they do not recognize and no one in their markets has ordered for dinner.

On a longer term, it is projected that between 2040 and 2060, the Southeastern and Southwestern US will become uninhabitable due to temperatures and fires that humans, livestock and crops cannot endure. Many large cites on the Eastern US seaboard will be underwater. Mass migration to more hospitable places in the US will be likely (Xu, et al., 2020).

The implications are clear. We cannot deal with global warming by simply restoring everything that is damaged, and then restoring it again after the next flood, for example. We either have to stem the use of fossil fuels or prepare for disruptive and eventually very different living conditions.

EARTH AS A SYSTEM

Looking at the overall system that needs to be influenced can facilitate addressing the challenges of climate change and likely consequences. As shown in Figure 5, the Earth can be considered as a collection of different phenomena operating on different time scales (Rouse, 2014a). Loosely speaking, there are four interconnected systems: environment, population, industry, and government. In this notional model, population consumes resources from the environment and creates by-products. Industry also consumes resources and creates by-products, but it also produces employment. The government collects taxes and produces rules. The use of the environment is influenced by those rules.

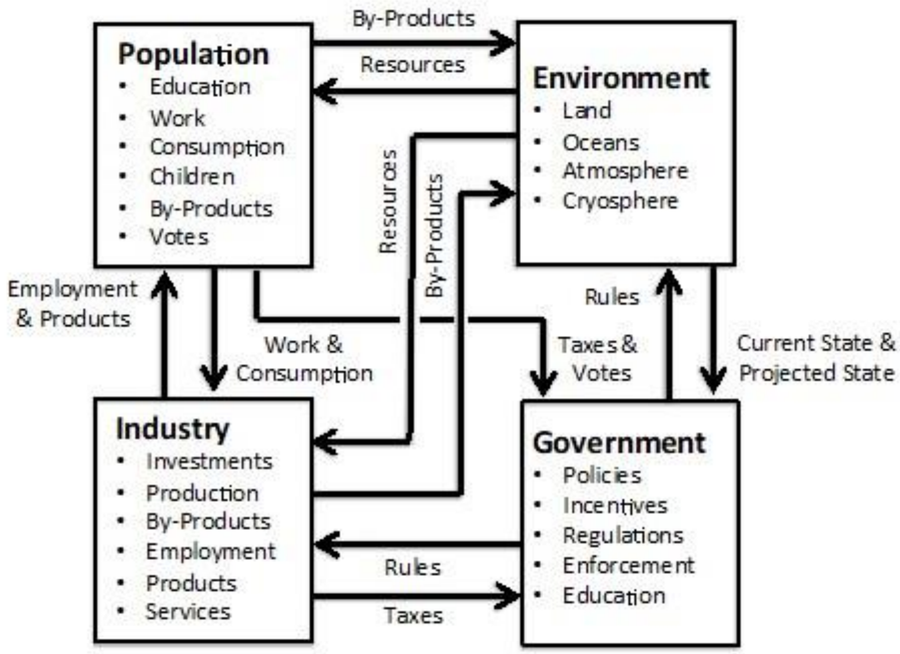

Figure 5. Earth as a System

Each system component has a different associated time constant. In the case of the environment, the time constant is decades to centuries. The population's time constant can be as short weeks or months. Government's time constant may be a bit longer, thinking in terms of years. Industry is longer still, on the order of decades for investments. These systems can be represented at different levels of abstraction and/or aggregation.

A hierarchical representation does not capture the fact that this is a highly distributed system, with all elements interconnected. It is difficult to solve one part of the problem, as it affects other pieces. By-products are related to population size, so one way to reduce by-products is to moderate population growth. Technology may help to ameliorate some of the by-products and their effects, but it is also possible that technology could exacerbate the effects. Clean technologies lower by-product rates but tend to increase overall use, for instance.

Sentient stakeholders include population, industry, and government. Gaining these stakeholders' support for such decisions will depend upon the credibility of the predictions of behavior, at all levels in the system. Central to this support are "space value" and "time value" discount rates. The consequences that are closest in space and time to stakeholders matter the most and have lower discount rates; attributes more distributed in time and space are more highly discounted. These discount rates will differ across stakeholders.

People will also try to "game" any strategy to improve the system, seeking to gain a share of the resources being invested in executing the strategy. The way to deal with that is to make the system sufficiently transparent to understand the game being played.

Sometimes gaming the system will actually be an innovation; other times, prohibitions of the specific gaming tactics will be needed.

The following three strategies are likely to enable addressing the challenges of climate change and its consequences:

- **Share Information:** Broadly share credible information so all stakeholders understand the situation.
- **Create Incentives:** Develop long-term incentives to enable long-term environmental benefits while assuring short-terms gains for stakeholders.
- **Create an Experiential Approach:** Develop an interactive visualization of these models to enable people to see the results.

An experiential approach can be embodied in a "policy flight simulator" that includes large interactive visualizations that enable stakeholders to take the controls, explore options, and see the sensitivity of results to various decisions (Rouse, 2014b). We return to this possibility later in this report.

MULTI-LEVEL INTERPRETATION

These findings and conclusions can be framed in a multi-level framework proposed by Rouse (2015, 2019, 2021, 2022), where the levels for this domain are people, processes, organizations, and government.

- Government: Elected officials have great difficulty trading off short-term versus long-term costs and benefits, due to a large extent to the concerns, values and perceptions of their constituents – citizens and companies.
- Organizations: The vested interests in energy extraction, refinement, and use are enormous and are naturally inclined to sustain status quo business models, and the benefits these models provide to these organizations.
- Processes: Processes for extracting, refining, and utilizing fossil fuels are well developed, employ millions of people, and represent trillions of dollars of stock market capitalization.
- People: People have long exploited natural resources and come to depend on the benefits of these resources in terms of both consumption and employment. Changing consumption habits is very difficult.

REPRESENTING POLICIES

The rest of this case study outlines the policy levers most likely to mitigate global warming, as well as mitigate the impacts of global warming. First we tailor the framework of Figure 3 to address policy portfolios rather than technology platforms. Twenty possible interventions are then outlined, ten for mitigating global warming and ten for mitigating the impacts of global warming. We then discuss five policy mechanisms for implementing these interventions.

Figure 6 provides a policy-oriented version of the model structure in Figure 3. What has changed? Functions in Figure 3 are interventions in Figure 6; solutions in Figure 3 are policies in Figure 6. Structurally, both models are identical.

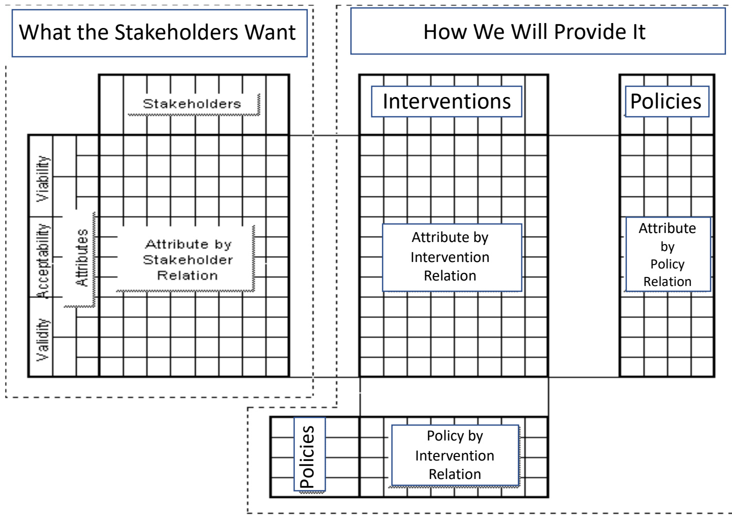

Figure 6. Model Structure for Policy Portfolios

INTERVENTIONS

Table 6 summarizes the 20 interventions in terms of which of five mechanisms are likely to be employed to implement each intervention. The first three interventions to mitigate global warming are not surprising -- decrease use of fossil fuels, decrease methane emissions, and eliminate coal-fired power plants. The next three emphasize increasing use of alternatives, including increased use of renewable energy, investing in home energy efficiency, and investing in clean energy public transit. The next two interventions address encouraging support of the changes implied by the first six including transitioning people to clean jobs and increasing education for these clean jobs. Finally, the last two interventions have longer-term payoffs including increased consumption of plant-based food and investing in reforestation.

The first ten interventions address mitigating global warming, while the next ten concern the impacts of global warming, particularly flooding, high temperatures, and fires. The first three interventions include deterring building in flood plains, encouraging flood proofing homes, and encouraging flood proofing businesses. The next three concern dealing with water and wind in terms of investing in dikes, levees, etc., investing in wetlands to absorb hurricanes, and investing in means to project “where the water will be,” which has been shown to help those affected to react more appropriately.

Considering the impacts of high temperatures as well as flooding, the next two interventions concern investing in raising roads to enable continuity of access and investing in means to address high temperatures and fires. Longer-term interventions include investing in educating K-12 and the whole population to understand threats and investing in developing jobs and training to respond to environmental threats and events.

Table 6. Interventions vs. Mechanisms for Mitigating Global Warming

	Intervention	Communicate	Educate	Incentivize	Invest	Regulate
Mitigating Global Warming	Decrease use of fossil fuels	√				√
	Decrease methane emissions	√				√
	Eliminate coal-fired power plants	√				√
	Increase use of renewable energy	√		√		√
	Invest in home energy efficiency	√		√	√	√
	Invest in clean energy public transit	√		√	√	√
	Transition to clean jobs	√	√	√	√	
	Increase education for clean jobs	√	√	√	√	
	Increase consumption of plant-based food	√	√			
	Invest in reforestation	√		√	√	√
Mitigating Impacts of Global Warming	Deter building in flood plains	√				√
	Encourage flood proofing homes	√		√		
	Encourage flood proofing businesses	√		√		
	Invest in dikes, levees, etc.	√		√	√	√
	Invest in wetlands to absorb hurricanes	√		√	√	
	Invest in means to project "where the water will be"	√			√	
	Invest in raising roads to enable continuity of access			√	√	√
	Invest in means to address high temperatures and fires			√	√	√
	Invest in educating K-12 and the whole population to understand threats	√	√		√	
	Invest in developing jobs and training to respond to environmental threats and events	√	√	√	√	

Mechanisms

There are five mechanisms for implementing the twenty possible interventions. The simplest mechanism is communication as USDA does to farmers and CDC does to the public in general. The next level of investment is education, both face-to-face and online. The classic example is the USDA Extension Services.

Beyond information and education, incentives can be provided to motivate people's behaviors. A recent example is federal and state rebates for buying battery electric vehicles (Liu, Rouse & Hanawalt, 2018). A higher level of commitment is investing in, for instance, funding education for clean energy jobs. Good examples are strongly increasing opportunities for solar panel installation and wind turbine repair (BLS, 2018).

A final mechanism is regulation. NHTSA's Corporate Average Fuel Economy (CAFE) standards regulate how far our vehicles must travel on a gallon of fuel. EPA Emission Standards Regulations provide another example. One benefit of this mechanism is the ability of the Executive Branch of the Federal Government to unilaterally issue regulations.

Strategies

Before deciding which interventions to include in the policy portfolio, we need to consider the nature of the investments of interest. As shown in Figure 1, we have found that there are four basic investment strategies that decision makers can use: optimize, adapt, hedge, and accept.

- If the success of investments of interest is certain, then there is little chance that decision makers will be surprised. Consequently, these investments should be optimized. If the unexpected cannot happen, then there is no chance of failure.
- If the investments of interest are not highly predictable, but can be appropriately modified when necessary, it may be in the best interest for decision makers to plan to adapt investments as warranted, i.e., not make major investments now.
- If the investments of interest are not very predictable and the decision makers have limited abilities to adapt and respond, it may be best to invest in hedge, i.e., make small investments in options available for later larger investments.
- If the investments of interest are totally unpredictable and there is no viable way to respond, then decision makers have no choice but to not invest, i.e., accept the status quo.

Figure 7 focuses on uncertainties in the effectiveness of interventions and uncertainties in the effectiveness of mechanisms.

Decision Making

The goal is to decide which interventions to include in the policy portfolio. This can be accomplished by forming a multi-attribute utility function (Keeney & Raiffa, 1993) with the following attributes:

- Intervention Effectiveness (IE): How well will the interventions work?
- Mechanism Effectiveness (ME): How likely will the mechanisms work?
- Required Investment (RI): How large investments will success require?

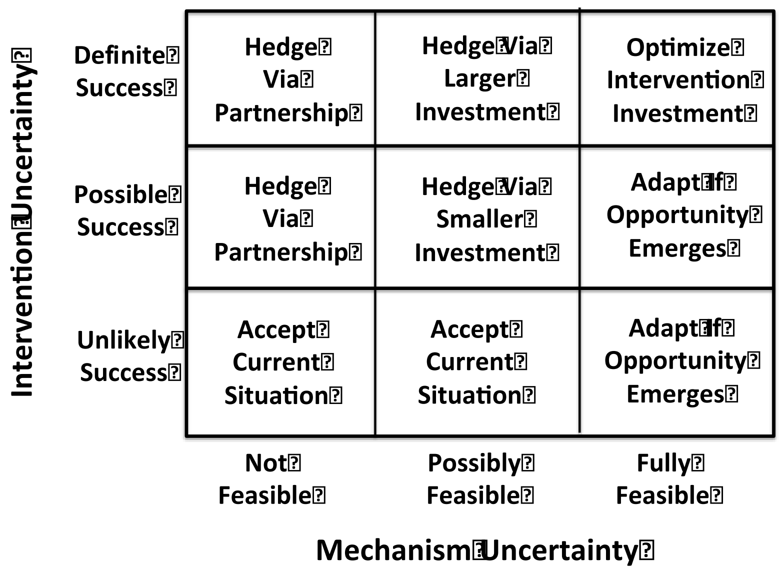

Figure 7. Strategies Versus Uncertainties

The expected utility of each intervention $E[U_T]$ can be calculated using

$$E[U_T] = W_{IE} \times P_{IE} \times U_{IE} + W_{ME} \times P_{ME} \times U_{ME} + W_{RI} \times P_{RI} \times (1 - U_{RI}) \qquad (4)$$

where $W_{IE} + W_{ME} + W_{RI} = 1$ and P_{IE} , P_{ME} , and P_{RI} are the probabilities of achieving U_{IE} , U_{ME} , and U_{RI} , respectively. $E[U_T]$ increases with IE and ME, but decreases with RI, hence the term $(1 - U_{RI})$ is employed to represent desires for smaller investments.

Table 7 summarizes IE, ME and RI for each intervention, assuming the mechanisms in Table 6 are employed. The entries in this table reflect the product of probabilities and utilities in the following ways:

- IE is high if the effects are direct and timely.
- ME is high if no Congressional authorizations and appropriations are required.
- RI directly reflects the level of investment needed.

Figure 8 summarizes the expected utilities for the ten interventions intended to mitigate global warming. Figure 9 summarizes the expected utilities for the ten interventions intended to mitigate the impacts of global warming. The weights (W_{IE}, W_{ME} and W_{RI}) vary from equal (all 0.333) to 0.6 for the most important attribute to 0.2 for the other two attributes.

Table 7. Interventions vs. Attributes

	Intervention	Intervention Effectiveness	Mechanism Effectiveness	Required Investment
Mitigating Global Warming	Decrease use of fossil fuels	High	High	Low
	Decrease methane emissions	High	High	Low
	Eliminate coal-fired power plants	High	Moderate	Low
	Increase use of renewable energy	High	Moderate	Moderate
	Invest in home energy efficiency	High	Moderate	Moderate
	Invest in clean energy public transit	High	Moderate	High
	Transition to clean jobs	Moderate	Moderate	High
	Increase education for clean jobs	Moderate	Moderate	High
	Increase consumption of plant-based food	Low	High	Low
	Invest in reforestation	Moderate	Moderate	Moderate
Mitigating Impacts of Global Warming	Deter building in flood plains	High	Moderate	Low
	Encourage flood proofing homes	High	Moderate	Low
	Encourage flood proofing businesses	High	Moderate	Low
	Invest in dikes, levees, etc.	High	Moderate	High
	Invest in wetlands to absorb hurricanes	High	Moderate	Moderate
	Invest in means to project "where the water will be"	Moderate	High	Low
	Invest in raising roads to enable continuity of access	High	Moderate	High
	Invest in means to address high temperatures and fires	High	Moderate	High
	Invest in educating K-12 and the whole population to understand threats	High	Moderate	Low

	Invest in developing jobs and training to respond to environmental threats and events	Moderate	Moderate	High

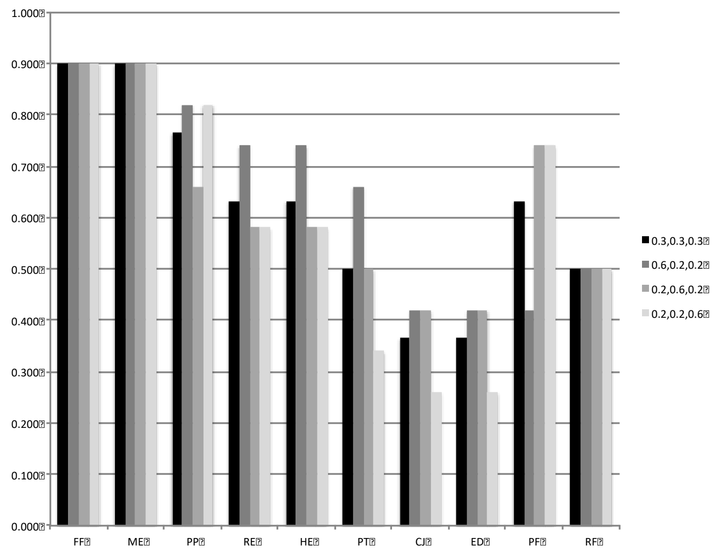

Figure 8. Expected Utilities for Interventions to Mitigate Global Warming

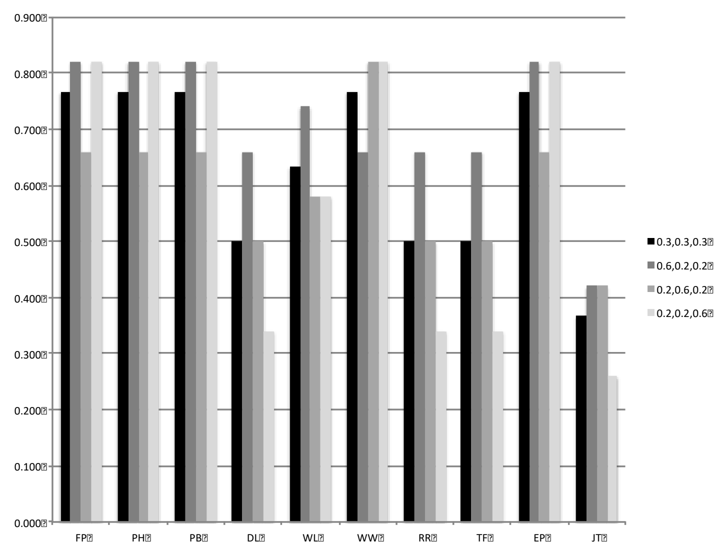

Figure 9. Expected Utilities for Interventions to Mitigate Impacts of Warming

The resulting policy portfolio includes those interventions with highest expected utilities. Six interventions (FF, ME, PP, FP, PH, PB) are high, almost independent of the weights because they have direct impacts, are easy to execute, and require low investments. These interventions are:

- Decrease use of fossil fuels

- Decrease methane emissions
- Eliminate coal-fired power plants
- Deter building in flood plains
- Encourage flood-proofing homes
- Encourage flood-proofing businesses

Three interventions (PF, WW, EP) have high utilities for certain weightings. They have indirect impacts, but are easy to execute and require low investments. These interventions are:

- Increase consumption of plant-based food
- Invest in means to project "where the water will be"
- Invest in educating K-12 and whole population to understand threats

Thus, the policy portfolio includes 9 interventions of the original 20. The 11 interventions excluded suffered from requiring high investment and/or needing Congressional approval.

How should one invest in these nine interventions? For the top 6, optimize is appropriate if feasible, especially since the investments required are low. The adapt strategy would needlessly delay action. For the bottom 3, a hedge strategy is appropriate in terms of investing in R&D and pilot projects to determine how best to refine these interventions. The accept strategy does not apply here, in part because we have been accepting global warming far too long.

INFLUENCING CHANGE

The success of the interventions depends on change at several levels as outlined in the earlier:

- Government: Countries consumption and production of energy, including key technologies and materials (Economist, 2020)
- Organizations: Companies' investments and competitive positions in alternative energy sources
- Processes: Infrastructure for storing and delivering energy, including charging stations
- People: Willingness and abilities to change energy consumption habits and preferences, as well as employment aspirations

Changes at all levels are important, but the focus here will be on the people level. Table 8 summarizes four levers of influence as they apply to the focus of change and the situation. Education and evidence provides an important lever as they did for the health risks of smoking. Rules and regulations, e.g., prohibiting smoking in restaurants helped as well. Social pressures from non-smokers contributed. Finally, the steadily increasing prices of cigarettes, due to greatly increased taxes, provided another incentive to quit smoking.

Societal benefits, especially during crises, can be leveraged in the same ways. People tend to come together over time as crises worsen. We have experienced this with wars, financial crises, and health crises. A consensus on global warming has yet to emerge, in part because many leaders have discounted or dismissed the evidence.

Table 8. Influencing People to Change

Lever of Influence	Focus & Situation	
	Personal Benefit (Not Necessarily in Crisis)	Societal Benefit (Especially in Crisis)
Education & Evidence Rules & Regulations Social Pressure Financial Incentives	Diet Smoking Exercise Environment	War Depression Pandemic Climate Change

However, it is difficult to ignore hurricanes, flooding, and fires. Similarly, it is incredulous to deny the seriousness of the pandemic with over 600,000 deaths in the US. Fortunately, one of the interventions in the policy portfolio is "invest in educating K-12 and the whole population to understand threats."

DISCUSSION

At this point, we have assessed the expected utilities of the twenty interventions, and the extent to which these assessments are sensitive to the weights in the multi-attribute utility function. It would be helpful to know how these interventions interact in terms of impact and possible synergies among mechanisms.

Such interactions could be addressed using a computational model, perhaps developed on the basis of the conceptual models in Figures 3 and 6 – see Appendix. This model could be hosted in an interactive visualization facility such as shown in Figure 10. This is termed an ***Immersion Lab*** because it enables stakeholders to be immersed in the complexity of their ecosystem (Yu, et al., 2016).

Developing an interactive visualization of an appropriate computational model enables people to see the impacts of interventions and explore potential tradeoffs. This embodies the strategy discussed earlier of creating an experiential approach to support hands-on exploration, discussion, and debate.

The methodology employed for this case study was first employed to assess alternative strategies for automotive OEMs (original equipment manufacturers) to address the market for driverless cars for disabled and older adults. The application in this case study did not involve a technology platform. It involved a portfolio of policies, pursed by federal, state, and local governments, to mitigate global warming. The absence of an integrated technology platform did not mean that the notion of design is not relevant. Investment portfolios should be designed.

The interventions considered here were gleaned from a broad review of relevant literature. However, the analysis reported cannot be deemed fully evidence based. Data on the effectiveness of the interventions and mechanisms, as well as their likely costs, need to be compiled and analyzed. Values, concerns, and perceptions of a broad set of important stakeholders need to be assessed and incorporated in multi-stakeholder, multi-attribute utility functions. This will lead to refinement of the policy portfolio presented here.

Figure 10. Example *Immersion Lab*

Nevertheless, this case study has demonstrated that a very complex policy problem can be approached comprehensively and systematically. The next step is to create an evidence-based interactive computational model that enables stakeholders to explore refinement and extension of the policy portfolio. This should lead to well-informed and well-articulated advocacy of investments needed to execute the interventions that can significantly mitigate global warming.

CASE STUDY 3: POLICY PORTFOLIO TO ENHANCE STEM TALENT PIPELINE

There is substantial concerns that the pipeline of STEM talent in the US will be inadequate to meet the needs of the economy in general and national security in particular. This cases study is associated with a project whose primary objective is formulation of alternative policy portfolios to enhance the STEM talent pipeline for both the DoD workforce and the US workforce more broadly, as well as to provide a means for stakeholders to interactively create and explore alternative policies and portfolios of policies.

BACKGROUND

This case study is focused on formulating a portfolio of policies to enhance retention of students in STEM programs in college. The National Center for Education Statistics (2013) provides an overview of the problem.

- Half of STEM majors leave these majors. Half switch to non-STEM majors; the other half leave college. A greater percentage on non-STEM majors switched majors.
- The intensity of STEM course taking in the first year, the type of math courses taken in the first year, and the level of success in STEM courses had the greatest impact on attrition.
- Taking lighter credit loads in STEM courses in the first year, taking less challenging math courses in the first year, and performing poorly in STEM classes relative to non-STEM classes were associated with an increased probability of switching majors for STEM

Sithole and colleagues (2017) provide a deeper analysis of the problem, first in terms of the nature of pedagogy. They report the following:

- Likelihood of graduation highly correlated with freshman performance
- Emphasis on academic mastery of concepts rather than applications relevancy
- High workload of STEM courses discourages retention
- Success is highly correlated with quality of academic advising
- Faculty are not trained to be undergraduate advisors
- Faculty are not trained in culturally-sensitive advising

They also consider the ways in which students themselves affect retention:

- Lack of proficiency in mathematics
- Proficiency not necessarily leading to success in engineering
- Study habits have varying impacts
- Peer mentoring can help
- Poor time management, especially for students that work
- Lack of Intrinsic motivation
- Lack of pre-college K-12 experiences
- Socio-economic factors

They provide three overall recommendations:

- "**Change Institutional Practices**. There are several practices that institutions can revisit. For instance, using other feedback-soliciting methods aimed at understanding the needs of the students well before early grade reports. For example, surveys from these students would provide a lead to attractors in these programs which may not be available in STEM fields. Such methods could involve early reflection papers or early course surveys

- **Provide Necessary Support to STEM Students**. This could be in the form of student peer mentoring programs. These programs require a sustainable source of funding to compensate student mentors. Institutional funding challenges for such programs can be alleviated through collaboration between STEM programs and private organizations. The collaborations also help to strengthen bridges between STEM faculty and corporate organizations, which is fundamental to the training and placement of STEM graduates. In addition, teachers should seek funding from Foundations and local private funding agencies
- **Professional Development of Teachers**. This needs to be done systematically and tailor-made to STEM teachers by conducting a needs assessment of the STEM teachers and then designing programs that address the identified needs. Also, there is need to address programming issues such when to conduct the professional development, duration of programs, and incentives for participating in the programs. It's also beneficial to include administrators in the professional development programs to ensure support for the STEM teachers."

POLICIES, STAKEHOLDERS & ATTRIBUTES

In this case study, four policies are considered:

- Attract better prepared students
- Provide student support
- Redesign processes to minimize hindrances
- A hybrid of support and processes

Four stakeholders are on interest:

- Potential and Existing STEM students
- Educational Institutions
- Employers
- DoD

Student supports of interest include remedial courses, individual tutoring, expert advising, and staff training. Process redesign, loosening prerequisite constraints, online courses to eliminate class size limits, and modularizing course structures. Modularization may, for example, involve ten 4-hour modules vs. 40 hours of traditional instruction, credits earned module by module, not course by course, and selected modules also offered online.

There are seven attributes of these policies of interest to stakeholders. \

- Acceptance rate
- Retention rate
- Graduation rate
- Faculty time
- Institutional costs

- Net STEM talent
- Net policy costs

MULTI-STAKEHOLDER, MULTI-ATTRIBUTE UTILITY MODEL

Figure 11 shows the nominal utility functions of stakeholders for attributes.

	STEM Students	Institutions	Employers	DoD
Acceptance Rate	(a) More is better	(d) Less is better		
Retention Rate	(c) Diminishing returns	(c) Diminishing returns		
Graduation Rate	(c) Diminishing returns	(c) Diminishing returns		
Faculty Time		(d) Less is better		
Institution Costs		(f) Diminishing decline		
Net STEM Talent			(a) More is better	(a) More is better
Net Policy Costs				(d) Less is better

Figure 11. Stakeholders' Utility Functions for Attributes

Figure 12 summarizes the assumed attribute levels. These assumptions were not empirically derived, but are based on in-depth literature reviews of stakeholders' general preferences.

	Better Students	Student Support	Improved Process	Support & Process
Acceptance Rate	Low	Moderate	Moderate	High
Retention Rate	High	Moderate	Moderate	High
Graduation Rate	High	Moderate	Moderate	High
Faculty Time	Low	Moderate	Moderate	High
Institution Costs	Moderate	Moderate	Moderate	High
Net STEM Talent	High	Moderate	Moderate	High
Net Policy Costs	Low	Moderate	Moderate	High

Figure 12. Assumed Attribute Levels

Equations 1 and 2 provided earlier were employed to construct on overall multi-stakeholder, multi-attribute utility model. Stakeholders' weights for the attributes of interest in Figure 11 were students (0.4, 0.3, 0.3), institutions (0.2, 0.2, 0.2, 0.1, 0.3), employers (1.0), and DoD (0.5, 0.5). Attribute levels were mapped as follows: low = 0.1, moderate = 0.5, and high = 0.9. We also evaluated 0.3, 0.5, and 0.7, but the rank orderings of policies did not change.

SENSITIVITY OF EXPECTED UTILITIES TO WEIGHTINGS

Figure 13 shows the sensitivities of expected utilities to alternative relative weightings of the important of stakeholders. Each weighting set involved one stakeholder weighted by 0.7 and the other three by 0.1. The four policies vary along the abscissa, while the weightings vary by color code.

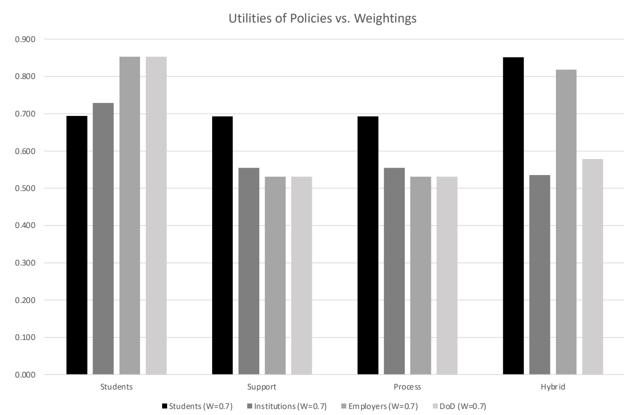

Figure 13. Sensitivity of Expected Utilities to Weightings

Several conclusions are readily apparent. **Better Students** is preferred by all stakeholders other than students as it yields more talented STEM graduates and requires less investment. **Hybrid** (student support + process improvement) is preferred by students and is a close second for employers. This policy provides success opportunities to more students, but it requires institutions and DoD to invest substantially. **Support** or **Process** by itself yields only moderate returns. However, the assumptions underlying these outcomes warrant careful reconsideration.

Consider the uncertainties associated with the policies of interest. For the retention policy portfolio, uncertainties include:

- Student Support – Extent, effectiveness and costs of remedial courses, individual tutoring, expert advising, and staff training are uncertain
- Process Redesign – Extent, effectiveness and costs loosening prerequisite constraints, modularizing course structure, online courses to eliminate class size limits, and student monitoring system are uncertain

Other policies of potential interest include investing in adoption of educational technologies; forming alliances among K-12, community college and industry; and increasing K-12 production of "STEM-ready" students.

UNCERTAINTY SPACE

Figure 14 depicts the requirements vs. technologies uncertainty space – this is Figure 2 tailored to this case study.

Requirements Uncertainty	Not Feasible	Possibly Feasible	Fully Feasible
Definitely Required	Hedge Via Partnership	Hedge Via R&D Investment	Optimize Educational Capability
Possibly Required	Hedge Via Partnership	Hedge Via R&D Investment	Adapt If Requirement Emerges
Not Required	Accept Current Situation	Accept Current Situation	Archive for Potential Later Use
	Technology & Cost Uncertainties		

Figure 14. Requirements vs. Technologies Uncertainty Space

Our conclusions, and the basis of these conclusions, are as follows:

- **Optimize** retention investments as the target population and needed interventions are clear; incentives for co-investments will likely be successful
- **Adapt** to trends in educational technology as one can exploit rather than invest in development; focus on accessibility and efficiencies of these technologies
- **Hedge** potential alliances among K-12, community college and industry as there are many alternative scenarios, e.g., geographies, and there is a wide range of surmountable barriers and hurdles to overcome across these stakeholders
- **Accept** the state of K-12 education due to local school boards controlling each school district, which will make widespread change extremely uncertain and highly expensive.

DISCUSSION

This case study has presented and illustrated an approach to designing policy portfolios to enhance the STEM talent pipeline in the US. The parameters within the models need to be tailored to particular contexts in terms of stakeholders' preferences and predictions of attribute levels. Nevertheless, this approach provides a framework for systematically exploring policy options and alternative investment strategies.

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 report 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 (Dantzig, 2018). It is also possible that sweeping organizational and societal trends will substantially disrupt this seemingly immense market opportunity (Rouse, 2019, 2021, 2022). The current pandemic is a case in point. The impacts of climate change are on the horizon.

The application in the second case study did not involve a technology platform. It involved a portfolio of policies, pursed by federal, state, and local governments, to mitigate global warming. The expected utilities of twenty potential interventions were assessed, as well as the extent to which these assessments were sensitive to the weights in the multi-attribute utility function. This case study demonstrated that a very complex policy problem can be approached comprehensively and systematically

The third case study presented and illustrated an approach to designing policy portfolios to enhance the STEM talent pipeline in the US. The parameters within the models need to be tailored to particular contexts in terms of stakeholders' preferences and predictions of attribute levels. Nevertheless, this approach provides a framework for systematically exploring policy options and alternative investment strategies.

The three case studies are compared in Table 9. Al three involved that same analysis steps

- Define Questions of Interest
- Characterize Investment Scenarios
- Determine Central Uncertainties
- Formulate Multi-Attribute Utility Model
- Identify Key Stakeholder Tradeoffs
- Perform Sensitivity Analyses
- Select Strategies of Optimize, Adapt, Hedge and/or Accept

While the seven steps are the same, the particulars of how they differ for each case study are substantial. Applications to technology platforms, policy portfolios, and investment portfolios involve very different scenarios, as well as differing uncertainties, attributes, and tradeoffs. Nevertheless, the logic of the analytic approach remains the same.

Table 9. Comparison of Three Case Studies

Steps of Analysis Process	Case Study		
	Driverless Cars	**Energy Policy**	**STEM Talent**
Define Questions of Interest	Meeting market needs	Reducing carbon emissions	Enhancing student talent pipeline
Characterize Investment Scenarios	Five alternative scenarios	Policy alternatives, interventions & mechanisms	Better students, student support, process redesign
Determine Central Uncertainties	Competitors & technologies	Industry & public response	Effectiveness & costs of interventions
Formulate Multi-Attribute Utility Model	Competitive advantage, strategic fit & ROI	Intervention & mechanism effectiveness, requires investments	Acceptance, retention & graduation rates, faculty time & costs
Identify Key Stakeholder Tradeoffs	Returns vs. risks	Effectiveness vs. investments	Outcomes vs. costs
Perform Sensitivity Analyses	Varying weightings	Varying weightings	Varying weightings
Select Strategies of Optimize, Adapt, Hedge and/or Accept	Two hedges & one accept; three of five alternatives	Six optimize and three hedge; nine of twenty alternatives	One optimize, one adapt, one hedge, and one accept of four alternatives

These three case studies have provided insights that enabled envisioning a software tool, the, ***Uncertainty Management Advisor***, which could have supported all three studies, and will hopefully assist with future applications of the methodology in this report. The appendix of this report outlines the conceptual design of this tool, including guidance for how it can be used in future applications.

Understanding and managing uncertainties need to be core competencies in companies, agencies, and institutions. As this report has argued, uncertainties need to be rigorously and systematically addressed. Managing for success must also include forecasting and managing potential failures (Rouse, 2021).

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REFERENCES

Al-Ashaab, A., et al. (2013). The transformation of the product development process into lean environment using set-based concurrent engineering. ***International Journal of Concurrent Engineering: Research and Applications***. 18 (1), 41–53.

Alderton, M. (2020). Why climate change is about to make your bad commute worse. ***Washington Post***, August 8.

Auto Alliance (2019). ***Assessing Transportation Needs of People With Disabilities and Older Adults: Report of Workshop 1***, Washington, DC: Auto Alliance.

BLS (2018). ***Fastest Growing Occupations***. https://www.bls.gov/ooh/fastest-growing.htm

Boer, F.P. (2008). ***The Valuation of Technology: Business and Financial Issues in R&D.*** New York: Wiley.

Carlson, J.M., & Doyle, J. (2000). Highly optimized tolerance: robustness and design in complex systems. ***Physical Review Letters***, 84 (11), 2529-2532.

Chambers, J. (1997). ***The Oxford Companion to American Military History***. New York: Oxford University Press, p 791.

Coram, R.C. (2002). ***Boyd: The Fighter Pilot Who Changed the Art of War***. Boston: Little, Brown.

Danzig, R. (2018). ***Technology Roulette: Managing Loss of Control as Many Militaries Pursue Technological Superiority***. Washington, DC: Center for a New American Security.

Deshmukh, A. et al. (2010). Valuing flexibility. ***Proceedings of the 2nd Annual SERC Research Review Conference***, November 9-10, College Park, MD.

Duckmanton, D. (2019). Why UX and UI should remain separate. ***UX Collective*** (uxdesign.cc), February 21.

Economist (2020). The changing geopolitics of energy. ***The Economist***, September 17.

Eppinger, S.D., & Browning, T.R. (2012). ***Design Structure Matrix Methods and Applications***. Cambridge, MA: MIT Press.

Feickert, A. (2009). The Marines Expeditionary Fighting Vehicle (EFV): Background and Issues for Congress. ***Congressional Research Service***, August 3.

Ferreira, S., Collofello, J., Shunk, D, & Mackulak, G. (2009). "Understanding the effects of requirements volatility in software engineering by using analytical modeling and software process simulation." ***Journal of Systems and Software***, 82, (10), 1568-1577.

Flavelle, C. 2020). Rising seas threaten an American institution: the 30-year mortgage. ***New York Times***, June 19.

Flavelle, C., & Mazzei, P. (2019). Florida Keys deliver a hard message: As seas rise, some places can't be saved, ***New York Times***, December 5.

Hanawalt, E.S., & Rouse, W.B. (2010). Car wars: Factors underlying the success or failure of new car programs, ***Journal of Systems Engineering***, 13 (4), 389-404.

Hanawalt, E.S., & Rouse, W.B. (2017). Assessing location attractiveness for manufacturing automobiles, ***Journal of Industrial Engineering and Management***, 10 (3), 73-89.

Hauser, J.R., & Clausing, D. (1988, May-June). The house of quality. ***Harvard Business Review***, 63-73.

Henkoff, R. (1994). Keeping Motorola on a Roll. ***Fortune***, April 18.

Keeney, R.L., & Raiffa, H. (1993). ***Decisions with multiple objectives: Preference and value tradeoffs***. Cambridge, UK: Cambridge University Press.

Laris, M. (2020). Downsides of self-driving cars could swamp benefits if DC region fails to act, study says. ***The Washington Post***, April 17.

Lempert, R.J., Marangoni, G., Keller, K., & Duke, J. (2018). ***Is Restoration an Appropriate Climate Policy Goal?*** Santa Monica, CA: RAND.

Lenton, T.M., et al. (2019). Climate tipping points – too risky to bet against. ***Nature***, 575, 592-595.

Lightbody, L., Fuchs, M., & Edwards, S. (2019). ***Mitigation Matters: Policy Solutions to Reduce Local Flood Risk***. Philadelphia, PA: The Pew Charitable Trusts.

Liu, C., Rouse, W.B., & Yu, X. (2015). When transformation fails: Twelve case studies in the automobile industry. ***Journal of Enterprise Transformation***, 5 (2), 71-112.

Liu, C., Rouse, W.B., & Hanawalt, E. (2018). Adoption of powertrain technologies in automobiles: A system dynamics model of technology diffusion in the American market. ***IEEE Transactions on Vehicular Technology***, 67 (7), 5621-5634.

Liu, C. Rouse, W.B., & Belanger, D. (2020). Understanding risks and opportunities of autonomous vehicle technology adoption through systems dynamic scenario modeling – The American insurance industry. ***IEEE Systems Journal***, 14 (1), 1365-1374.

Lucero, D.S. (2018). The mash-up rubric: Strategies for integrating emerging technologies to address dynamic requirements. ***Proceedings of 28th Annual INCOSE International Symposium***, Washington, DC, July 11.

Mattis, J. (2019). Interview, ***Meet the Press***, October 13.

Mellody, M. (2014). ***Can Earth's and Society's Systems Meet the Needs of 10 Billion People? Summary of a Workshop*. ** Washington, DC: National Academies Press.

Mikaelian, T., Rhodes, D.H., Nightingale, D.J., & Hastings, D.E. (2012). A logical approach to real options identification with application to UAV systems. ***IEEE Transactions on Systems, Man, and Cybernetics – Part A. Systems and Humans***. 42 (1), 32-47.

Moggridge, B. (2007). ***Designing Interactions***. Cambridge, MA: MIT Press.

Myers, S.L. (2001). Pentagon panel urges scuttling howitzer system. ***New York Times***, April 23, Section A, Page 1.

NAP (1983). ***Changing Climate: Report of the Carbon Dioxide Assessment Committee***. Washington, DC: National Academy Press.

NCES (2013). STEM Attrition: ***College Students' Paths Into and Out of STEM Fields: Statistical Analysis Report***. Washington, DC: US Department of Education, National Center for Educational Statistics.

Pennock, M.J., & Rouse, W.B. (2016). The epistemology of enterprises. ***Journal of Systems Engineering,*** 19 (1), 24-43.

Proulx, A. (2016). ***Barkskins: A Novel***. New York: Schribners.

Ross, A.M., & Rhodes, D.H. (2008), Using natural value-centric time scales for conceptualizing system timelines through Epoch-Era Analysis. ***Proceedings of INCOSE International Symposium***, 18 (1),1186-1201.

Rouse, W.B. (1991). ***Design for success: A human-centered approach to designing successful products and systems***. New York: Wiley.

Rouse, W.B. (1992). ***Strategies for innovation: Creating successful products, systems, and organizations***. New York: Wiley.

Rouse, W.B. (1993). ***Catalysts for change: Concepts and principles for enabling innovation***. New York: Wiley.

Rouse, W.B. (1998). ***Don't jump to solutions: Thirteen delusions that undermine strategic thinking.*** San Francisco, CA: Jossey-Bass.

Rouse, W.B. (2005). A theory of enterprise transformation, ***Journal of Systems Engineering***, 8 (4), 279-295.

Rouse, W.B. (2007). ***People and organizations: Explorations of human-centered design***. New York: Wiley.

Rouse, W.B. (2010). Options for surveillance and reconnaissance. In W.B. Rouse, Ed., ***The Economics of human systems integration*** (Chap. 15). New York: Wiley.

Rouse, W.B. (2104a). Earth as a system. In M. Mellody, Ed., ***Can Earth's and Society's Systems Meet the Needs of 10 Billion People?*** (pp. 20-23). Washington, DC: National Academies Press.

Rouse, W.B. (2014b). Human interaction with policy flight simulators. ***Journal of Applied Ergonomics***, 45 (1), 72-77.

Rouse, W.B. (2015). ***Modeling and visualization of complex systems and enterprises: Explorations of physical, human, economic, and social phenomena***. New York: Wiley.

Rouse, W.B. (2019). ***Computing possible futures: Model based explorations of "What if?"*** Oxford, UK: Oxford University Press.

Rouse, W.B. (2021). ***Failure Management: Malfunctions of Technologies, Organizations, and Society***. Oxford, UK: Oxford University Press.

Rouse, W.B. (2022). Designing policy portfolios. ***Transforming Public-Private Enterprises: Understanding and Enabling Innovation in Complex Systems***. Oxford, UK: Oxford University Press.

Rouse, W.B., & Boff, K.R. (2004). Value-centered R&D organizations: Ten principles for characterizing, assessing & managing value. ***Journal of Systems Engineering***, 7 (2), 167-185.

Rouse, W.B., & McBride, D.K. (2019). A systems approach to assistive technologies for disabled and older adults. ***The Bridge***, 49 (1), 32-38.

Rouse, W.B., Howard, C.W., Carns, W.E., & Prendergast, E.J. (2000). Technology investment advisor: An options-based approach to technology strategy. ***Information • Knowledge • Systems Management***, 2 (1), 63-81.

Rouse, W.B., Verma, D., Lucero, D.S., & Hanawalt, E.S. (2021). Strategies for addressing uncertain markets and uncertain technologies. ***Proceedings of Annual Acquisition Research Symposium***, Naval Postgraduate School, May 11-13.

Hoboken, NJ: Systems Engineering Research Center, Stevens Institute of Technology.

Samenow, J., & Freedman, A. (2020). Hot ocean waters along East Coast are drawing in weird fish and supercharging hurricane season. ***Washington Post***, July 31.

SEI, IISD, ODI, Climate Analytics, CICERO, and UNEP. (2019). ***The Production Gap: The Discrepancy Between Countries' Planned Fossil Fuel Production and Global Production Levels Consistent with Limiting Warming to 1.5°C or 2°C. https://www.sei.org/publications/the-production-gap-report/***

Senge, P. (1990). ***The Fifth Discipline***. New York: Doubleday/Currency.

Silver, M.R., & De Weck, O.L. (2007). "Time-expanded decision networks: A framework for designing evolvable complex systems." ***Journal of Systems Engineering***, 10, (2),167-188.

Singer, D., Strickland, J., Doerry, N., McKenney, T., & Whitcomb, C. (2017). ***Set-Based Design***. Alexandria, VA: Society of Naval Architects and Marine Engineers, Technical and Research Bulletin 7-12.

Sithole, A., Chiyaka, E.T., McCarthy, P., Mupinga, D.M., Bucklein, B.K., & Kibirige, J. (2017). Student attraction, persistence, and retention in STEM programs: Successes and continuing challenges. ***Higher Education Studies***, 7 (1), 46-59.

Sobek, D.K., Ward, A.C., & Lifer, J.K. (1999). Toyota's principles of set-based concurrent engineering. ***Sloan Management Review***, 40 (2), 67-83.

Waterman, J. (2019). Our national parks are in trouble: Overcrowding, invasive species, climate change, and money woes. ***New York Times Magazine***, November 22.

Xu, C., Kohler, T.A., Lenton, T.M., Svenning, J-C., & Scheffer, M. (2020). Future of the human climate niche. ***Proceedings of the National Academies of Sciences***, 117 (21), 11350-11355.

Yu, X., Rouse, W.B., & Serban, N. (2011). A computational theory of enterprise transformation. ***Journal of Systems Engineering***, 14 (4), 441-454.

Yu, Z., Rouse, W.B., Serban, N., & Veral, E. (2016). A data-rich agent-based decision support model for hospital consolidation. ***Journal of Enterprise Transformation***, 6 (3/4), 136-161.

PROJECT TIMELINE & TRANSITION PLAN

1. What is the long-term transition goal for the research if continued?
    a. With three case studies completed, this methodology is fairly mature for applications to a range of domains – vehicle platforms, energy policy, education policy.
    b. We have discussed possible applications in the DIB for government and industry adoption, but have not gained specific commitments to proceed.

2. List the potential tools, guides, educational units, or other artifacts that resulted from this research that might be used by external sponsors if the long-term transition goals are met?
    a. We have developed a conceptual design of a software tool to support use of the methodology – Uncertainty Management Advisor – but are reluctant to proceed with software development until we secure engagement from user organizations.

3. Which of these might be or are planned to be incrementally delivered in a future research task?
    a. The Uncertainty Management Advisor will be developed and deployed when a suitable user organization has been successfully recruited.

4. Did you identify any transition partners? Are there other advocates or potential adopters of this research?
    a. We worked with General Motors on the first case study and discussed possible applications with GM Defense and the Air Force Rapid Capabilities Office.

5. Was the research piloted with a potential transition partner? Are there others who would conduct pilot use of the research if fully funded?
    a. General Motors was very actively involved in the first case study. We talked with key stakeholders for the second (energy) and third (education) case studies.

APPENDIX A: UNCERTAINTY MANAGEMENT ADVISOR

The goal is to create an interactive environment where users can explore market/mission uncertainties and technology uncertainties, understand tradeoffs, develop strategies, and frame a portfolio of options that merit investments. Central to success in achieving this goal will be first addressing User Experience (UX), then User Interface (UI), and then the functional and software architectures (Moggridge, 2007). The figure below clarifies the distinctions between UX and UI.

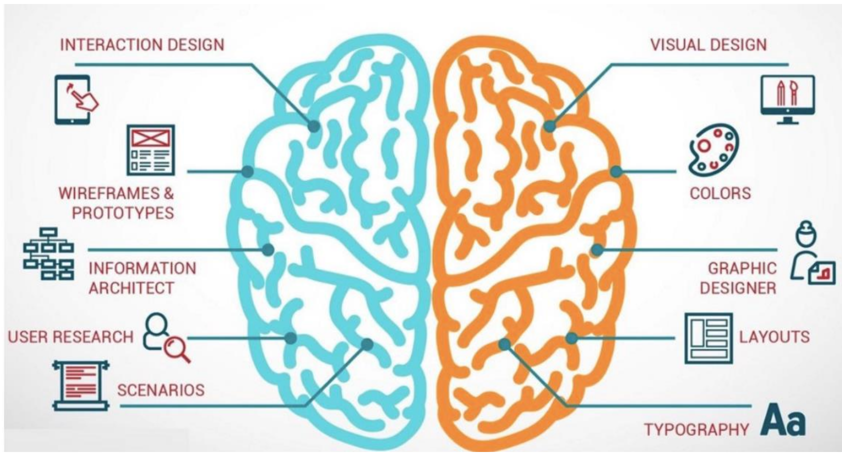

Figure 15. How UX and UI Differ (Duckmanton, 2019)

User Experience (UX)

The ***Uncertainty Management Advisor*** (UMA) is intended to support users of the methodology developed by in this report and applied to three case studies Thus, UMA is not a general-purpose tool. This helps considerably to define the UX.

The users' goal is to address and answer the 20 questions associated with the analysis workflow listed below. This involves defining entities, e.g., stakeholders, and relationships between entities, e.g., attributes and functions. This involves direct entries, choices from menus, and decisions about strengths and forms of relationships.

In the process, users are defining, populating, and manipulating the representations in Figures 3 and 6 in the body of the report. The central premise is that stakeholders need to perceive products and services to be valid, acceptable, and viable (Rouse, 1991, 2007):

- 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.

Note that costs include the efforts needed to learn and use products and services, not just the purchase price.

The model structure in Figures 3 and 6 provides the basis for computing the expected utilities of alternative solutions or courses of action. Some alternatives will have low expected utilities and are typically shelved. Several alternatives may have sufficiently higher expected utilities and will be maintained in the feasible set. There is no rush to winnow this set to a single alternative.

The uncertainty management framework in Figures 1 and 2 in the report can help to address decisions for how to approach the alternatives remaining in the feasible set.

- If the phenomena of interest are highly predictable, it is in your best interest to **optimize** products and services to be as efficient as possible.
- If the phenomena of interest are not highly predictable, it may be best to plan to **adapt** if you can respond to potential issues faster than the ecosystem changes.
- If the phenomena of interest are not very predictable, it may be best to **hedge** your position and consider modest investments to prepare for contingencies.
- If the phenomena of interest are totally unpredictable and there is no viable way to respond, you have no choice but to **accept** the status quo, assuming it remains in the feasible set.

Decisions might be made, for example, to optimize one alternative, adapt for another, and hedge for two others. The result is a portfolio of investments.

User Interface (UI)

Users need to complete the following eight steps, in any order they prefer, particularly after a first pass is completed.

1. Specify Goals – project/program name, objectives
2. Identify Stakeholders – name, weight, description
3. Define Attributes – name, units, min, max, description
4. Stakeholders' Desires – weight, utility function form
5. Define Functionality – functions that provide attributes
6. Define Solutions – functions of users and competitors/adversaries' solutions
7. Assess Solutions – expected utility vs. validity, acceptability, viability
8. Improve Solutions – selected attributes, percent change, functions affected

These steps will be indicated on the main menu. Steps 1-6 involve completing templates. Steps 7-8 are displays of computed results.

User Assistance

- Sensitivity analysis of weightings of the importance of stakeholders and by weightings of attributes by stakeholders
- How to improve by a chosen percentage of one or more attributes and the functional changes needed to achieve improvements
- Expert advice on decisions to **optimize**, **adapt**, **hedge** and **accept**, including historical examples of relevant past decisions and outcomes

Functional Architecture

The functional architecture is shown in Figure A2, with the following definitions:

- Model specification – stakeholders, attributes, functions, solutions
- Parameter selection – weightings, of stakeholders and by stakeholders
- Relationship selection – functional forms of utility functions
- Model execution – expected utilities for validity, acceptability, viability
- Sensitivity analysis – attribute weights addressed by +/- variations
- Expert advice – assessment of fit of potential decisions to data
- Model curation – archival of versions of models for subsequent reuse

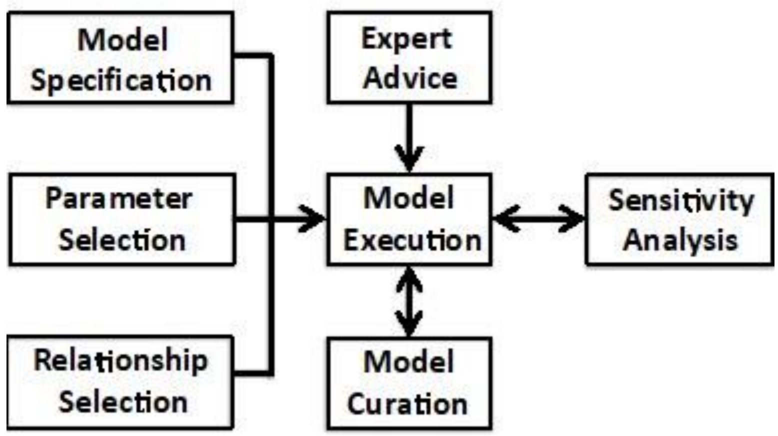

Figure 16. Functional Architecture of Uncertainty Management Advisor

Twenty Questions

The following 20 questions will be addressed throughout the course of a study employing the ***Uncertainty Management Advisor***, which will help users address these questions.

1. What is the nature of the program or project of interest and why is important?
2. Who are the key stakeholders in the success of this program or project?
3. What are stakeholders' concerns, perceptions and values?
4. How do these translate into attributes of importance?
5. Are any particular attribute levels required, i.e., "must haves"?
6. How important are these attributes to each of the stakeholders?
7. Are there key tradeoffs or are they yet to be determined?
8. What are your alternative courses of action, e.g., investments?

9. How do your courses of action differ, e.g., performance, cost, schedule?
10. What are competitors’ or adversaries’ alternative courses of action?
11. How do their courses of action differ, e.g., performance, cost, schedule?
12. What data are available to characterize your courses of action?
13. What data are available to characterize competitors’ or adversaries’ courses of action?
14. How are competitors or adversaries likely to respond to each of your alternative courses of action?
15. What changes of your courses of action would best deter these responses?
16. What are your contingency plans for addressing their responses?
17. What attribute level changes would most effectively enable your responses?
18. How might these attribute level changes be accomplished?
19. Do these changes affect the ranking of alternative courses of action?
20. Does all of the above suggest new courses of action and strategies?

APPENDIX B: LIST OF PUBLICATIONS RESULTED

Rouse, W.B., Verma, D., Lucero, D.S., & Hanawalt, E.S. (2021). Strategies for addressing uncertain markets and uncertain technologies. ***Proceedings of Annual Acquisition Research Symposium***, Naval Postgraduate School, May 11-13.

Rouse, W.B. (2022). Designing policy portfolios. ***Transforming Public-Private Enterprises: Understanding and Enabling Innovation in Complex Systems***. Oxford, UK: Oxford University Press.