System Architecture Decisions Under Uncertainty:
A Case Study on Automotive Battery System Design

by

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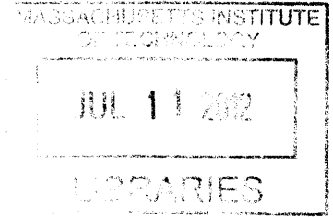AT THE

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ABSTRACT

Flexibility analysis using the Real Options framework is typically utilized on high-level architectural decisions. Using Real Options, a company may develop strategies to mitigate downside risk for future uncertainties while developing upside opportunities. The MIT-Ford Alliance has extended the techniques of flexibility analysis beyond high-level architecture to core product design decisions in future vehicle electrification. This thesis provides a methodology for a real-time support framework for developing novel engineering decisions.

Risk is high in new product introduction. For hybrid and electric vehicles, market demand and technology forecasts have substantial uncertainty. The uncertainty is anticipated, as the high voltage battery pack hardware and control system architecture will experience multiple engineering development cycles in the next 20 years. Flexibility in product design could mitigate future risk due to uncertainty. By understanding the potential iteration of core technologies, the engineering team can provide flexibility in battery pack voltage monitoring, thermal control, and support software systems to meet future needs.

The methodology used in this thesis has been applied in a Ford-MIT Alliance project. The Ford and MIT teams have valued key items within the core technology subsystems and have developed flexible strategies to allow Ford to capture upside potential while protecting against downside risk, with little-to-no extra cost at this early stage of development. A novel voltage monitoring technique and a unique flexible thermal control strategy have been identified and are under consideration by Ford. The flexibility methodology provided motivation and support for unique decisions made during product design by the Ford team.

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Chapter 1: Introduction

The automotive industry has a long, notable history. Initially a development in product innovation as a disruptive technology displacing horse drawn carriages, automotive transitioned into a process innovation and human interface design differentiation industry, developing cheaper, safer, and more user-friendly vehicles (Abernathy, 1978). Recent developments in battery technology and vehicle electrification are pushing the industry into a new, internal disruptive phase. Product innovation in electrified vehicles creates opportunities and uncertainties in what had been a mature industry, where uncertainty was mainly in consumer vehicle styling preference rather than in core technology choices. Complex hybrid electric vehicle systems are moving technology focus from the engine block to control systems and holistically designed new powertrain technology. Upstart companies (e.g. Tesla and Fisker Automotive) are entering (and exiting) the industry signaling potential disruptive product innovations (Utterback, 1996). Now is an exciting and turbulent phase for the automotive industry. The winner will be the one that can seize the opportunity and best handle the uncertainties in both technology selection and market demand.

Demand forecasting traditionally is based on econometrics models, past sales history, and consumer choice modeling. In the case of a mature stable product, an automotive company like Ford may be able to predict, with reasonable accuracy, the upcoming sales of the Ford F-150, a major product line. However, unanticipated macroeconomic issues, such as the recession in 2008 - 2009, have completely invalidated the earlier sales volume forecasts for large trucks and SUVs, the profit center of the US automotive companies. As the industry approaches a new,

untested, unknown technology like hybrid vehicles, uncertainty is extremely high due to technology performance uncertainty and consumer hesitation.

The Chevy Volt is a good example for illustrating the demand forecasting challenge. Multiple companies are developing the product innovation of a plug-in hybrid vehicle (PHEV), and the Volt was the first to market from a major company. As a product innovation, the Volt runs on pure electric power for up to 35-miles before requiring a supplemental gasoline engine to recharge the batteries while driving (Chevrolet). Unfortunately, uncertainty in consumer demand is high due to the novelty of the car, and sales have been substantially lower than what General Motors (GM) had forecasted (Clayton, 2012). Furthermore, the core technology within the battery pack has been plagued with questions due to crash testing by the National Highway Traffic Safety Administration (NHTSA) (Tran, 2012). Although NHTSA has found no fault or problem with the Volt, the negative press is affecting public perception and further dampening market demand. The Volt has had production shut down due to lack of demand, not long after relatively high public sales forecasts (Clayton, 2012). The Volt shows the challenges of product innovation and novel technology. Long term demand forecasting for product innovations is highly uncertain, and a company can seriously suffer from placing the wrong bet.

This thesis focuses on developing a real-time decision support for engineering flexibility in design to help mitigate the impact of uncertainty in product innovation with novel core technology. In particular, the challenges associated with flexibility in hardware development are addressed. Real options in engineering design is a method developed by de Neufville, and has been successfully applied to large infrastructure projects (Guma, Pearson, Wittels, de Neufville,

& Geltner, 2009). In the realm of product design, the existing case studies only take a rear-view mirror, after the fact analysis. Therefore, the research question that this thesis intends to answer is:

Will flexibility and real-options support of advanced technology development lead to novel choices by the engineering team when applied to an on-going engineering design project?

The rest of this thesis is organized as follows:

- Chapter 2 provides a description of flexibility methodology and its use, both in real options and product design applications.

- Chapter 3 describes real options techniques in detail.

- Chapter 4 describes battery technology and the control challenges in the automotive industry.

- Chapter 5 is a case study of the Ford team's usage of flexibility concepts.

- Chapter 6 describes the real-time support of the Ford thermal control team in choosing concepts based upon real options based flexibility methodology.

- Chapter 7 provides a final discussion of additional research areas and the summary of the project.

Chapter 2: Literature Survey—Flexibility in Product Design and Development

2.1: Defining Flexibility

Flexibility is a term referring to the ability to modify and adapt in response to changes in circumstances. Design flexibility can be used to maximize returns by capturing value from uncertainty (de Neufville & Scholtes, Flexibility in Engineering Design, 2011). Design for flexibility involves three essential aspects: (1) what is uncertain, (2) what can be done in the design to handle the uncertainty, and (3) when to apply the flexibility strategies in the product lifecycle.

This chapter provides a review of design for flexibility techniques in the literature, including Product Line Architecture Flexibility, Product Line Manufacturing Flexibility, Product Evolution Flexibility, R&D Flexibility, and Product Subsystem Flexibility. The product lifecycle timeframe for flexibility can be separated into four phases: research and development (R&D), product design and development (PDD), manufacturing, and during operation after sale (Saleh, Hastings, & Newman, 2003). The first three are within the control of the producer. In post-sale consumer usage, flexibility may have been designed by the producer, but is activated or sought by the consumer. (Although in some cases the producer is the consumer of its own product.) Saleh, Hastings and Newman use flexibility to change the system after it has been fielded; this thesis addresses flexibility pre-manufacture. Multiple techniques fall under the broader

definition of flexibility, or the systems ability to change without negative consequences (Saleh, Hastings, & Newman, 2003) (Fricke & Schulz, 1999).

Flexibility is used to address various uncertainties, including market, technological, future use, and regulatory (Greden, de Neufville, & Glicksman, 2005). It can be implemented in one phase (e.g. R&D), but used in another (PDD). Usage can be active (there is an agent choosing to activate) or passive (the flexibility activates automatically as part of the system). The producer or the consumer, depending upon the phase of development, may activate the flexibility.

In this thesis, there are five steps to take in order to determine flexibility and the value of flexibility (de Neufville & Scholtes, Flexibility in Engineering Design, 2011):

1. **Identify Uncertainty:**

   a. This could be market demand, technology uncertainty or other, application specific uncertainties (manufacturability, reliability, etc....)

2. **Determine the Phase for Incorporating Flexibility:**

   a. R&D, PDD, Manufacturing, or Consumer Usage

3. **Determine the Phase for Activation of Flexibility:**

   a. R&D, PDD, Manufacturing, or Consumer Usage

4. **Identify the agent of flexibility activation:**

   a. Manufacturer or consumer, active or passive

5. **Establish a flexible solution to increase expected project value**

a. Evaluate technology, business case, and known flexibilities to determine value, positive or negative.

After following these five steps, the designer must access a design methods toolkit to find and value solutions. In this chapter, steps 1-4 are discussed, followed by a presentation of flexible solutions, with a discussion of how each might apply to the real-time support provided to Ford. Chapter 3 discusses the business case, and chapter 4 describes the technology.

2.2: Steps 1-4 - Identifying Uncertainty, Phases, and Agents of Activation

For established products in stable markets, the focus of the company will be on reducing the cost of the process. Process innovation creates value for a company through efficiency. Light bulbs (electric lamps) went through many phases of process innovation, decreasing cost and increasing reliability and efficiency (Utterback, 1996). In stable markets, process innovation is used to capture existing markets or branch into ancillary markets. Flexibility can be used during process innovation, e.g. flexible manufacturing, to respond to demand fluctuations due to exogenous factors.

When a technology is disrupted, uncertainty is high in both potential consumer demand and reliability (or applicability) of the new technology. In times of product innovation these uncertainties create hesitation in product development; the product design and architecture is unsettled. The study of computer hard drive disruption by Christensen shows that the Winchester hard disk architecture continued to be disrupted in each new hard disk size. The architecture and technology changed in each generation, and the highly profitable incumbent was

unwilling (or unable) to address the new market and architecture due to uncertainty (Christensen, 2003).

As described in the introduction, electrified vehicle platforms have many characteristics of a disruptive market. The battery research team at Ford is dealing with uncertainty in both technology and consumer demand for their vehicles. They are involved in product design and development, and intend to use flexibility during the product design and development process to mitigate uncertainty. Using the five steps presented previously:

1. **Identify Uncertainty:**
    a. Electrified Vehicle Market Demand
    b. Battery Technology and Requirements
2. **Determine the Phase for Incorporating Flexibility:**
    a. Product Design and Development
3. **Determine Phase for Activation of Flexibility:**
    a. Product Design and Development
4. **Identify the agent of flexibility activation:**
    a. Product Design Team, Active use of options
5. **Establish a flexible solution to increase expected project value**
    a. Determined using real-time support with real options techniques

The project team determined steps 1 and 2; they have an understanding of uncertainties and are involved in product design and development. Step 3 became clear during the real-time support

period due to the uncertainties involved and is described in Chapter 6. Step 4 identifies the real options framework used in support of Ford, described in detail in Chapter 3. Step 5 is the establishment of flexibility in the system.

Proposed methods of flexibility vary in both phase of incorporation and phase of activation. A brief survey of flexibility methods follows. The discussion of various methods of flexibility will focus on (1) when the method is used, (2) by whom, and (3) for what uncertainties. The methods may have extension beyond those proposed in the literature, and should be used as part of a flexibility toolkit for steps 4 and 5 of the method proposed in this thesis.

2.3: Design for Changeability

Design for changeability attempts to address flexibility in the product design phase. Flexibility, agility, robustness, and adaptability are considered attributes of system design for multiple changing use case conditions. A system can be made agile ("the property of a system to implement necessary changes rapidly"), robust ("deliver their intended functionality under varying operating conditions without being changed") and adaptable ("capability to adapt itself towards changing environments to deliver its intended functionality") (Fricke & Schulz, 1999). Here, flexibility "represents the property of a system to be changed easily and without undesired effects". (Fricke & Schulz, 1999)

The product designer attempts to design a system that is responsive to change, within a range of quantifiable, anticipated uncertainties. An example of adaptability in design for change might be the run flat tires used on high-end vehicles. A systems engineer has anticipated the use case and

designed the tire to operate in a non-optimal inflation condition. The uncertainty for the designer and user is when, or if, a flat tire will occur; not whether or not the tire will continue to operate. An adaptable system has a "baked in" dynamic capability for a pre-programmed use case, not resulting from an outside decision maker. In this example, design for changeability incorporates flexibility during product design and is activated without user intervention at a later time.

2.4: Flexibility for the Consumer During Ownership

Technology purchases are fraught with uncertainty, due to differing standards, compatibility, and obsolescence risk. Consumer electronics transition rapidly requiring regular upgrades. Designers can use flexibility to provide insurance for consumers.

Ulrich and Eppinger identify key areas where a product is designed for flexibility for changing consumer conditions. They list 7 areas of flexibility for the consumer: Upgrade, Add-on, Adaptation, Wear and Tear, Replaceables, Flexibility in Use, and Reuse (Ulrich & Eppinger, 2008). As an example, computers have flexibility during use/ownership. The consumer can upgrade standard components (memory, hard drive, graphics) after purchase and ports like USB (Universal Serial Bus) are designed for flexible updates. The flexibility provides an option for the consumer to activate at a later date.

2.5: Flexibility for Manufacturers in Markets using Platforms

Product line architectures can be made flexible for attacking multiple market segments or generating a diversity of products using an inexpensive platform in the architecture. This creates flexibility within the product line itself and lowers overall production cost, while reducing risk in

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market demand by providing diversification. The product designer can create platforms to reduce uncertainty in market demand, supply chain, or technology during product design or manufacture.

A platform refers to a baseline system with common subsystems and defined interfaces (Meyer, 2007). Combined with a platform, classic flexibility in technology is further defined by modularity. A module (or subsystem) can be removed and upgraded with no impact to the rest of the system, creating flexibility via interface management. In defining an interface, the module maker can create new technology or an advanced feature with the single constraint of interface compatibility.

Meyer defines the steps to product line platforms using modular components, from definition of the architecture, subsystems and interfaces, to planning for the product evolution (Meyer, 2007). By standardizing subsystems and interfaces, platforms mitigate uncertainty in the future of the product supply chain. If designed with commonality, the platform components will be similar, if not identical. Additionally, platforms simplify product lines by fundamentally limiting total flexibility in the system, creating "rules" for product creation. An attribute can only be satisfied if it falls under the standard interface protocol. Although modularity is often used for reduction of cost and expansion of markets, it may provide solutions in a real options framework (Baldwin & Clark, 2000).

Again, the personal computer has been built on a modular platform for many years, providing manufacturers the ability to swap components in and out to expand their product line. Common

bus structures provide an interface and the motherboard is typically designed with multiple interface standards. Processors from Intel are a modular subsystem within the Intel product line and can be replaced easily, until a new product line is introduced. They are flexible within a product line, and are only limited by the interface definition. Platforms are very valuable for flexible product design and development as well as manufacturing due to commonality, and can also be activated by the consumer, as in the USB description above.

2.6: Flexibility in Product Design and Development for the Manufacturer

Flexibility can be useful for product evolution, particularly with anticipated markets. By using open spaces or flexible structures, a manufacturer can leave room for next generation product enhancements, due to expected customer requirements changes. Added space and flexibility may come at a cost, due to non-optimal design (and potential added cost) for future evolution. In many cases, uncertainty and the risk of investment in flexibility is low. Keese et. al establish methods for enhancing flexibility in future product design evolution in an industrial case study of the Lids Off jar opener evolution. The Black and Decker Lids Off is a jar opener. A natural extension of a jar opener might be a bottle and can opener. Hence the evolution to the "Open-It-All Center", with the additional attributes for opening bottles and cans. With this expected evolution, large reuse is possible from one product to the next and open spaces may be created for the evolution (Keese, Tilstra, Seepersad, & Wood, 2007). With expected product evolution, both the designer and the manufacturer enjoy the benefits of flexibility.

Professor Olivier de Weck proposes a methodology to develop a flexible product line that is based on a product platform using a flexible platform design process. Product design can be

used to provide flexibility in manufacturing for shifting demand or requirements at a later date. Whereas traditional platforming provides flexibility within boundaries due to the defined interfaces, de Weck's seven-step process is used to identify and value flexibility in the platform using financial analysis. They aim to "demonstrate how to select flexible elements by projecting exogenous uncertainty into the platform and to quantify both the additional upfront investment required to achieve this flexibility as well as the downstream benefits resulting from the investment" (de Weck, Suh, & Chang, Flexible product platforms: framework and case study, 2007).

De Weck's case study on automotive panel design assigns vehicle elements as flexible or inflexible, and determines the value of each. As an example from the study, the floor pan is deemed inflexible; the roof panel is flexible. At the top-level architecture, de Weck creates a differentiated product that can respond to demand and requirements changes, while identifying key platform components that are left out of traditional reuse analysis (de Weck, Suh, & Chang, Flexible product platforms: framework and case study, 2007). Rather than taking the traditional design for commonality approach of using as many identical components as possible, de Weck has used a prioritization approach to flexibility.

The methodology used by de Weck has many similarities to the work in this thesis, identifying uncertainty and developing flexibility using real-options valuation methods. The primary difference between this thesis and the case study on flexible product platforms is the uncertainty in the core technology due to product innovation and the real-time access and support provided for Ford rather than another case study.

2.7: Flexibility in R&D

Research and Development (R&D) is a highly uncertain investment. Due to the nature of R&D, there exists high uncertainty in technology and market demand. Technology researched for one application often finds a second, third, or fourth life in a new one. Post-Its are a ubiquitous example, as the reusable glue was an innovation looking for a product, taking multiple years to find a home on the work desk (3M).

Flexible design in R&D is incorporated due to uncertainty. A microchip may be created with multiple interfaces, in order to tolerate usage in a range of system applications. A Field Programmable Gate Array (FPGA) is a reconfigurable processor, used widely in R&D projects prior to productization, where a dedicated processor will eventually be used. Leaving flexibility in a component, system, or application allows the R&D team to acknowledge the risk that their product may or may not be directly tied to a known end product or application. When the application becomes clear during product design, the FPGA might be replaced by a cheaper, non-flexible dedicated microchip.

From a business standpoint, R&D is difficult to value. Just as the science and engineering team must remain flexible due to the uncertain outcome of research, the business team must assess the value of research to the firm and the future market. A venture capital approach is to invest in multiple companies. Using baseball parlance, most will strikeout, one or two will hit a single and one will hit a home run, justifying the total investment portfolio (Sproul). R&D is an investment in a market option, one that is exercised upon successful completion of the project.

2.8: Flexibility Summary

This thesis is an application of flexibility in product design with new, uncertain technology requirements and highly uncertain product demand. The next section of this chapter will describe the real options valuation method and how it can be applied to projects with uncertainty. Chapter 6 is a description of real-time support of the intersection of flexibility in technology design, the value of product design projects, and a method for options thinking to enhance the expected value of a product design project with market and technology uncertainty. In designing a real options methodology, many flexible solutions already discussed can be used and are evaluated in the proper timeframe (product design) and circumstances (product innovation). Flexibility can be used to increase value, particularly when flexibility has been built-in for active decision-making based on incoming data based on future conditions.

Chapter 3: Flexibility Valuation Modeling Approaches With Real Options

Traditional business case models use point forecasts to determine the Net Present Value (NPV) of a project. NPV is used to compare projects at "present value." It assumes that future cash flows are worth less than current cash flows, as are future capital expenditures (CAPEX). The equation for NPV is defined as:

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1 + r)^i}$$

where n is the period over which the analysis is done (often in "years"), r is the discount rate, or the competing rate of interest as a benchmark, and CF is the cash flow. For a very safe investment, the discount rate might be the rate on a similar duration US Treasury bill. For a riskier investment, such as a startup venture, a substantially higher rate may be used. A short-term CAPEX would be a negative cash flow at year 0, while sales in year 10 would provide positive cash flows.

A traditional model might project a 10-year demand curve, sales price, and unit cost, providing cash value for comparison across various competing projects. Design decisions would be made from this point forecast, treating future estimates as "fact". At best, the future is incredibly difficult to predict, even in the short term. At worst, it is impossible.

Assuming static behavior in an NPV assumes a priori knowledge of future conditions. Additionally, this type of financial model assumes passive management; incoming data does not lead to decision-making, as the point forecast means that no decisions need to be made. As an example, in a new product introduction, a 10-year NPV would utilize a typical demand curve estimate from any number of econometric demand curve models. Perhaps in year 1 the analyst is relatively close to what will actually happen, but at year 0, it is impossible for the business analyst to truly know whether or not the new product has been a success in year 10. In the traditional NPV model, there is zero chance of product failure, nor any chance of very high success in the product. The analyst has asserted the mean estimate of outcome and used it for analysis. Thus, this is an unrealistic methodology for developing a business case due to the inability to predict the future.

A more detailed analysis may recognize uncertainty in the system. Socrates had the Oracle at Delphi, Operations Managers have the normal distribution, and analysts have expert forecasts. An analyst might calculate three NPV models from an expert's forecast, one with high-demand, middle demand, and low demand, for a "best, average, and worst" case scenario. By bracketing the decision process, the analyst has recognized uncertainty and is able to provide an estimate of deviation from the expected NPV (ENPV). The ENPV continues to be the same, as the middle "average" case will provide the same answer to the analyst who ran a static NPV. Additional work is completed with the same answer; management will continue to choose the "expected case".

Recognition of uncertainty might drive an NPV simulation over a distribution of outcomes. It is not impossible for the analyst with 3 scenarios to fit a curve to those same values, developing a simple model for demand of the new product. Again, the expected value is the answer to the problem. As the analyst increases the sophistication of the model, there is an acknowledgement that the future is uncertain. This additional step in analysis leads to acknowledgement without action; the analyst continues to develop a passive model of future conditions. Management will not respond to future conditions in the model.

Once an uncertainty analysis has been completed, a "real options analyst" will begin to develop test cases for "actions". In other words, if demand for a new product falls to 50% of the original projection, a manager would close down production, zeroing future cost associated with manufacturing, marketing, etc.. By acknowledging this action, the real options NPV analyst begins to establish thresholds over the Monte Carlo simulation where the product will be shut down, thus protecting the manufacturer against downside risk. If expected demand in year 5 is 10,000, and simulated demand in year 5 is 10, the manager would shut down production. There is a cost to shut down, but that will most likely be substantially lower than the cost of continued production due to both fixed and recurring costs. The analyst can establish the value of the shut down cases and run screening models to evaluate them. For a real option, the analyst will examine where flexibility in the system may be placed to enhance the ability to shut down. (de Neufville & Scholtes, Flexibility in Engineering Design, 2011)

On the other hand, demand may be much higher than anticipated and the manager will want to expand. In the original analyst's passive model, there may have been variable cost due to

economies of scale. In this new model, the analyst must also acknowledge expansion of either a

manufacturing facility or the cost of an additional contract manufacturer. By establishing the

ability to produce beyond the originally expected value, the analyst has created upside potential.

If we build the facility to product 10,000 units in year 5, but demand in the simulation is 20,000

units, the additional potential revenue is lost unless there is an embedded method for expansion.

If we want to limit downside losses and create upside potential, are there any actions that can be

taken now to create an easier path for either (de Neufville & Scholtes, Flexibility in Engineering

Design, 2011)?

3.1: Options

In this research, options are defined as the right, but not the obligation, to do something (de

Neufville & Scholtes, Flexibility in Engineering Design, 2011). Options are insurance against

future events. They are used to mitigate the risk of uncertainty. In financial markets, an option

is insurance that is purchased, allowing the owner to exercise the option at a later date, or allow it

to expire. Financial options have been well covered by the Nobel Prize winning Black-Scholes

theory (Black & Scholes, 1972).

As an example of how a financial option might work, a broker may purchase an option to buy

Apple at $500 by a certain date (e.g. within one month), to protect against downside risk in

Apple. The broker now has the option (but not the obligation) to purchase Apple at that price in

one month. If Apple is selling for $480, the broker will allow the option to expire. If it is selling

for $600, the broker will exercise the option and pocket the profit. This option has come at a

cost to the broker in both situations, but the cost of this option has been calculated in highly liquid markets and provides insurance to the broker as incoming data arrives.

This thesis uses physical "options", or "real options", rather than financial. These options are also actively exercised or allowed to expire at a future date, based upon incoming data. The development of options flexibility may be necessary in the product development phase for situations involving product innovation and novel technology, to allow an incumbent company to capture value in new technology and markets. (de Neufville & Scholtes, Flexibility in Engineering Design, 2011)

3.2: The Garage Case

Professor Richard de Neufville at MIT has provided an example on how point forecasts will frequently lead to non-optimal decisions, given that future forecasts are assumptions, not fact. The "Garage Case" is a study on the building of a parking garage structure at a new shopping mall (de Neufville, Scholtes, & Wang, Real Options by Spreadsheet: Parking Garage Case Example, 2006). A parking garage is a long-term investment with a high initial CAPEX. How many levels should be built for the garage? If we estimate too low for future usage in order to limit downside losses, the garage will be full all the time and additional potential revenue will be lost. If we estimate too high in trying to capture upside, the garage will be mostly empty and we will have spent additional CAPEX. Forecasting demand is difficult, as many exogenous factors can impact predictions. In the garage case, demand could have a distribution of potential outcomes (i.e. adding uncertainty to our assumptions) showing the potential for large losses

when demand does not materialize (e.g. when a competing mall is built in the future), while the upside is "capped" by the number of floors (limiting demand when retail is booming).

Professor de Neufville has developed a third way to evaluate the problem, using flexibility to create an "option for future action" for the garage developer. Ultimately, the garage developer would like to limit downside losses with the "option" to capture upside gains. For example, the parking garage might be built with stronger pylons and prefabricated connectors on the upper level, such that expansion in the future is possible. Here, the uncertainty is demand, the time for developing the flexibility is in product design and manufacturing, and the time for exercising the option is during consumer use (de Neufville, Scholtes, & Wang, Real Options by Spreadsheet: Parking Garage Case Example, 2006).

There will be an additional per floor CAPEX for the initial structure due to strengthening, but the initial garage will have fewer floors than originally forecast using the static NPV. Simulating over the range of outcomes and incorporating this "option to expand" into the simulation, the overall project value is increased, as the developer is able to capture the upside potential and limit downside losses. The overall expected value of the project has increased (de Neufville, Scholtes, & Wang, Real Options by Spreadsheet: Parking Garage Case Example, 2006).

There is generally a cost to flexibility and in some cases the flexible solution will cost more. For example, when the original point forecast is close to being exact, the developer will have spent additional, unnecessary money in strengthening the structure. However, the overall expected value of the project has increased, indicating that more often than not, the flexible solution

produces additional value for most demand outcomes. In fact, the optimal initial design has changed from six levels in the static NPV, to five levels in the Monte Carlo NPV, to 4 levels in the flexible, real options solution (de Neufville, Scholtes, & Wang, Real Options by Spreadsheet: Parking Garage Case Example, 2006)). By acknowledging uncertainty in the predictions and embedding logical decisions in potential future outcomes, the potential project value has increased.

The Garage Case is an example of Sam Savage's "Flaw of Averages". The flaw of averages states that the expectation value of a function is not the same as the function of the expectation value, unless the function is linear. Savage notes that crossing a river with an average depth of three feet should be easy; unless, of course it is 2.5 feet deep over 95 feet with one small, but noticeable, gap of 5 feet long, and 12.5 feet deep! In most cases, the average does not represent a good basis for decision-making (Savage, 2000). In the garage case, the function for the number of parking spaces available vs. parking spaces used is linear until the garage reaches capacity, at which point the function hits zero. Thus, using a model based on the expectation value is incorrect, and a Monte Carlo simulation enhances the understanding of the situation.

In the garage case, the flexibility arrives in the initial construction of the building. Multiple examples of staged construction exist, including the Tufts Dental School and the HCSC building in Chicago (Pearson & Wittels, 2008). Vertical phasing is a flexibility in real estate, as in tight city construction lateral phasing, or adjacent buildings, may not be available. Building a stronger base for vertical phasing is an investment in the future. In real estate or large capital construction, potential areas of flexibility are system level and require little information on the

core technology. A screening model can be created to evaluate highly sensitive parameters. In the Garage Case, the screening model is the NPV and the evaluation of flexibility in the system stems from strengthened construction concepts. Flexibility assessment requires either system-level or technical knowledge in order to establish potential areas of flexible design.

Black-Scholes theory deals with large, liquid markets and the price of insurance ("options") in those markets; real estate development has individual, unique projects. Rather than looking for real options "on" a system or project, the Ford-MIT collaboration developed real options "in" the system for flexibility. A real option "on" a project is very similar to a financial option, an option to invest in a project that will expire at a given time. An example of a real option "on" a project might be for expansion of a pharmaceutical venture, or whether or not to invest in expansion given a risky outcome on the venture itself (Johnson & Li, 2002). This decision requires little to no knowledge of the underlying technology; an analyst could determine the option value (the value of expansion with a good outcome) by speaking with experts. There is no flexibility "in" the design, just flexibility in expansion (or shut down) decisions. The project itself is a "black box" with underlying, unknown technology (Wang & de Neufville, 2005).

The Ford project was interested in real options "in" a project. In this thesis, the options are not obvious, as the key area of flexibility comes from technical knowledge of the system and the challenges that exist within the core technology, described in detail in Chapter 4. These options are typically built into the system during product design and are designed with a long time frame of uncertainty, both in requirements and scale. Additionally, they require knowledge of the underlying technology for engineering design of these options (Wang & de Neufville, 2005).

Flexibility within the system enables the option to be taken through active participation at a future date (or allowed to expire). Valuation of these options is highly challenging, as the values are unknown due to the unique nature of the project. Frequently the question of value has never been asked, or the underlying technology provides indirect value only.

As an example of the complexity in valuation of engineering components "in" a system, in automotive the consumer drives the car and assesses how it feels. Individual components/attributes provide indirect value to the consumer. Without these attributes, the customer cares, as the car doesn't start or perform. Without brakes a car has no value; customers expect them. Valuing the brakes is a difficult process.

In a financial analysis, the engineering cost and unit cost of brakes will provide a substantial negative NPV. With a "black box" view, a financial analyst might ask to remove these components due to lack of direct value to the customer. The engineering team will consider them non-negotiable for operation of the "black box", i.e. the automobile. Then they may agree on the lowest unit cost possible to meet performance. The traditional cost analysis is difficult to utilize and can potentially lead to wrong answers, without stakeholder cooperation (in this case the consumer, the engineer, and the analyst).

When designing real options "in" a system, the components themselves often have value to the engineering team and not to the customer, creating an asymmetric response from management. Justification of added cost for an option can only be done if engineering value can be tied to customer value. An example provided by de Neufville of a real option for a consumer "in" an

automobile is the spare tire. It is used if and when it is needed, but otherwise held in the trunk of the car and designed to be similar to the existing tire. The purchase of the spare tire is a real option, designed as insurance against a possible outcome. There is added cost (and time) for the consumer if used, but it's designed to be used under the potential condition of a tire failure (de Neufville, et al., 2004). The customer values this additional security and is willing to pay for it.

An additional element of real options "in" projects is path dependency (Wang & de Neufville, 2005). Decisions will be made upon incoming data. In early stage development, with a great deal of uncertainty, a staged investment plan can be a valuable flexibility. The Iridium satellite phone constellation is a typical engineering-style project. The design of the system is a complex, but tractable, engineering optimization. However, there is a large uncertainty in total demand. The deployment time for the satellite system is long; multiple launches are required. Adoption rate of the technology is highly uncertain and, in retrospect, it is clear that the emergence of a competing technology, cell phones, limited the market for a satellite phone system (de Weck, de Neufville, & Chaize, Staged Deployment of Communications Satellite Constellations in Low Earth Orbit, 2004).

3.3: Real Options "in" Systems

Professor Olivier de Weck has looked at the failure of satellite phone systems, and established the value of staged deployment in uncertain markets. The satellite phone companies could have lost substantially less money by designing the satellite constellation to deploy in stages, limiting the number of initial launches and allowing the company to establish data before releasing the next stage. Thus, they would have protected against downside risk while allowing themselves

the ability to capture the upside potential users (de Weck, de Neufville, & Chaize, Staged Deployment of Communications Satellite Constellations in Low Earth Orbit, 2004). The uncertainty was in demand, as satellite phones were a substantial product innovation. The flexibility would be built into the deployment plan (product design) and activated during consumer use by the manufacturer. The satellite study is a backward looking view of "what went wrong" and asks the question, "How could flexibility have saved this project?" The value of this thesis is the application of real-time support for establishing flexibility "in" the system.

Flexibility "in" advanced research projects can provide value for the product design phase. Advanced research has been described as an option, wherein investment is made in order to have the opportunity to move forward with a product in later years. If an analyst ran an NPV on a research program, a company would never invest, as at the beginning of the project, the final outcome may have, optimistically, a 10% chance of success in 5-years. With enough investments the overall payoff may be high and, since data will continue to arrive, long-term R&D projects are staged investments, where the progress is evaluated along the way. Thus, flexible decisions will be made on incoming data.

Real options in R&D are well-described in an overview by Dean Paxson. There are multiple challenges for real options applications to R&D, including predictions of success for the R&D program, assigning values to the R&D process, and acquiring realistic R&D data (Paxson). Battery pack development for hybrid vehicles at Ford Motor Company has multiple similar uncertainties. It is part of advanced R&D for Ford moving into product design and development. The real-time support for Ford Motor Company in this thesis began with evaluation of

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uncertainty in demand and/or consumer preference, which had minimal impact on the decision making process. This was followed by finding the key uncertainty: overall performance requirements.

As an embedded member of the decision making team for Ford Motor Companies advanced R&D team on battery packs, the MIT team had the opportunity to influence product design decisions for flexibility IN the system, assisting in the generation of concepts for added value in early stage product decisions. Based upon the methodology of both real options and flexibility in design, a staged investment process was proposed, along with an assessment of flexibility in the design process. Chapter 6 will describe the methodology used for support of Ford Motor Company, with the "option" designed to enhance flexibility to meet the overall requirements of the project.

Chapter 4: Hybrid Battery Pack Maintenance and Control

Forecasting battery Engine Control Unit (ECU) measurement/information demands over the next 10 years is highly unlikely to yield accurate results. The architecture for the battery management system may be impacted by the future uncertainties in technology. For example, an architecture optimized for NiMH would assume more series battery cells than Li-ion, due to the voltage difference between the two (~3.6 V vs. 1.2 V).

Hybrid vehicle technology has made 3 battery transitions in the modern electrified vehicle era (~1995-present). Lead-acid batteries, identical in composition to those under the hood, were the first to be used, included in the General Motors EV1 Battery Electric Vehicle (BEV). Their overall energy density is limited; energy per unit area for vehicle propulsion is low in both theory and practice, as lead is a heavy element. Phase two of battery development involved nickel metal hydride (NiMH) batteries, an improvement in total energy and power per unit weight. The 2nd generation EV1 used NiMH batteries, an example of technology transition between model years. Finally, Lithium-ion batteries have begun to appear in electrified vehicles (the 2012 Nissan Leaf BEV. 2013 Ford Fusion Hybrid, etc....), with new challenges in control of the technology (Battery Research Team, 2011).

Professor Chao-Yang Wang from Penn State University likes to compare batteries to humans. They are sensitive to temperature, need to recharge, age, and are unable to work 24 hours a day (Wang C.-Y. , 2011). Cold temperatures deplete the usable charge within the battery by changing the anode/cathode electro-potential and lowering cell voltage; the reaction rate is exponential with temperature. High temperatures create risky situations with runaway type

behavior, presenting the risk of explosion. Much like a team, the battery pack is only as good as its weakest member; a below-average battery will limit any large grouping of cells. If one battery cell ages faster than the others, the entire pack must be replaced, as a new cell will only create imbalance (Andrea, 2010) (Wang C.-Y. , 2011).

The battery pack is designed as a combination of cells in series, parallel and/or groups. A modular style HEV battery pack contains M series-connected battery modules. Within a module, monitoring and control may be done at a cell-level, module level, or a combination of both. Each module contains N cells (of voltage V_{cell}) in C parallel rows for a total:

$$Vpack = \frac{M \times N \times Vcell}{C}$$

(Note that for a system designed of individual cells, not modules, M=1 and N=total cells, while for a single module system M= total cells and N=1) The individual cell current, I_{cell}, limits the output current of the battery pack due to the series connection. The total power available within the battery pack is defined as:

$$Power\ Output = C \times M \times N \times Vcell \times Icell$$

Most power will be associated with vehicle movement; a portion is lost as heat, requiring thermal monitoring and control of the battery pack. Depending upon the class of vehicle (truck, SUV, passenger vehicle), the architecture and size of the battery pack and battery management system

will change, including thermal management, due to the high power flow during charging and discharging (similar to varying engine size and fuel tank capacity in gasoline vehicles). The total information content required for the control of the battery pack will be, at a minimum, linearly related to the number of sensors attached.

Monitoring, maintenance, and control of battery cells are increasingly important for long-life, high performance batteries. The goal of any battery control system is to obtain additional efficiency for the vehicle while preventing negative events and extending battery life. The system may benefit from flexibility; a control system designed for a NiMH battery would not be entirely reusable for a Li-ion pack for multiple reasons. First, the voltage is different. Second, NiMH batteries are self-limiting in voltage, while Li-ion batteries run the risk of explosion in an overvoltage condition. Thus, additional voltage control is required for Li-ion (Battery Research Team, 2011).

Li-ion batteries are the near future, and must be operated within a Safe Operating Area (SOA). As noted, the SOA will change with battery chemistry. The battery pack cannot be overcharged nor over-discharged, to prevent permanent damage. Lifetime will be reduced by multiple factors, including high dc currents, high peak currents, and high temperatures. Very high temperatures can lead to fires in the battery (Andrea, 2010). The potential variations in chemistry within the lithium-ion battery family create requirements uncertainty for battery pack control systems.

As an initial short list of key uncertainties in the future of HEV/EV design from an engineering design standpoint, five clear technology based uncertainties exist, with some influences from market uncertainty:

a) Battery chemistry (and/or electricity sources) may change.

b) Voltage/current may be different per vehicle depending upon the cell design (e.g. higher current chemistries).

c) Voltage/current may change due to vehicle class/customer power preferences.

d) The number of cells in series may change, both in total for the vehicle and also within the integer grouping of those cells into a module.

e) The communication bus and protocol may expand beyond the current controller area network (CAN)-bus system.

As automotive companies expand the fleet of HEVs and EVs, the uncertainty in battery pack control requirements increases. Although platform architectures are preferable, the rapid development of battery technology and the variable power requirements of vehicle classes present uncertainties surrounding vehicle design, technology, and consumer preference. An example of requirement variables is shown in Table 4.1 for 3 existing vehicles (Idaho National Laboratory and Electric Transportation Engineering;) (Fuhs, 2009) (Wong, 2010):

Table 4.1: Current Production Vehicle Requirements

Vehicle	Battery Type	Number of Series Cells	Volts
Nissan Leaf	Li-ion	96 in 2 rows	360
Chevrolet Volt	NiMH	168	202
Ford Escape	NiMH	250	330

Macroeconomic conditions clearly affect battery choices and cell arrangements. The purpose of this thesis is to apply business theory to support detailed technical decisions given market and technology uncertainty. As noted in Chapter 2 and 3, applying flexibility in a real options application requires knowledge of the underlying battery technology.

With 2 different battery chemistries (and potential sub-chemistries of Li-ion on the way) and 3 different voltages shown for 3 different vehicles, irrespective of future advances in technology, the ECU requirements have uncertainty in all aspects of measurement and control content. If designed using a platform based architecture, the risk of inflexibility is high, as an engineer must design with potential future consumer preferences and battery uses in mind. A full hybrid (FHEV) design differs from a plug-in hybrid (PHEV) design, which differs from a battery electric (BEV) design, in capacity, power, use case, and range. Professor Wang lists the primary differences as follows (Wang C.-Y. , 2011):

Table 4.2: Vehicle Range and Capacity Requirements

Vehicle Type	Battery Capacity (kWh)	Pure Electric Range (miles)
BEV	25	100
PHEV	15	50
FHEV	2	NA

These variations and uncertainties impact the engineering design process. A company may choose the most conservative route, in order to guarantee performance. Another choice may be the lowest unit cost, in order to provide the highest return on unit investment. As described in Chapter 2, the real options framework allows the user to accept uncertainty and assume that as new information arrives, rational decisions are made, limiting downside risk, and capturing upside potential when the situation is not "as forecast". As engineering requirements become clear, the engineering team would benefit from flexibility, in order to make rapid decisions based on incoming data.

An FHEV or PHEV has different control constraints beyond that of either a BEV or an internal combustion engine powertrain as the dynamic merging of EV and engine combinations adds information requirements for the control system. Choices made in number of cells, current capacity per cell and chemistry of the cell will all change the engineering design process. The battery control system must measure, at a minimum, current, voltage, temperature, and state of charge (SOC) of the battery, cell balance/equalization, and fault/failure modes (Sen, 2009) (Fuhs, 2009). Each measurement is critical to maintain safe and efficient battery operation. An

effective battery maintenance system should be developed with flexibility in critical operational areas for minimum variation in future control. Is there a way to maximize potential return by using flexibility and the real options framework?

Chapter 5: Battery Voltage Monitoring, Maintenance, and Control

Battery pack voltage control and maintenance is typically accomplished by monitoring per cell voltage to establish the individual cell SOC. Near real-time measurements are used to monitor and maintain batteries within an optimal SOC range for improved safety and battery lifetime. Periodically, when the series cells are unbalanced in SOC beyond an acceptable range (they are typically held in a range around 50% SOC for an FHEV), a rebalancing cycle is performed as part of the SOC maintenance, removing or adding charge from each individual cell to a predetermined, matching cell voltage (Andrea, 2010).

Future battery pack sizes are expected to vary greatly by customer preference, with FHEV, PHEV, and BEV batteries ranging from 2-kWh to 30-kWh, with different requirements for SUVs, trucks, and passenger vehicles (Wang C.-Y. , 2011). An ideal attribute for the battery pack would be near-unlimited expansion capacity, to accommodate all requirements for battery power and energy. A modular architecture, with independent, autonomous sensors and cell SOC balancing control, would satisfy this engineering need, with flexibility to address future battery pack uncertainty. However, this architecture has two significant negative attributes. First, the hardware cost is typically higher due to the per-cell "smart" sensing and control circuitry. The second is that the added cell level electronics hardware increases manufacturing complexity.

Ford uses a more centralized architecture on its production vehicles. The architecture contains all control intelligence and most of the sensors, combining multiple functions into a small number of integrated circuits, connected via passive wires to the battery cells. This architecture is low cost and easily manufactured (up to the limit of very high wire counts). However, it has

limited capacity for expansion, caused by one key component within the architecture. Table 5.1 summarizes the two architectural ideas at the extremes (fully centralized or modular) that can be considered. It is desirable to generate a new architecture that can satisfy the three key attributes in the Pugh Chart of expansion, cost, and manufacturability.

Table 5.1: Attributes of Centralized and Modular Architectures

Architecture/Attribute	Centralized	Modular
Expansion	o	+
Cost	o	-
Manufacturability	o	-

5.1: Evaluation of Expansion Flexibility in the Ford Architecture

A Ford product design engineer has been investigating the battery control architecture. In May 2011, as part of the ongoing technical exchanges with Ford, the MIT team (Professor de Neufville and Dr. Van Eikema Hommes) visited Ford and presented to the battery engineering team the idea of designing flexibility into engineering solutions, including flexibility for expansion, discussed in Chapter 2. With the concept of designing for flexibility in mind, the product engineer evaluated the current architecture at Ford.

The architecture is partitioned due to engineering requirements. Many sensor controls in partition A are easily scalable within the centralized unit. For example, there may be on the

order of 5 type 1 sensors in partition A, so an addition of 1 sensor minimally affects the centralized architecture; there is space for this change. However, a key, non-scalable component is an impediment for expansion of the controller, due to footprint limitations when the cell count or battery power increases, limiting the range of applications for this architecture.

The product engineer identified the primary goal for improving expansion: a flexible architecture. The key component is part of the maintenance function, and can be physically separated from the other circuitry and sensors within the centralized controller. The Product Engineer has invented an autonomous architecture, maintaining isolation within the centralized controller. The autonomous architecture solves the problem by pushing the specific maintenance function to the cell level, increasing overall battery pack flexibility for upcoming HEV, PHEV, and BEV vehicles. He has transformed the most constricting part of the centralized architecture into a modular component without adding costly active components. The architecture can be implemented at the cell level with no negative impact to manufacturability. His solution has created flexibility with near-equivalent cost, improving the expansion attribute without negative impact to other attributes. Therefore, no further quantitative analysis for the benefit of flexibility is needed in this case. Table 5.2 summarizes the overall effect of his development.

Table 5.2: Position of Product Engineer's Flexible Design

Architecture/Attribute	Centralized	Product Engineer	Modular
Expansion	o	+	+
Cost	o	o	-
Manufacturability	o	o	-

The product engineer indicated that the MIT-Ford collaboration was a strong influence in his thinking in how to partition the problem for maximum flexibility within the engineering requirements and that he will be applying for a patent for the solution.

Chapter 6: Battery Thermal Control

Hybrid vehicle thermal control is a critical system attribute. It has future uncertainty: as battery technology changes, requirements for temperature control also change. Control systems for well-established battery chemistries, including Lead-acid and Nickel-Metal Hydride, have stabilized and been well understood and are described in detail in Chapter 4. The industry transition to Li-ion chemistries creates additional requirements due to performance uncertainties in lifetime, low temperature response (behaves sluggishly) and high temperature response (performance degradation, and, in extreme cases, danger of explosion and fire) previously noted.

At the top architectural level, the battery pack is designed to limit the interaction between the battery chemistry and environmental elements. The battery cells are fully sealed with external voltage connection points. The cells are placed in an impact-resistant, environmentally sealed metal compartment. The metal compartment is electrically isolated from the vehicle chassis. This is the environment within which the battery thermal control strategy operates.

Li-ion battery packs require an aggressive thermal control strategy. The current standard production architecture for battery temperature control in full hybrid vehicles (FHEV) is sealed-cabin-air cooling. Air intake ports located above the rear seats provide a flow channel for cabin air, drawn via fans, to enter into the battery enclosure, secured in the trunk. The generic solution is shown graphically in Figure 6.1 (EETimes).
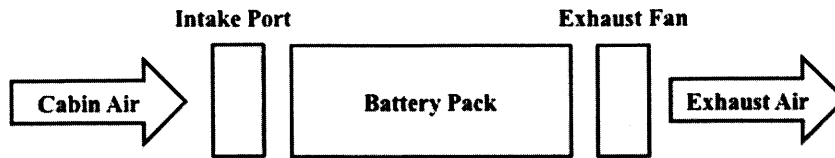
Intake Port   Exhaust Fan

Cabin Air →   [ ]   Battery Pack   [ ]   Exhaust Air →

Figure 6.1: Sealed-cabin-air cooling

The cabin air battery cooling architecture currently meets the requirements for most full hybrid vehicles and is used across the industry in production vehicles. The general concept is that cabin-air will be conditioned to an acceptable temperature by the vehicle occupants, which is also suitable for battery operation, described in Chapter 4.

Although this is a viable solution for current applications, the future holds several uncertainties. First, many PHEVs or BEVs require additional power and energy, using more batteries than the FHEV. The physical size of the batteries limits the ability to package the battery inside the trunk, as evidenced by the choices made by Nissan and GM in designing the Nissan Leaf BEV and Chevy Volt PHEV, both placing a very large battery pack beneath the vehicle. Second, as Li-ion batteries become well understood and technology advances, batteries may be operated at higher thermal loads with fewer cells in order to reduce cell cost and pack size. Similar trends have been observed in the Lead-acid and Nickel-metal Hydride batteries. Third, PHEVs or BEVs may have increased thermal requirements due to the higher dependence on the electric powertrain. Therefore, the cabin-air battery cooling architecture may not be sufficient for these future thermal demands. To insure against the uncertainties in future battery temperature control requirements, alternative battery cooling architectures should be investigated during the advanced battery system and vehicle architecture development phase.

In fact, vehicles in the market already include several cooling architectures different from the cabin air-cooling solution. The Chevy Volt uses underbody-mounted batteries with liquid cooling. The Nissan Leaf uses passive air-cooling with underbody-mounting. The recently released Ford Focus BEV uses a tight temperature control technique with both active heating and cooling elements (Siri, 2010) (Ford). The Leaf has been designed to utilize airflow during driving to cool the battery system. The Volt has suffered from robustness problems due to the negative test results discussed in Chapter 1. The Ford Focus BEV was designed for all environments, with highly regulated temperatures using many components.

In support of Ford, the MIT team has analyzed a group of unique Ford-specific thermal control concepts. The research program with Ford Motor Company required substantial proprietary data exchange. Our real-time support effort is not publishable directly. A comparison between proprietary thermal architectures was completed for Ford; here the technique is described with generic architecture names. The method used will be demonstrated with a sanitized version of the data, using publicly available sources of information as frequently as possible.

6.1: Architecture Evaluation Across Vehicles

In order to compare the technology in use, the Ford engineering team and the MIT research team utilized Pugh Chart analysis (Table 6.1). Inputs for the Pugh Chart came from all areas of technical expertise for solution ranking, with 1 being best and 4 worst. Attributes were also ranked and weighted by priority (not shown in Table 6.1 due to proprietary reasons). Traditional attributes of cost, robustness, packaging, and performance were used in the baseline analysis; the MIT team's participation mainly contributed to the assessment of the Flexibility attribute. For

this portion of the analysis, flexibility reflects the ability of the thermal control system to support the potential thermal loads across vehicle types, FHEV, PHEV, and BEV.

Looking at specific attributes within the chart, Architecture 4 is the best-cost solution, with lowest score winning. It has the fewest unique components, with Architecture 1,2, and 3 each requiring more components at higher cost. Architecture 1 scores poorly on the overall Pugh Chart when flexibility, robustness, packaging and performance are taken into account. It is unable to meet some requirements of the system. Architecture 2, 3, and 4 are potential solutions for all possible vehicles, FHEVs, PHEVs, and BEVs, and therefore more adaptable to future technology and market uncertainties given their high flexibility value. There may also be consumer value to these architectures compared to architecture 1.

Table 6.1: Attributes of a Thermal Control System

(1 = Best, 4 = Worst)

Architecture /Attribute	Architecture #1	Architecture #2	Architecture #3	Architecture #4
Cost	2	3	4	1
Flexibility	4	2	2	2
Robustness	3	4	2	1
Packaging	4	2	3	1
Performance	3	2	1	4
Sum	16	13	12	9

6.2: Flexibility Valuation Modeling Approaches

The flexible valuation modeling approach described in Chapter 2 was used to compare these four architectures for flexibility. In order to develop a model of the potential outcomes, a Monte Carlo simulation was designed to account for the uncertain vehicle mix in potential future sales. There are three stages to developing a flexible Monte Carlo analysis. First, a "fixed forecast" NPV is developed, incorporating all key estimates. A point forecast for market demand for hybrid vehicles is generated using multiple sources of forecasting information. JD Power estimates global hybrid demand at 7.3% of total sales in 2020, or 5.2 million units (Tews & Perlman, 2010). Ford sold 5.3 million vehicles globally in 2010 out of about 72 million total light vehicles sold, for about a 7.4% market share (Stenquist, 2011) (J.D. Power and Associates, 2011). Assuming that Ford will be aggressive in the hybrid market given their wide range of planned products, it is reasonable to estimate that Ford will achieve at least the 7.4% market share of the 5.2 million units sold in 2020, or close to 400,000 vehicles.

In the second stage, sales projections were converted to a normal distribution with uncertainty based on the wide ranges in forecasts that have been seen in the past. Hybrid forecasts are highly uncertain. In 2003, JD Power estimated 500,000 sales by 2008 (Hybrid Market Forecasts, 2006). Realized sales were 314,000 (hybridcars.com, 2009). For 2011 sales, in Q3 2008 JD Power estimate 1,000,000 sales in 2011 and a market share of over 6% (Omotoso, 2008). Actual sales were 270,000 and a 2.1% market share (Hybrid Cars, 2012). These are not exceptions; there are many expert predictions of hybrid sales with very similar deviation (Hybrid Market Forecasts,

2006). Uncertainty tends to increase with the number of years from the date of forecast. It is reasonable to expect that a 5-year timeframe will differ from 10-years and 15-years.

Demand is the primary driver of uncertainty and forecasting, as described in Chapter 2, with demand itself driven by multiple factors, including recessions, regulations, and gas prices. Given the uncertainty in predictions, we'll assume from the prior forecasts that Ford sells 400,000 electrified vehicles in 2020, but acknowledge high uncertainty of ~200,000 as a standard deviation when building the demand model. We use the median of 400,000 to provide the peak of a normal distribution. One standard deviation is assumed to be 200,000 a 50% value from the peak. A more sophisticated median, deviation, and distribution could be acquired from propriety data, but are not included in this thesis.

Finally, a flexibility rule is incorporated for any uncertainty that might impact sales. A flexibility rule is an "if" statement within the simulation that represents a decision management might make, given changing circumstances. Management "exercises the option" that flexibility represents when conditions arise. For the garage case in Chapter 2, management would expand based upon prior year demand, e.g. "if prior year demand > x, expand 1-level in next year".

In this simulation, it is believed that there is a small chance that the PHEV will be the dominant sales driver in the future. If that outcome arises, the team will re-engineer all models to capture this market. As an example, changing Architecture 1 into Architecture 2 will incur large NRE and tooling costs as the changes are made. Architecture 3 and 4 overlap strongly and the modifications are less significant to capture this new market without additional cost. A more

expensive, but more flexible, architecture could be used for rapid transition to capture the PHEV market.

This simulation's primary assumptions and uncertainties are:

- Relative unit cost (Estimated additional cost of thermal components, using expert estimates (not detailed) at beginning of project)
  - Architecture 1-$60, Architecture 2-$60, Architecture 3-$80, Architecture 4-$10
- Uncertainty in demand (due to fuel prices, CAFE, etc.)
  - Demand: 180,000 in 2015 rising to 400,000 in 2020 total for PHEV, FHEV, and BEV in Ford's fleet.
- Risk for demand to shift to PHEV/BEV, creating one-time Non Recoverable Engineering cost (NRE) and manufacturing tooling cost to shift from air-cooling to alternatives:
  - Small chance of dominating in later years (10% by 2026)
- Cost of NRE and manufacturing tooling investment
  - Change architecture from one to another due to PHEV/BEV preference
  - ($x per vehicle style for minor change to $y for major changes, sanitized, numbers proprietary)
- Some architectures may increase consumer comfort and convenience. In this model, such a feature was valued at $100 per vehicle increase in customer's willingness to pay. This number is uncertain, but is used to help differentiate

architectures. Additional marketing research is planned to better quantify the value of such a feature.

The initial model used 2000 Monte Carlo simulations, randomly sampling consumer demand. The simulation was designed with a user-input page for Ford's proprietary data for increased accuracy beyond the initial study using publically available demand and sales forecast data. The results of the Monte Carlo simulation for all four architectures are presented in Figure 6.2.
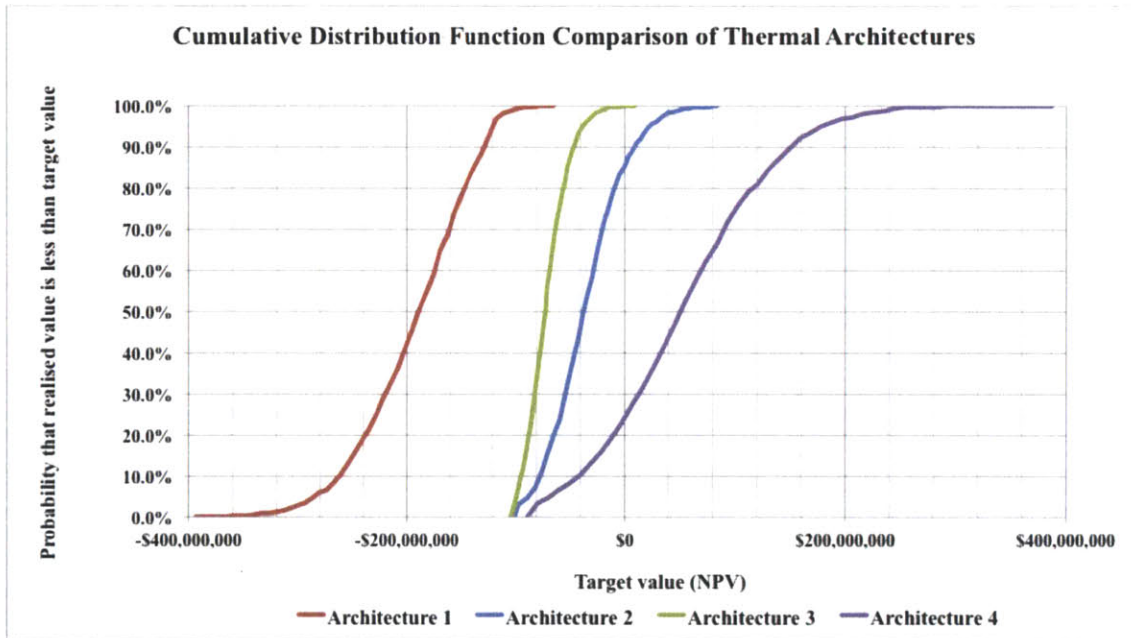

Figure 6.2: NPV Comparison of Thermal Architectures Under Uncertainty

The simulation results indicate that Architecture 2, 3, and 4 have better NPV cumulative distribution curves than Architecture 1. This result is caused by two factors. First, Architecture 2, 3, and 4 can be used for PHEVs and BEVs as well as FHEVs, capturing future sales without additional engineering cost that would be required for architecture 1. Second, Architecture 2, 3, and 4 are associated with positive consumer willingness-to-pay values due to secondary effects.

Additionally, architecture 4 has less components than 2 and 3, further driving down the unit cost, making it the leading choice among the four alternatives.

Another interesting observation is that the flexibility rule for dominant vehicle type has a small impact. The model shows that customer preference for FHEV vs. PHEV or BEV will have limited impact on design flexibility due to the strong influence of willingness-to-pay valuation. Figure 6.3 shows a simulation of NPV *without* the added value of the customer comfort and convenience feature, to better understand the impact of assigning a secondary effect value to the thermal architecture. It is clear that architecture 2 has a small advantage over architecture 1 due to flexibility in this case (i.e. the impact of NRE and tooling costs during a FHEV to PHEV/BEV transition). The results again indicate unit cost as the core driver to favor architecture 4 valuation.

This second simulation illustrates a key challenge to conclusions based upon the macroeconomic model. Although the flexibility analysis clearly indicates that architecture 4 is the most valuable architecture, due to its low unit cost and willingness-to-pay value, the simulation is missing a critical element: the risk that the anticipated technical solution will not meet requirements once it is designed and integrated into an actual vehicle. The team is looking for the lowest cost solution that *meets performance needs*.
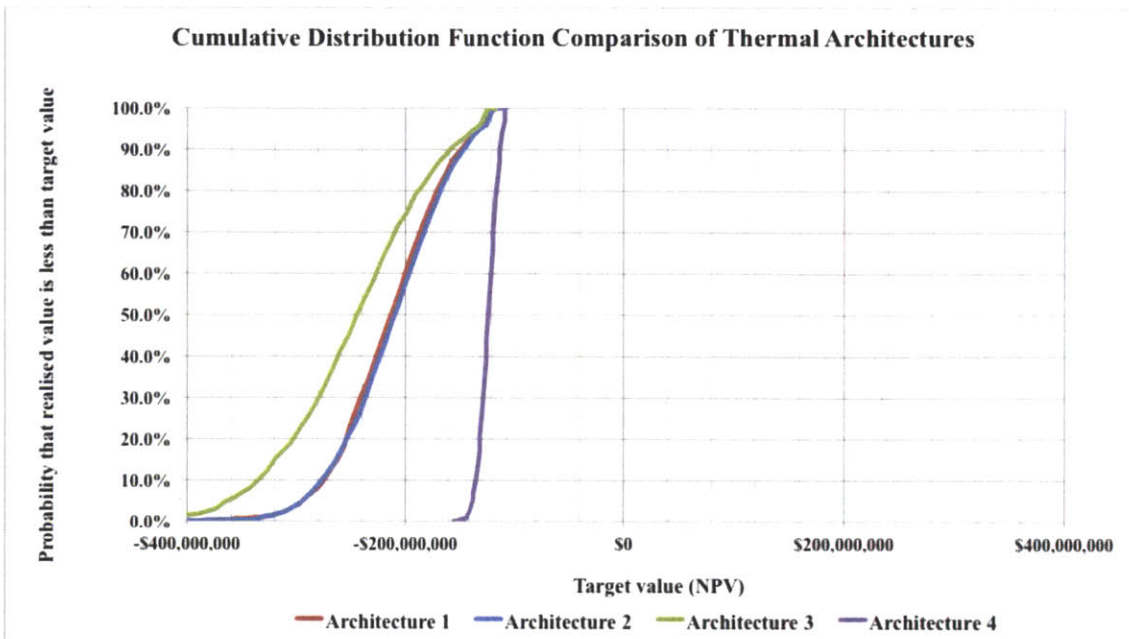
Cumulative Distribution Function Comparison of Thermal Architectures

Architecture 1 — Architecture 2 — Architecture 3 — Architecture 4

Figure 6.3: NPV Comparison of Thermal Architectures Under Uncertainty without Willingness to Pay

6.3: Developing Flexible Cooling System Solutions

After evaluation of flexibility among potential future vehicles (FHEV, PHEV, and BEVs), there can be additional flexibility within the potential solution space. Many required performance attributes are undefined for electric vehicles. E.g., will acceptable operation of full heat removal be required for ambient temperatures of 30 C, 35 C, 40 C, 45 C or 50 C (or other)? Is limiting fuel economy and horsepower acceptable due to high temperatures in more aggressive environments and, if so, to what level (E.g. driving in Death Valley)? What will be the tradeoff for the number of cells vs. power? Overdesigning (and increasing cost) by using more cells operated at lower power will decrease Watts/unit area, while using less cells but operating them more aggressively will increase Watts/unit area. What is the requirement on Watts/unit area? New hardware products tend toward overdesign for risk reduction, at a high cost.

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Uncertainty in final requirements, both due to uncertainty in end product goals as well as base technology, makes the ability to switch between architectures very valuable at this early stage of the product design process, preventing product delay or overdesign cost. In addition, the ability of the architecture to be accepted into a vehicle program and, beyond that, to be manufactured will greatly affect the architecture choice. Architecture 4 may provide the highest expected NPV due to its low unit cost, according to Figure 2, as minimal components are required. At this stage of analysis, approximate success metrics can be used to evaluate these technologies. Given the wide range of uncertainties in both technology and performance, architecture 4 may have a 60% chance of performance success, based upon expert estimation. With acceptable battery performance, there would be a 90% chance of the battery thermal control technology being accepted into a vehicle program. If the manufacturing team is brought into the program early enough, a successful design should have a 95% chance of being manufacturable. Looking at this risk of failure, the choice for architecture investment is no longer clear. Maintaining flexibility due to uncertainty in technology will provide value to the engineering team and can mitigate risk taken in developing the lowest unit cost solution. Strategic architectural planning of each concept will impact detailed engineering planning.

The management decision process typically contains a series of "gates" (providing flexibility), with uncertainty (and value) at each phase of program design, and decisions to be made about the direction for the next step. A manager typically makes phased decisions (described in Chapter 3) based upon continued incoming data. A decision tree structure, using Monte Carlo NPV simulations with the same estimates for unit cost, valuation, and demand as Figure 6.3, can be used to model this phased decision making process.

Figure 6.4 shows the value of the architecture 4 investment program given uncertainties in technical performance, vehicle program acceptance, and manufacturability. Chance nodes (representing the current expert appraisal of the chance that the research team, vehicle program, or manufacturing group will decide to accept or reject the design) are represented by red circles. Blue triangles indicate end points with the respective "total probability" of that outcome. The green "Decision" value indicates the risk-adjusted value of the project. A tree has been created for each architecture, with each tree representing a potential decision; the tree has been edited for clarity, showing only the architecture 4 decision, as this is the most valuable.
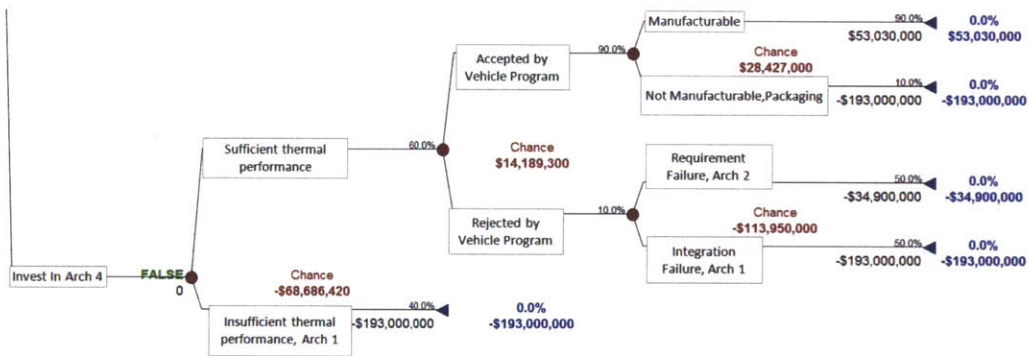

Figure 6.4: Decision Tree of investment in architecture 4 only

If the architecture were to fail at any stage, it would be necessary to default to a more established solution, a high-cost, "gold-plated" solution, or suffer product delay or cancellation. In a phased decision making process, the probability of success in performance, in acceptance to a vehicle program, and in the ability to manufacture are large risks to program success. The NPV is adversely impacted by the need to default to an alternate, less valuable architecture and could cause abandonment of the vehicle program. These risks can be mitigated by investment in a flexible architecture. At this early stage of development, when performance metrics are unclear,

the team has asked the following flexibility question: "Is there a way to rapidly transition from one architecture to another if the chosen architecture does not meet the as yet unwritten specification?"

After evaluating flexibility from a real options perspective, many flexibility techniques described in Chapter 1 can now be utilized and there will be a complete answer to steps 1-5 from Chapter 2. For example, is there enough overlap in these architectures that Ford could design something similar to a platform? Or, can design for commonality be established as a flexible solution that can be used as a real options technique? The thought process of designing for commonality might reduce overall risk by developing a flexible architecture, and enabling a phased decision making process with less risk. An investment in architecture 4, with the acknowledged performance uncertainty, becomes viable provided that there is a conceptual design investment in the alternate architectures. The design will have additional value to Ford, as engineering time for design of a "common" architecture is inexpensive; delays in implementation, or late stage "surges" of effort, are very expensive. A substantial impediment is the non-common components, including additional space or routing, which must be reserved until the architecture is known. For example, should the team attempt a novel architecture, but reserve space for a gold-plated version? At this early stage in the development of architecture, reserving space in a vehicle program is inexpensive. The team is protecting against downside risk and potentially capturing upside gain by investing in the inexpensive architecture first, with low unit-cost and viability across multiple vehicle architectures, while maintaining a highly compatible conceptual development of architectures that are more probable for success (but more costly on a per-unit basis).

The simulation in Figure 6.5 shows greater value for Ford with investment in a commonality-based solution among architectures 2 and 4, due to the increased value of the fallback architectures. The total project valuation at each end node is represented by the 50% value on the distribution curve of outcomes.
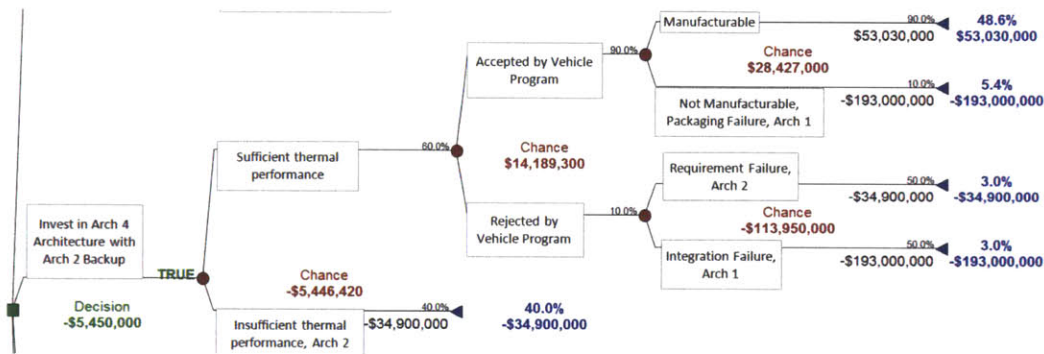

Figure 6.5: Decision Tree representing phased decision making with architecture 4 and architecture 2 fallback

The simulation incorporates engineering, manufacturing, and unit cost. The expectation value for the project outcome is negative for both cases; the goal is to minimize the total cost of the project, as we are not assigning substantial positive value to thermal control. The total value of the project has been reduced to a $5 million dollar loss rather than the initial $69 million dollar loss, $64 million dollars in savings through the phased decision making process.

A loss of $5 million dollars does not sound particularly appealing during a business case discussion! However, this simulation is focused primarily on cost to the program rather than the revenue side, so a decrease in total cost is a substantial benefit to the bottom line. Revenue is

mainly assigned to the system as a whole as opposed to individual components. Thus, a large reduction on the cost side, although still negative, will have an equally large impact on net profit.

6.4: Additional Considerations in Uncertainty in Requirements

Further work on the model has been accomplished, but due to the proprietary nature of the arrangement, the details of that work are not in this thesis. A brief overview of additional model components includes:

- The ability to provide equivalent thermal response given a baseline fuel economy benefit
- The warranty risk due to varying components in each architecture
- Brand risk due to either component failure or performance lag

This portion of the financial model has been used to further quantity the decision process. The added model fidelity provided further data for the team to determine where design for commonality should be applied and for which architectures.

Beyond the existing model, there are two areas of uncertainty that may be probed in future research. First, battery chemistry should improve over the next 10-15 years. There is also uncertainty in new potential sources of electric energy. Will hydrogen fuel cells be used to create energy for an electrified platform? Will a Lithium-air battery overtake Lithium-ion? These technical opportunities may impact thermal design, and should be approached over a long-time horizon. The effort in this thesis was for long-time horizon market uncertainty and short-

time horizon technical uncertainty; long-time horizon technical uncertainty is a natural extension of this work and would be a viable follow-on project.

Second, there may be concern over events that occur well outside of the probability estimation of the team, either due to a lack of data or a miscalculated risk assessment. These events may have high impact to the company. While it is true that a company cannot prepare for all use cases, certain events may occur due to a lack of preparation. When faced with high uncertainty in technology and markets, the choice of the upper and lower bounds of the simulation parameters can be made to reflect our decision on how much uncertainty we want to prepare for, but must also be balanced with the impact of the cost of "insurance".

A negative event in performance will be more likely in a design based upon limited technical data. Even with strong technology knowledge and all system design tools available, it is unlikely that GM would have predicted the public damage caused by the NHSTA testing of the Chevy Volt, discussed in the Chapter 1. To GM, this event has caused great damage. Was this an unknowable event or a calculated risk, i.e. could the battery pack designer have predicted the event or not? An investigation of this case could provide useful in further understanding the uncertainty in battery pack design and assist in developing appropriate upper and lower bounds for future simulations.

Chapter 7: Summary

The choices made by Ford for this program have been informed by the discussion of uncertainty, flexibility, design for commonality, and real options based financial analysis. The details of their technical choices are not part of this thesis, but the general thought process used has been illustrated with the discussion shown through real-time support of the decision making process.

The team adopted a commonality-based flexible solution, and can transition from one architecture to another based upon changes in vehicle requirements, with little impact to the vehicle program cost and timing. Acknowledging the risk of meeting requirements and investing in a flexible architecture, the team will easily be able to "fallback" to a more aggressive architecture solution if the lowest unit cost architecture is unable to meet requirements. Beyond the design stage, if the architecture is rejected at the vehicle program or manufacturability level, the team will still be able to change rapidly due to the prior investment in flexibility.

Revisiting the core question of this thesis: will flexibility and real-options support of advanced technology development lead to novel choices by the engineering team when applied to an on-going engineering design project? For this project, the answer is yes. The real-time support of the Ford engineering team has shown the value of flexibility and real options in the product design phase. Challenged with questions of flexibility, the Ford team has established novel solutions (with patent applications) to enhance the value of their design project by using the real-options framework to evaluate the value of their product design choices.

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