2013-05-17

A Mathematical Model for Quantifying System Evolvability Using Excess and Modularity

Morgan Wesley Parry Tackett
Brigham Young University - Provo

A Mathematical Model for Quantifying System Evolvability

Using Excess and Modularity

Morgan W. P. Tackett

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Christopher A. Mattson, Chair
David T. Fullwood
Tadd T. Truscott

Department of Mechanical Engineering

Brigham Young University

May 2013

ABSTRACT

A Mathematical Model for Quantifying System Evolvability
Using Excess and Modularity

Morgan W. P. Tackett
Department of Mechanical Engineering, BYU
Master of Science

An important factor in system longevity is service-phase evolvability, which is defined as the ability of a system to physically transform from one configuration to a more desirable configuration while in service. These transformations may or may not be known during the design process, and may or may not be reversible. A study of 210 engineered systems was performed and found that system excess and modularity allow a system to evolve while in service. Building on these observations, this thesis introduces mathematical relationships that map a system's excess and modularity to that system's ability to evolve. These relationships are derived from elastic potential energy theories. The use of the evolvability measure, and other related measures presented herein, are illustrated with simple numerical examples and applied to the design of US Navy nuclear aircraft carriers. Using these relationships, it is shown that the Navy's new Ford-class aircraft carrier is the most evolvable carrier designed to date. Though the evolvability relationships introduced here are generically derived based on excess and modularity, the aircraft carrier example presented considers only the system excess.

Keywords: reconfigurability, modularity, flexibility, adaptability, transformation, evolvability, service-phase evolution, system changes, system space, reconfigurability envelope

ACKNOWLEDGMENTS

First, I thank my dear, sweet wife for all of her love and support through my graduate school experience; this would have been a lot harder without you. I thank my mother who has always been supportive of my ambitions and continues to be one of my biggest fans. I acknowledge all of the hard work and late nights of my graduate advisor, Dr. Chris Mattson, on my behalf, and appreciate him as the man who taught me to not shy away from hard things. I express my appreciation for my committee members, Dr. Fullwood and Dr. Truscott, for their help in making my research better. I thank my band of brothers: Brandon, Jaron, Dallon, and W. C. the III, for all of their encouragement and support. Go Team Tackett! People have often said to me, "I can't believe you are getting a Masters degree in engineering." Thus, I thank most importantly, my Father in Heaven for endowing me with the ability to accomplish something that is unbelievable.

Lastly, I would like to recognize the National Science Foundation (Grant CMMI-0954580) for funding this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

C	Measure of excess in a system
M	Measure of modularity in a system
E	Measure of a system's evolvability
U	Measure of utility from excess and/or modularity to enable future evolution
g_c	Gain per unit excess
g_m	Gain per unit modularity
n_{fc}	Number of excess factors
n_{fm}	Number of modularity factors
B	Measure of benefit (utility) from ideas using excess and/or modularity
$n_{g_{c_j}}$	Number of gains using the *i*th excess factor
$n_{g_{m_j}}$	Number of gains using the *i*th modularity factor

CHAPTER 1. MITIGATING EMERGENT SYSTEM BEHAVIOR THROUGH SYSTEM EVOLVABILITY

The objective of this thesis is to develop quantitative relationships for evaluating system evolvability, which is presented in Chapter 2. The broad objectives of this research are presented in this chapter to show the need and foundation for a quantitative model of system evolvability. The general goals are to discover principles governing the evolvability of complex engineered systems as future needs emerge after deployment, and understand how those principles can be connected to value-driven design. This research can provide a better understanding of the extent to which system evolvability could be used to reduce negative emergent system behavior. Furthermore, quantitative measures of evolvability can be used in conjunction with effective and existing decision making tools to improve the system design process.

1.1 Complex Engineered Systems

Complex Engineered Systems (CES) are unusually challenging to design. This is because CES (i) have elaborate internal interactions that couple numerous subsystems and disparate organizational and technological disciplines [3], (ii) have long development times [4], (iii) remain in service for extended periods of time [5], and (iv) exhibit unanticipated emergent behavior that is often detrimental to system functionality and longevity [3].

Although CES provide essential benefits to modern society, the US workforce is not currently well equipped to successfully design them – especially in the present environment of growing complexity [3, 6]. For example, the Joint Strike Fighter (JSF) has grown in complexity over its predecessor (F-16 Fighter Jet) by one order of magnitude in number of subsystems and two orders of magnitude in subsystem interactions [7]. As a result, the JSF design program is at least five years and 117 billion dollars over budget [7–10].

Furthermore, because it is prohibitively difficult to predict all potential use scenarios and operating environments [11], CES often operate in scenarios very different than those originally conceived. Due to the challenges in designing CES, they can have limited performance flexibility once deployed and in service [12]. This means that in-service systems are not designed to react well to new and emergent system needs. Though the understanding that numerous inherent interactions and the inevitability of emergent behavior are at the root of CES failure [3], the understanding of how to handle them is severely limited [13–17].

1.2 Top-Level View of Research

Two general questions for this research are: To what degree can a system's ability to evolve in-service mitigate negative emergent behavior? Also, what principles govern the design of systems that are capable of evolving in response to such behavior? Expected outcomes of this research include: (i) an empirical study aimed at discovering triggers and approaches for service-phase evolution; (ii) quantitative measurements and representations of service-phase system evolution; (iii) quantitative assessment of the expected utility benefit of CES evolvability; and (iv) exploration into the extent by which expected system longevity and narrowness of task influences the design benefits achieved via evolvability. The contributions of this thesis focus directly on outcomes (i) and (ii).

1.2.1 Scope of the Overall Research

Successfully understanding and handling the inherent interactions and emergent behavior of CES will require the efforts of many researchers and potentially take decades. Fortunately, there are many who recognize the importance of improving these capabilities in CES design [6, 14, 18, 19]. Individually, however, steady progress can be made in small steps. Such steps, which are centered on studies of fundamental CES design difficulties, will form a foundation for tackling this extremely difficult and unequivocally essential job to successfully design CES. Ultimately, the scope of this research is centered on one fundamental CES design difficulty – handling emergent system needs and mitigating negative emergent behavior from those needs for in-service systems.

To further clarify, new needs result in new system requirements; new system requirements result in new system output and potential new system design features. For this purpose, we will refer to this as need-driven emergent behavior. The necessary decision regarding need-driven emergent behavior is to decide if the new system output meets the new system needs. On the other hand, environment-driven emergent behavior can be observed. Under this scenario, the system is exposed to a new unanticipated environment. The new environment results in new system performance; new system performance results in changes to how well the system meets the original needs. The necessary decision for this scenario is to assess if the degradation of system value is tolerable or not.

In summary, the broad focus of this research is need-driven emergent behavior for in-service systems. The objectives are threefold: (i) to discover in what ways a system's ability to evolve affects the system's ability to positively react to emergent needs; (ii) to understand the relationship between system complexity, narrowness of task, and system evolvability; and (iii) to discover the principles that govern the trade-offs between these concepts with the intent to improve decision making in CES design.

1.2.2 Potential Impact

The security and economy of the modern US society are inextricably tied to CES. These systems include commercial aircraft, telecommunication satellites, military weapon systems, and many others. In the present environment of growing complexity, today's CES are at risk of becoming less flexible in service. This ultimately means less system agility, which for example will result in higher commercial aircraft development costs, and consequently, higher air travel costs for travelers. In addition, satellites and deployment costs will be more expensive, leading to higher telecommunication costs for end users. Furthermore, CES are at risk of having more expensive weapon system development and deployment, which means higher taxes for US citizens. Simply stated, every US citizen would benefit from a stronger national engineering workforce that is more fully equipped to design and sustain CES. This research aims to improve the ability to design agile systems that avoid such unwanted cost increases to society.

In February 2012, the NSF and NASA held a workshop on CES [6]. This workshop convened approximately 120 individuals from academia, government, and industry disciplines to discuss the needs and promising directions in the area of CES design. A recurring theme that emerged from the workshop was the concept of system evolution and the need to control and capitalize on it. This research directly seeks to understand in-service evolution, the relationship between system design, and the potential for systems to evolve and succeed through evolution. Specifically, this research explores the relationship between emerging needs and the ability to meet those needs through principles of system evolvability.

1.3 Detailed Description of Four Research Areas

For systems that can be easily replaced, or that are designed for short life cycles, generational evolution has proven to be an effective design strategy [20,21]. However, as the expected life cycle of a system increases or replacement becomes more difficult, evolution extending beyond the design phase is often necessary [22,23]. This is driven by the inability of predictive models to adequately guide the design to full functionality until the system has been put in service [10,24]. Physical state changes of an in-service system have been studied to achieve multi-able systems [25–28] or robustness to planned, yet uncontrollable changes [29,30]. However, state changes in response to unforeseen needs have been significantly understudied.

Two assumptions drive this research. First, certain high-level system functions will always remain consistent. For instance, an unmanned aerial vehicle (UAV) will always have functions associated with flight. The second assumption is that while the future states of the system are uncertain, the unforeseen needs are bounded. Continuing the UAV example, desired aircraft speed must be greater than zero and constrained by some upper bound. Here, the desired speed represents an input flow into the system model. Using this construct, three potential scenarios result: (i) system function is consistent while input flows change; (ii) input flows remain consistent while functionality is added/removed; and/or (iii) system functionality is added/removed and input flows undergo change.

A value model is based on the proposition that technical performance measurements, system properties, and the utilities associated with them, can be equated to a measure of monetary value. This is particularly useful for optimization methods, as value need only be a relative measure of goodness. A value function that facilitates the decision between system replacement, rejecting the new degraded performance, or evolving the system to achieve desired performance, may be represented by:

$$V = f(\text{Ability to meet needs, evolvability strategy, time in service, reliability, cost}) \tag{1.1}$$

Many methods exist to quantify the reliability and cost of a system once components have been specified [31–33]. As such, the first three terms in Equation 1.1 represent characteristics of evolvability that require scientific investigation if designers are to understand and manipulate service-phase evolution. To use value in a quantifiable and comparative manner, it is important to first understand how to measure the ability of a system to accommodate unforeseen needs. Specifically, it is important to characterize the potential in a system and understand how product architecture decisions enable or constrain realized opportunities.

1.3.1 What is an Effective Quantification of a System's Ability to Meet Unforeseen Needs?

By considering unforeseen needs, the future is not a set of states that can be described probabilistically; rather, there is a set of future state paths that may prove to have a higher dimensionality than the designer perceives. The concept of service-phase evolution is a useful and intriguing way to consider handling system uncertainty. This is depicted in Figure 1.1 and described below.

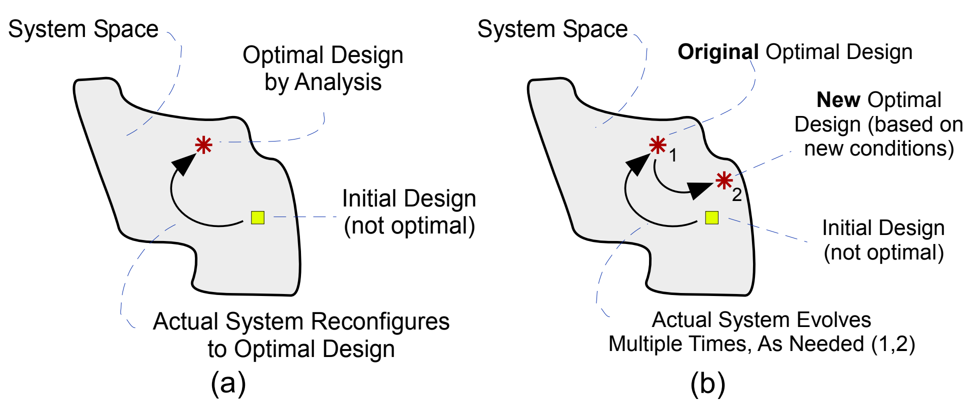

Figure 1.1: System space of an evolvable system where a system reconfigures once (a) and evolves to needs (b)

Figure 1.1(a) shows a *System Space*, indicating the set of system designs that satisfy system requirements. For the purpose of this simple illustration, anything within the space is feasible, while anything outside is infeasible. Within the system space, an optimal system design exists (indicated by the star) and is found by analytical methods (for this simple illustration). Assume that upon pursuing a physical realization of the optimal design, the designers find that the initial system (indicated by the box) is sub-optimal. Having been designed to be reconfigurable, the initial system reconfigures to the desired optimal state. Figure 1.1(b) indicates that the optimal system goals may change with time, and that the evolvable system follows the new goal as often as needed.

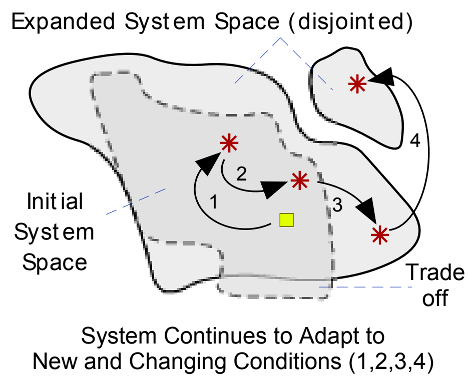

Figure 1.2: Evolved system space in response to unforeseen intent

Now, consider a more extreme scenario. After operating for many years, the needs placed on a large-scale engineered system significantly change. In response, the System Space drastically morphs to accommodate these new requirements (see Figure 1.2). An evolvable system could use its ability to physically adapt, potentially even while in use, to the new optimum in Figure 1.2 identified by Configuration 3. Modular reconfigurations at some later time could also allow the system to transition to the requirements dictated by Configuration 4.

Capitalizing on service-phase evolution will allow system designers to focus less on characterizing uncertain needs and conditions, and more on the design of systems capable of a wide range of performance. Characterizing the System Space provides a region in which a system exists. The next research question explores how product architecture decisions govern movement within the System Space.

1.3.2 What Relationships Exist Between System Architecture Decisions and Evolutionary Capabilities?

System decompositions exploring product architecture often yield insights into the organized grouping of functional elements and the definition of system interfaces. The interaction between function structure and internal interfaces in product platform design, for example, has led to the definition of modular and integrated architecture strategies [19, 31]. Characterized by their changeability, modular architectures are comprised of separate components that can be connected and re-arranged in ways that do not affect other aspects of the system [34–36]. This ease of changeability, however, often comes at the expense of overall system performance. Conversely, integrated architectures have internal interfaces spanning multiple components or functional elements. It has been shown that, especially for complex systems, an integrated architecture strategy results in systems with greater performance [19, 31]. Yet, the coupling enabling this performance makes these systems more difficult to redesign or change as new needs arise.

For systems capable of changing their configuration after deployment, a major decision centers on when these transitions should occur. Research in reconfigurable system design [26] has described this notion by differentiating between off-line and on-line configuration changes. Off-line changes occur during the down-time between operational uses of the system. Patterson et al. and Pate et al. [37, 38], for example, have explored how a set of interchangeable engines and wings can be used to change the physical configuration of a UAV between sorties. In contrast, on-line configuration changes allow a system to continue operation while it undergoes the transition process.

Simultaneously considering the relationship between product architecture and configuration-state planning highlights the challenges of achieving service-phase evolution. As integrated product architectures are often more difficult to change, a value-maximizing proposition may involve pre-planning a majority of the system potential movement prior to deployment. Accommodating unforeseen user needs in this scenario might be more effectively accomplished using adaptability, often signified by continuous domain changes in the system potential. If a modular architecture strategy is chosen, the ability to plug-and-play components can lead to discontinuous, but larger, changes in the system potential. Furthermore, each choice may require strategic "over-design" to certain elements of the product architecture.

The objective of this second research question is to understand the extent by which different product architecture strategies can meet unforeseen needs. In sum, these first two research questions are designed to help clarify how system architecture decisions impact evolvability, and how the impact of the configuration change can be measured. The remaining two research questions explore how expected system longevity and narrowness of task impact decisions regarding the extent of service-phase evolution.

1.3.3 How are Service-phase Evolution Strategies Driven by Expected System Longevity Knowledge?

To some extent, all systems are capable of undergoing service-phase evolution. However, implementing this approach for all systems may be grossly ineffective. Certain systems (e.g., consumer products) are specifically designed for short life cycles. This decision is often made for products characterized by markets that are rapidly changing or experiencing technological breakthroughs, and for products that are quickly consumable. For example, cell phones from a decade ago have nearly no evolutionary capabilities. As these systems have become more "smart", service-phase evolution has appeared through software with downloadable apps to customize the device (increasing the user's perceived value of the device). Opportunities for hardware evolution in short life cycle consumer goods are nearly non-existent.

Complex systems, on the other hand, are significantly more expensive and often have longer expected service lives. For instance, six space shuttles were used for manned space flights from 1981 to 2011. Special mission requirements necessitated service-phase evolution that led to orbiter add-ons, including orbital laboratories, boosters for launching payloads farther into space, logistics modules, and Canadarm. Missions included manned space flight, scientific experiments, space station docking, spacewalks, and satellite launching and repair [39, 40]. Additionally, the orbital laboratory Spacelab was itself evolvable, using a modular architecture to support special missions [41]. Further, commercial systems such as satellites [42, 43] could demonstrate service-phase evolution by reconfiguring their antennas in response to contracts that are changed or renewed every five years. This configuration change is necessary to control where the antenna points (which market area) and the size of the swath to maximize efficiency.

A major challenge in system design is predicting the outcome of design decisions as they are being made. This challenge is further aggravated by the fact that decisions at the early phases of system design often have the greatest impact. [44]. Research in design-phase evolution has explored the concept of inheritance, claiming the next generation of a system combines old and new components [45]. Mechanisms of variation and selection are applied in response to changing contexts or needs. Once a threshold of change is reached, a new system is created that inherits properties, components, and infrastructure from the previous design. Complex engineered systems, however, can require initial investments that prevent frequent replacement. When a system's full lifespan is considered, Epoch-Era analysis [46–48] can be used to understand the effect of changing needs as a function of time. Each unit of time, or an epoch, is a period of fixed needs and operating conditions. Using the following construct, the objective of this third research question is to explore how the value of evolution is impacted by expected system longevity in the presence of unforeseen needs.

1.3.4 How does Narrowness of the Task Drive the Need for Service-Phase Evolution?

Finally, the expected longevity of a system may not be the only motivation for exploiting service-phase evolution. Rather, the range of tasks required of the system often drives the need for evolution. The F-117, for example, was designed in the early 80's to conduct air-to-ground missions. Only one variant of this aircraft was ever created and the aircraft is no longer in service [49].

In contrast, the Lockheed C-130 Hercules (see Figure 1.3) has been enormously successful because the versatility of its design imparts the ability to perform many different tasks. Designed in 1951 to meet the needs of the Korean War [50], initial design requirements specified a certain cargo capacity, the ability to take off from short airstrips, and the ability to fly slow enough for paradrops. Service-phase evolution has since allowed the C-130 to be successfully used as a cargo transport, a refueling aircraft, a weather reconnaissance aircraft, and a combat gunship; these are only a few of the C-130's 52 variations [51, 52]. The C-130 is still in production today.

As the C-130 had a broader scope of possible missions, a greater value from service-phase evolution was achieved. The F-117 – much like a finely-tuned sports car – had a narrow range

Figure 1.3: Lockheed Martin C-130 Hercules

of tasks that limited the value of service-phase evolution. Previous work by Lewis et al. [53] developed a method to traverse the Pareto frontier (set of non-dominated design solutions) of a single concept to account for the changes in environment/need over time. This methodology has been further extended to identify products that traverse the Pareto frontiers of a set of diverse concepts [29,54]. Ultimately, the objective of this final research question is to explore the relationship between narrowness of task, system value, and service-phase evolution strategy.

1.4 Key knowledge Gap from the Literature to Address

We believe that there are various existing systems that have successfully evolved in service. Some were specifically designed to evolve, while others have done so serendipitously. As such, the principles of successful in-service system evolution exist, however unarchived they may be. An examination of 210 products and systems has led to the extraction of general measures of system excess and modularity, which enable system evolvability (see Appendix A).

Current design tools for system evolvability from the literature are provided in Section 2.1 of Chapter 2. Although system evolvability tools exist, they do not individually provide rich enough information to understand evolvable system interactions and System Space characterization. While many changeable and reconfigurable systems exist, there is no established manner of assessing the value of such a system, especially in the presence of unforeseen user needs. Further, a recent paper discussing the future of Value-Driven Design (VDD) [14] has highlighted the increased need for use, validation, and dissemination of this approach in engineering design research. Therefore, in Chapter 2, we develop metrics that characterize system evolvability and provide greater understanding of system possibilities within system evolution.

CHAPTER 2. MODEL FOR QUANTIFYING SYSTEM EVOLVABILITY

2.1 Introduction

In this section, we reiterate pertinent background information for the development of system evolvability models. Complex Engineered Systems (CES) have complex internal interactions that couple numerous subsystems from disparate disciplines, making them extremely challenging to design. *Design-phase evolution* is the process by which such systems evolve from embryonic ideas, to rough embodiments, to refined architectures. This kind of evolution is the primarily goal of the system design, engineering design, and product design process.

However, because CES remain in service for extended periods of time where conditions change, it is prohibitively difficult to predict all future operating scenarios and environments while the system is being designed. In contrast to design-phase evolution, *service-phase evolution* is the process by which an in-service system physically transforms from one configuration to a more desirable configuration. This transformation may be reversible should the need for system survival demand it.

The desire for service-phase evolvability stems from the belief that systems capable of evolving to meet unforeseen needs, environments, and market opportunities have safer, more long-term value than those that do not [6]. This belief is supported by the literature. Hanisch and Munz, for example, discuss how the evolvability of manufacturing systems is necessary to mitigate emergent behavior due to human deficiencies and changes to the goals or focus of the system [55]. The need for adaptable product platforms is discussed by Madni, who states that architectures will need to evolve because of the emergence of new technology, changes to the concept of operations, and the repurposing of the platform for new missions [56]. Service-phase evolution is also proposed as a means of increasing system sustainability and robustness/resiliency [57].

Yet, while the need for service-phase evolution is soundly established in the literature, our understanding of how to best realize such capabilities is not fully developed [58]. Toward this goal, Beesemyer et al. discuss three important factors that must be understood when designing for service-phase evolution: 1) the trigger of the change, 2) the agent making the change, and 3) the predicted system lifecycle [59]. Patents and products with flexibility were studied by Keese et al. to generate principles that could guide designers interested in leveraging evolvability in the future [60]. Twenty-four guidelines were generated in this work across the topic areas of modularity, parts reduction, spatial considerations, interface decoupling, and adjustability. Use of these principles has been demonstrated when leveraged with Change Modes and Effects Analysis (CMEA) [61] for future evolvability [62] and with the definition of High-Definition Design Structure Matrix (HD-DSMs) capable of modeling the interactions between subsystems [63]. A process exploring evolvability through modularity was also recently introduced by van Beek and Tomiyama by linking workflow, function-behavior-structure models, DSMs and interface identification, and stakeholder analysis [64].

A limitation of the above approaches is that they mainly serve to establish guidelines for a designer. More quantitative approaches that focus on service-phase evolution typically try to capture the value associated with such a system. Sandborn and Herald propose the use of Bayesian decision networks as a way of measuring system viability [65]. In their work, viability is an aggregation of system producibility, supportability, and evolvability. Likewise, a process linking the changes necessary to a system, the cost model, and net present value is introduced by Suh et al. in their discussion of flexible product platforms [66]. This work is further developed with the introduction of a Delta DSM approach capable of better handling uncertainty and estimating the probability associated with a change in net present value [67]. Finally, an approach for calculating an evolvability advantage is introduced by [68] who use Epochs as static snapshots of the system. In this work, Monte Carlo simulations and Markov probability matrices are used to analyze the execution of "change mechanisms" [68].

Motivated by these prior works, the current paper introduces and illustrates the use of mathematical relationships capable of mapping a system's excess and modularity to the system's ability to evolve. Such relationships will enable system engineers to quantitatively include system evolvability as a performance criterion during the design process, and quantitatively evaluate the utility of evolutionary options while a system is in service.

Ultimately, the degree to which a system should be made evolvable while in service is a strategic choice. The strategies for service-phase evolution are generally to achieve multi-ability systems [12, 26, 27, 69, 70], system robustness [29, 71–74], or as proposed in this thesis, a method to respond to unforeseen needs. Whatever the strategy may be, the quantitative relationships developed in this thesis allow system engineers to evaluate the degree to which a system is evolvable, and the utility of system evolution.

The remainder of this chapter is presented as follows: Section 2.2 presents an accepted theory upon which the developments are built. Section 2.3 introduces the evolvability measures. Section 2.4 presents simple numerical examples and a practical aircraft carrier example. Concluding remarks are provided in Section 2.5.

2.2 Technical Preliminaries

The mathematical relationships presented in this thesis for mapping a system's excess and modularity to its ability to evolve are based on Hooke's law and the simple theory of elastic potential energy. Therefore, in this section, we provide a few statements regarding these theories and why they are used as a foundation for the relationships developed in Section 2.3.

The relationships upon which mechanical behavior of materials is founded are almost entirely based on observations and experimental testing [75]. Furthermore, most engineering applications in mechanics of materials deal with large enough pieces of matter that average properties can be assumed [75]. Similarly, observation of factors that enable evolution in engineered systems is used to study evolvability attributes (see appendix A), where it is found that system excess and modularity enable a system to evolve while in service. In this thesis, systems and configurations are measured on a sufficiently large scale that average properties can be assumed.

One relationship in material behavior theory that is particularly useful in the context of this thesis to describe evolvability is Hooke's law. Based on observation and testing, Hooke's law states

$$F = k\,x \tag{2.1}$$

where F is the physical load experienced by an object, k is the elastic spring constant for that object, and x is the deformation of that object. Clearly, Hooke's law is an approximation of an output (F) to an input (x) in the elastic region, where the variables related to force are usually displacement and force per unit area, rather than force itself [75]. Similarly, system *utility* from excess or modularity to enable future evolution can be described as a force, where the variables related to utility are gain per unit excess or modularity, and input variables of excess and modularity. For this reason and for the purposes of this thesis, utility is analogous to force. This argument is reiterated in Section 2.3, where the simple representation of Hooke's law is used to quantify the utility of excess and modularity to enable future evolution.

Building on Hooke's law, objects that deform under prescribed loads or deformations and then return to their original shape store elastic potential energy. In addition, elastic potential energy stored within the object is represented by the area under the force-deformation curve for a given object. For the case where k is a constant and the object is initially undeformed, the elastic potential energy is

$$P_e = \int F dx = \int k\, x\, dx = \frac{1}{2}\, k\, x^2 \tag{2.2}$$

where the load experienced (F) is applied over the distance (x). The object's elastic potential energy can then be used by the object to restore its shape. Similarly, systems with excess and/or modular can evolve to new configurations using that excess or modularity in the system – such systems can be thought of as storing *evolvability energy*. Such strong correlations suggest that the model for elastic potential energy may be useful in modeling system evolvability. As shown in the next section, this simple representation of potential energy (P_e) can be used to quantify the degree to which a system is able to evolve, while the relationship $F = \partial P_e / \partial x$ can be used to quantify the utility of excess and modularity to enable future evolution from the evolvability in a system.

2.3 Model Development

We examined 210 engineered systems and found that system excess and modularity allow a system to evolve while in service (see appendix A). Similar studies support this finding [60, 76]. Building on these observations, this section introduces the mathematical relationships that map a system's excess and modularity to that system's utility and ability to evolve.

2.3.1 New Developments

Two models are introduced in this thesis: (i) a model to quantify the utility of excess or modularity to a system, termed *utility* and denoted as U; and (ii) a model to quantify the degree to which a system is evolvable, termed *evolvability* and denoted as E. The definitions of these and other model parameters are provided below.

> Excess (C) is the quantity of surplus in a system once the necessities of the system are met. For example, if an aircraft carrier's power plant produces 200 MW, and the carrier requires 180 MW to operate, then the excess is 20 MW. The units of excess are consistent with the feature or factor of the system being evaluated for excess (e.g., W, lb, ft^2, ft^3, \$).
>
> Modularity (M) is a measure of a system's ability to remove, to add, or to rearrange modules. At the desired level of decomposition, existing methods may be used to quantify the degree to which a system is modular [77]. The units of modularity are characterized by the system (e.g., number of modules, number of interfaces, number of interface types).
>
> Utility (U) is the value of meeting system objectives through having excess or being modular. In other words, *utility* as used in this thesis is the value of excess and modularity to enable future evolution.
>
> Gain per unit excess (g_c) is defined as the utility per unit of excess.
>
> Gain per unit modularity (g_m) is defined as the utility per unit of modularity.
>
> Evolvability (E) is defined as the potential energy (ability) to evolve from one system configuration to another, using system excess and modularity, as intended to meet specific new system objectives.

The general relationship between utility (U), excess (C), and modularity (M) is

$$U = g_c\,C + g_m\,M \tag{2.3}$$

where g_c and g_m represent the unit gains for excess and modularity, respectively. As represented, we believe *how much* the excess and modularity are valued is important. Consequently, this information is captured in the unit gains (g_c and g_m) described above, which represent the utility/excess curve and utility/modularity curve. The nature and determination of these gain parameters is described in Section 2.4.1. This general relationship of utility connects excess and modularity to system objectives through gain parameters and stems from Hooke's law presented in Section 2.2. Limitations of this simple model are discussed in the concluding remarks.

Considering system evolvability as the potential to evolve, we believe that excess (C) resources and/or modular architecture (M) can be used to carryout system evolution. Following the same reasoning that supports any potential-energy based model, the evolvability (E) energy is the sum of the areas under the utility/excess curve (g_c) and the utility/modularity curve (g_m). Therefore, the general relationship between system evolvability (E), excess (C), and modularity (M) is

$$E = \int_{c_1}^{c_2} g_c \, C \, dC + \int_{m_1}^{m_2} g_m \, M \, dM \tag{2.4}$$

where c and m represent the limits of integration. In addition to modeling utility, it is important to understand the ability a system has for future evolution, which is why quantifying system evolvability is valuable. Also, when the evolvability of a system is known the utility can be evaluated by

$$U = \frac{\partial E}{\partial C} + \frac{\partial E}{\partial M} \tag{2.5}$$

From the developed relationships, it can be seen that six parameters (g_c, C, g_m, M, E, U) and two general equations (Equation 2.3 and 2.4) are involved in the quantification. Any four of these parameters can be treated as independent parameters, depending on the information available about a system.

We present simple and complex examples in Section 2.4, to test the proposed relationships and illustrate their usefulness in evaluating system evolvability.

2.3.2 Model Use with Complex Engineered Systems

In using the general relationships developed in this thesis, one expansion that exists for CES is that many factors are considered simultaneously. In the context of Equation 2.3 and 2.4, this means that multiple excess factors, for example, are evaluated $C = [C_1 \; C_2 \; \ldots \; C_{n_{fc}}]$, where n_{fc} is the number of excess factors considered. As an example, consider an aircraft carrier. One excess factor to consider may be electrical power generation from the onboard nuclear power plant, and another excess factor to consider may be cargo capacity. For any CES, there will be many excess factors to consider. The same is true for modularity factors. When evaluating the utility of multiple excess factors, multiple modularity factors, and multiple gains per unit excess and unit modularity, the following equation may be used:

$$U = \sum_{i=1}^{n_{fc}} [g_{c_i} C_i] + \sum_{i=1}^{n_{fm}} [g_{m_i} M_i] \tag{2.6}$$

where n_{fc} is the number of factors for excess, n_{fm} is the number of factors for modularity, g_{c_i} is the i-th gain per unit of excess, C_i is the i-th factor of excess, g_{m_i} is the i-th gain per unit of modularity, and M_i is the i-th factor of modularity. Likewise, the evolvability of a system when considering multiple factors is

$$E = \sum_{i=1}^{n_{fc}} \left[\int_{c_i}^{c_{i+1}} g_{c_i} C_i \, dC_i \right] + \sum_{i=1}^{n_{fm}} \left[\int_{m_i}^{m_{i+1}} g_{m_i} M_i \, dM_i \right] \tag{2.7}$$

As seen in the equations, we assume uncoupled unit gain parameters for multiple factors, and that excess and modularity are uncoupled parameters. Future studies would benefit from exploring the potential coupled nature of these parameters and terms.

Another complexity that exists when considering CES is that for any given excess factor, for example, there may be multiple concurrent ways to use it to meet new system objectives. Any such ways to obtain utility will be termed *ideas* and the obtained utility of ideas will be termed *benefit*.

> Benefit (B) is the value (utility) of a new configuration or idea for meeting system objectives through using excess or modularity.

To illustrate, consider again the aircraft carrier power plant with 20 MW of excess power; 5 of the 20 MW may be used for additional electric heating, while 10 of the 20 MW may be used to add a laser-guided targeting system. It is necessary to determine the unit gains associated with the ideas. For such scenarios the following relationship captures the complexity:

$$B_j = \sum_{j=1}^{n_{gc_j}} \left[g_{c_{ij}} C_{ij} \right] + \sum_{j=1}^{n_{gm_j}} \left[g_{m_{ij}} M_{ij} \right] \tag{2.8}$$

where $g_{c_{ij}}$ represents the i-th factor of excess, j represents the j-th idea, and $g_{m_{ij}}$ represents the i-th factor of modularity, j represents the j-th idea. Also, $n_{g_{c_j}}$ is the number of ideas using excess and $n_{g_{m_j}}$ is the number of ideas using modularity.

There is a cost to implement ideas into a system. This cost in excess and modularity to carryout the ideas will be called *demand* and denoted as $D_{C_{ij}}$ for excess and $D_{M_{ij}}$ for modularity. The feasibility of implementing the ideas can be tested by

$$C_{i\,\mathrm{new}} = C_i - \sum_{j=1}^{n_{g_{c_j}}} \left[D_{C_{ij}} \right] \tag{2.9}$$

$$M_{i\,\mathrm{new}} = M_i - \sum_{j=1}^{n_{g_{m_j}}} \left[D_{M_{ij}} \right] \tag{2.10}$$

where $C_{i\,\mathrm{new}}$ and $M_{i\,\mathrm{new}}$ must be greater than or equal to zero for the ideas to be feasible.

After implementing the selected ideas, the remaining evolvability in a system will be

$$E_{\mathrm{new}} = \sum_{i=1}^{n_{fc}} \left[\int_{c_i}^{c_{i+1}} g_{c_i} C_{i\,\mathrm{new}} \, dC_{i\,\mathrm{new}} \right] + \sum_{i=1}^{n_{fm}} \left[\int_{m_i}^{m_{i+1}} g_{m_i} M_{i\,\mathrm{new}} \, dM_{i\,\mathrm{new}} \right] \tag{2.11}$$

where $C_{i\,\mathrm{new}}$ is the remaining excess and $M_{i\,\mathrm{new}}$ is the remaining modularity in a system. Consequently, the demand in system evolvability (work) to carryout the selected ideas is

$$\Delta E = E - E_{\mathrm{new}} \tag{2.12}$$

Notice that utility (U) and benefit (B) will emerge with physically meaningful values that can be interpreted without comparison. In contrast, the evolvability (E) measures themselves are most useful when used as a comparative measures (reference frame) when evaluating multiple systems, or designs, or ideas. Scaling is also an important factor when comparing calculated values for multiple factors in CES. Therefore, we demonstrate how values for multiple excess factors can be normalized in Section 2.4.2.

2.4 Examples

In this section, we illustrate the use of the relationships developed in Section 2.3. The simple examples highlight the use of linear and nonlinear utility functions, and the complex example evaluates US Navy nuclear aircraft carriers.

2.4.1 Simple Examples

This section demonstrates how to numerically evaluate the utility (U) and evolvability (E) of a system and also demonstrates the relationships graphically. The purpose of these demonstrations is to show that an elastic potential energy formulation can be used to quantify system evolvability. We recognize that the general relationships (Equation 2.3 and 2.4) can be extended beyond linear approximations by specifying non-constant unit gains (g_c, g_m). Both constant and non-constant unit gain scenarios are illustrated in this section.

Linear Scenario

Consider a small cargo transport vehicle, where the independent variables are chosen as g_c, g_m, C, and M. The vehicle excess (C) in cargo volume is 4 m^3, and the modularity (M) is enabled by a tow hitch interface on the vehicle; the system modularity is quantified as 3 modularity units. The value of modularity for this simple example is assumed for the purpose of illustration, but methods in [77] may be used to quantify the degree of modularity in a system. The unit gains associated with excess and modularity are 2 units of gain/m^3 excess and 1 unit of gain/modularity, respectively.

To quantify the utility of the vehicle's excess and modularity to enable future evolution, we evaluate Equation 2.3 and find that the utility (U) is 11. Likewise we evaluate the vehicle's evolvability using Equation 2.4, where $c_1 = 0$, $c_2 = 4$, $m_1 = 0$, $m_2 = 3$, and find the evolvability (E) to be 20.5 (utility·excess·modularity).

Given the utility and evolvability calculated above, we now consider the effect of using excess and modularity to evolve to other potential configurations. One potential configuration or idea considered for this simple example is to add an air conditioning unit to the vehicle. The benefit of this idea (B_1) is 14 cooling units (as per Equation 2.8). The demand (cost) from the system to implement the idea in excess (D_C) is 1 m^3 and the modularity demand (D_M) is 1 modularity unit. As is apparent in this simple example, the system has the needed resources (excess and modularity) to evolve to the new configuration. Alternatively, Equation 2.9 and 2.10 can be used to evaluate the feasibility of implementing multiple ideas.

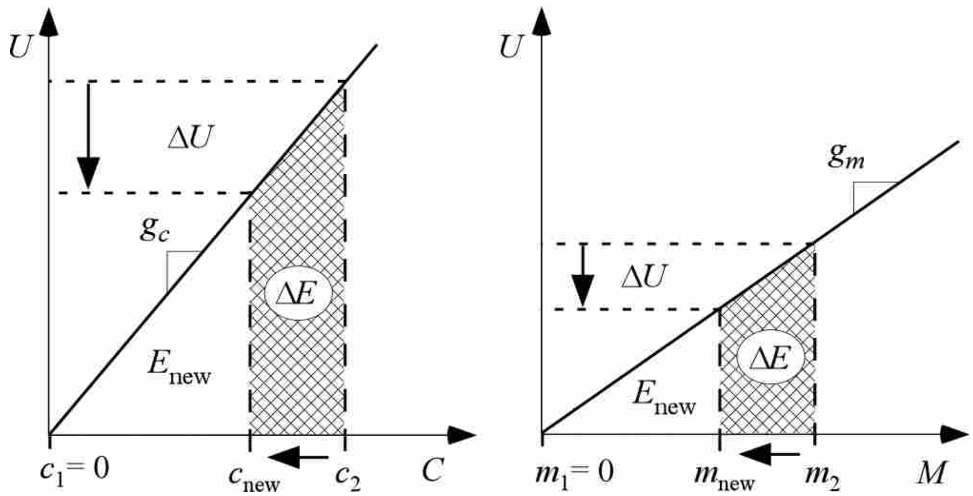

Figure 2.1: A graphical representation of the change in utility (U) and evolvability (E) for excess and modularity with constant unit gain measures

Upon deciding to implement the idea, the new (remaining) excess and modularity are measured at $C_{\text{new}} = 3$ m^3 and $M_{\text{new}} = 2$ modularity units, respectively. Also we evaluate the remaining evolvability in the vehicle using Equation 2.11, where E_{new} is 11 (utility·excess·modularity). The demand in evolvability to implement the idea is calculated using Equation 2.12, and ΔE is 9.5 (utility·excess·modularity) for this simple example.

The scenario of using a vehicle's cargo volume and tow hitch to evolve is graphically represented in Figure 2.1, where all the parameters from the general relationships Equation 2.3 and 2.4 are illustrated. In addition, we have shown and calculated the vehicle's evolvability (20.5), which is the area under the curves from c_1 to c_2 and m_1 to m_2, and the demand (cost) of the vehicle's evolvability (9.5) ΔE to gain cooling ($B_1 = 14$) in order to meet new system objectives (evolution). Another important metric shown is the utility of excess and modularity to enable future evolution ($U = 11$) and its change (ΔU) of 3 utility units to gain (benefit) 14 cooling units in order to meet new system objectives.

This simple example shows that one way to model system evolvability is as elastic potential energy, which allows the trade-offs of evolution to be quantitatively evaluated.

Nonlinear Scenario

The following illustration is a modification to the above cargo vehicle scenario, where the unit gain parameters are changed from constant to non-constant, thus producing a nonlinear utility curve, where $g_c = \ln(C)$ units of gain/m^3 excess, and $g_m = f(M)$ units of gain/modularity, where $f(M) = 3\,e^{-(M-\mu)^2/(2\sigma^2)}$, $\mu = 2$, and $\sigma = 1$.

The utility function related to excess (which follows a natural log curve) demonstrates that at some threshold, adding more excess to the system has minimal increase in the utility of excess for future evolution. On the other hand, the utility function of modularity for evolution (which follows a Gaussian distribution) demonstrates that at some threshold, adding more modularity to the system decreases the utility of modularity for evolution. We are not completely aware that this utility curve exists in practice, however, we point out that the proposed models are able to mathematically represent such a curve. To evaluate the evolability of the vehicle, we first evaluate the utility using Equation 2.3, where the utility of excess and modularity for evolution is $1.39 + 1.82 = 3.21$. Next, we evaluate the system's evolvability using Equation 2.4, where $c_1 = 1$ and $c_2 = 4$, and $m_1 = 0$ and $m_2 = 3$. The evolvability (E) is $2.54 + 12.67 = 15.21$ (utility·excess·modularity).

As in the previous example, we consider possible new configurations of the vehicle. Two future configurations or ideas are proposed to improve the cargo vehicle's traction, where the first idea is to add mass and the second idea is to add a negative lift airfoil. The demand to implement the first idea (D_C) is 1.5 excess m^3 and the demand to implement the second idea (D_M) is 1.5 modularity units. We evaluate the feasibility of these ideas using Equation 2.9 and 2.10, where both are deemed feasible. Next, we state the benefit to the system of the ideas as follows: benefit of the first idea (B_1) is 1 traction unit, and the benefit of the second idea (B_2) is 1 traction unit, which could be calculated using Equation 2.8.

The benefit of the two ideas meet the same new system objective of improved traction, and are therefore quantitatively comparable. Also, both ideas have the same demand value and benefit value to the system, which would indicate that implementing either idea would have the same effect, if these were the only parameters considered. However, comparing the evolvability and utility of excess and modularity to enable evolution of the system for the two ideas are notably different.

If only the first idea is implemented, $C_{\text{new}} = 2.5\ \text{m}^3$; the remaining evolvability in the system using Equation 2.11, where E_{new} is $0.79 + 12.67 = 13.46$ (utility·excess·modularity), and using Equation 2.3, the utility is $0.91 + 1.82 = 2.73$. If only the second idea is implemented, $M_{\text{new}} = 1.5$ modules; the remaining evolvability in the system using Equation 2.11, where E_{new} is $2.54 + 8.6 = 11.14$ (utility·excess·modularity), and using Equation 2.3, the utility is $1.39 + 3.85 = 5.24$.

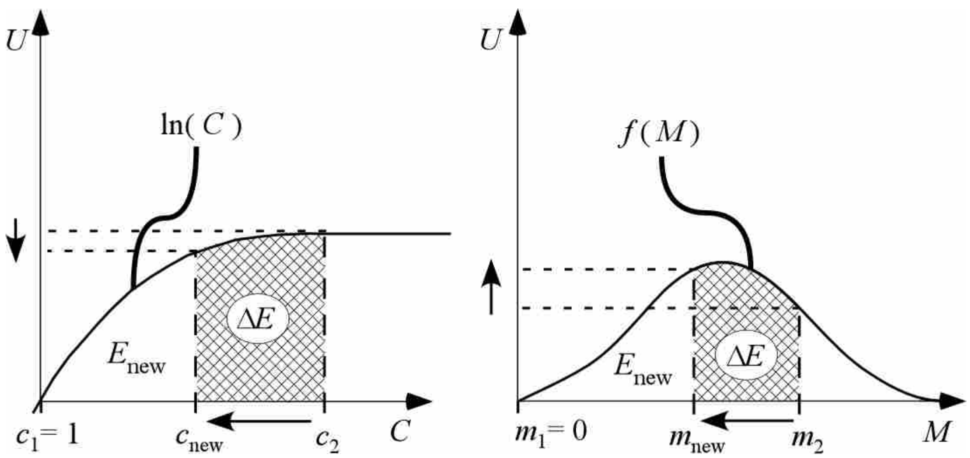

Figure 2.2: A graphical representation of the change in utility (U) and evolvability (E) with non-constant unit gain measures

This snap shot scenario is graphically represented in Figure 2.2, where all the parameters from the general relationships Equation 2.3 and 2.4 are illustrated. In addition, we have shown and calculated the system's evolvability, the demand in system evolvability to implement idea one ($\Delta E = 1.75$) and idea two ($\Delta E = 4.07$), where both ideas improve vehicle traction ($B_1 = 1$ and $B_2 = 1$) in order to meet new system objectives.

Information that the developed relationships have provided is that a modularity value of 3 corresponds to a negative slope on the modularity utility curve for this scenario. Thus, a modularity value less than 2 (μ=2) is shown to raise the utility of modularity for evolution, but still decrease the evolvability in the system. This is an illustrative example, where modularity is penalized at high values of modularity because of the potential failures at module interfaces. Therefore, implementing idea two would increase the utility of modularity for evolution to 5.24 from 3.21, while still removing evolvability (4.07 utility·excess·modularity) from the system. Also, the added benefit (B_2 = 1) of vehicle traction in order to meet the new system objective would increase.

These illustrations show how unit gain parameters (g_c and g_m) can be represented as constant and non-constant through different utility curves. Three different utility functions (linear, natural log, and Gaussian distribution) were shown. Methods for determining gain parameters can be formal or informal. Formal determination is based on existing data such as that provided in [2] and described in the section below. Informal determination involves stakeholder intuition. While informal, our observation is that stakeholders can indeed place a value on a certain amount of excess or modularity. Methods such as Physical Programming help decision makers establish utility functions based on easy to define physically meaningful parameters [78].

These simple examples of a cargo vehicle help to show how the developed models and calculated values can capture metrics for system evolvability. One advantage of these relationships shown is the ability to numerically quantify system evolution interactions to aid decision making.

2.4.2 Complex Example

Figure 2.3: Nimitz-class nuclear aircraft carrier, USS John C. Stennis [1]

In this example, we consider US Navy nuclear aircraft carriers (see Figure B.1) and demonstrate how to quantitatively evaluate their utility (U) of excess for evolution, and their evolvability (E). While the relationships in this thesis are derived based on excess and modularity, we consider only the system excess. This is done through choosing critical factors for excess (i), evaluating excess factors (C_i), and normalizing excess factors into percentages. Furthermore, we point out how unit gains per excess (g_{c_i}) can be determined. In addition, the new ElectroMagnetic Aircraft Launch System (EMALS) and current steam catapult (STEAM) are considered as ideas with their respective benefit (B_j) to the system. The purpose of this example is to show that the developed relationships can be used to quantify system evolvability, and that the quantification aligns well with what the Navy qualitatively reports about the aircraft carrier's ability to evolve.

Nuclear aircraft carriers are a great example of CES; they have long development cycles, are a significant capital investment, and must stay relevant in the changing landscape of modern warfare [79]. General design requirements for aircraft carriers include: launch and recover aircraft, operate for 50 years, only refuel the nuclear core once, and project military power by operating in many different missions [80].

The US Navy has recognized the growing demand for modular platforms to meet evolving needs, environments, and technology, and have consequently started to implement evolvability into ships and defense systems to enable configuration changes while in service [79]. This provides the opportunity to apply the proposed models of evolvability in this thesis to aircraft carriers, and more specifically, to the Nimitiz-class and Ford-class aircraft carriers.

The US Navy currently operates ten Nimitz-class aircraft carriers, which were designed in the early-60's [79]. The USS George H.W. Bush is the last of the Nimitz-class carriers and was commissioned in 2009 [81]. Presently, the United States is building a new class of nuclear aircraft carriers called the Ford-class. In regard to ships and aircraft, Jonathan W. Greenert, the Chief of Naval Operations (CNO) of the US Navy, said that, "the design of future platforms also must take into account upfront the volume, electrical power, cooling, speed, and survivability needed to effectively incorporate new payloads [configurations] through their service life" [79]. In addition, a report written for the US Department of Defense (DOD) states that limiting factors for new technology insertion into Nimitz-class carriers are weight, stability, and electrical power [82].

Using these references, the top-level factors of excess for aircraft carrier evolvability are simplified here as displacement, volume, stability, and electrical power.

The US Navy uses varying measures for determining the service life of a platform [2]. One such measure is service life allowance, which is the allowance (margin) built into platforms to maintain the platform's service life in-spite of changes. Service life allowance measures in aircraft carriers are presented as excess in the system; in the remainder of this thesis, service life allowance will be referred to as excess. In addition, normalizing the values into system percentages is used to mitigate scaling problems. The excess values are normalized by taking the maximum or limit value minus the actual value, then dividing by the actual value, refer to Appendix B. For the Nimitz-class: excess displacement is 0.48% [82] (limit is 91,878 Long Tons (LT) and actual is 91,440 LT), excess volume is 3% [82] (limit is $14.42E^6$ ft^3 and actual is $14E^6$ ft^3), excess stability measured by the center of gravity (KG) is 3.57% [83] (limit is 48.5 KG and actual is 46.82 KG), and excess electrical power is 0.618% [82] (limit is 193.9 MW and actual is 192.71 MW). For the Ford-class: excess displacement is 7.5% [82] (limit is 107,500 LT and actual is 100,000 LT), excess volume is 4% (flexible infrastructure [81], limit is $15.288E^6$ ft^3, and actual is $14.7E^6$ ft^3), excess stability (KG) is 8.57% [80] (limit is 48.5 KG and actual is 44.67 KG), and excess electrical power is 48.4% [80] (limit is 581.7 MW and actual is 392 MW).

To illustrate how utility curves can be determined for overall systems or multiple factors in a single system, we present and describe Figure 2.4, which is adapted from [2]. Figure 2.4 demonstrates that, for US Navy vessels a formal determination of a utility curve for service length (years in service) as a function of displacement (tons) can be derived from existing data. Cable [2] concludes that there is a useful correlation between actual service life of Navy vessels and the vessels' excess displacement. We use this correlation as a guide to determine utility curves for this example.

The gain measures for the Nimitz-class are calculated using a utility of excess to enable future evolution of 20 excess service life years (yr), meaning that if the Nimitz-class carrier environment does not change, the system could stay in service for an additional 20 years beyond the expected 50 service life years. The value of 20 excess service life years is based on US Navy calculations of service life allowance [2].

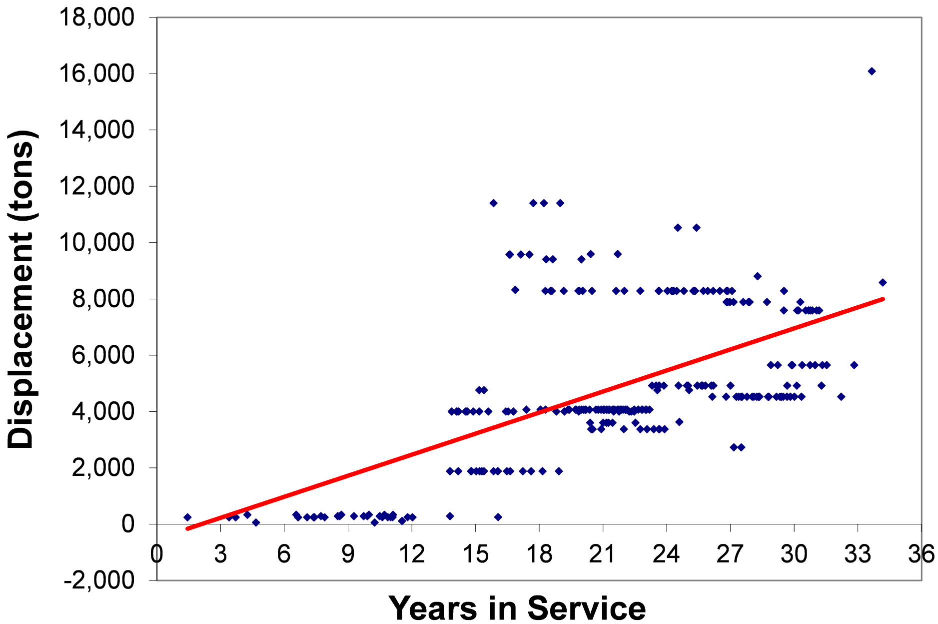

Figure 2.4: Plot of service length as a function of displacement for all decommissioned Cruisers, Destroyers, Frigates, and Patrol Craft built after World War II. Adapted from [2]

Table 2.1: Four Top-level Nimitz-class Aircraft Carrier Factors in Excess Percentage and Gain Parameters

Utility:	Displacement		Volume		Stability		Electrical Power	
Excess Service Life (yrs)	$g_{c_1}(\frac{yr}{\%})$	$C_1\%$	$g_{c_2}(\frac{yr}{\%})$	$C_2\%$	$g_{c_3}(\frac{yr}{\%})$	$C_3\%$	$g_{c_4}(\frac{yr}{\%})$	$C_4\%$
Nimitz-class	10.4	0.48	1.67	3	1.4	3.57	8.1	0.618

Table 2.1 presents the gain measures and excess values for the Nimitz-class aircraft carrier top-level factors. The utility of excess service life is evaluated with values from Table 2.1 and using Equation 2.6

$$\begin{aligned} U &= [10.4(\frac{\text{yr}}{\%\text{Disp.}})(0.48(\%\text{Disp.})) + 1.67(\frac{\text{yr}}{\%\text{Vol.}})(3(\%\text{Vol.})) + \\ 1.4 &\ (\frac{\text{yr}}{\%\text{Stab.}})(3.57(\%\text{Stab.})) + 8.1(\frac{\text{yr}}{\%\text{Elec.}})(0.618(\%\text{Elec.}))] \\ &= 20\ (\text{yr}) \end{aligned} \tag{2.13}$$

Table 2.2: Demand in Excess Percentage C_{ij} Values for Ideas EMALS and STEAM

Benefit: $\frac{\text{discharge}}{\text{seconds}}$	Displacement $C_{1j}\%$	Volume $C_{2j}\%$	Stability $C_{3j}\%$	Electrical Power $C_{4j}\%$
EMALS_{i1}	0.241	0.0651	0.334	3.27
STEAM_{i2}	0.529	0.174	1	0

In this example, constant gain measures are used to simplify the evaluation and easily demonstrate the use of the models. The evolvability of the system can be evaluated using Equation 2.7

$$\begin{aligned} E &= \frac{1}{2}[g_1(C_1)^2 + g_2(C_2)^2 + g_3(C_3)^2 + g_4(C_4)^2] \\ &= \frac{1}{2}[10.4(0.48)^2 + 1.67(3)^2 + 1.4(3.57)^2 + 8.1(0.618)^2] \\ &= 19.2\ (yr \cdot \%) \end{aligned} \tag{2.14}$$

Thus, the Nimitz-class aircraft carriers have an evolvability of $E = 19.2$ (yr·%). This information is useful as a starting point of evolvability, when evaluating potential future configurations.

We now consider how the system's excess can be used to evolve to new configurations. Advancements in the area of energy storage, pulsed power, power conditioning, and controls have led to the development of the new EMALS [84]. The EMALS has many advantages over the conventional STEAM, including fewer personnel for operation and maintenance, more power, and reduced stress on aircraft frames from improved peak-to-mean acceleration ratio [80]. This thesis will focus on the benefit of aircraft launch systems through discharges per seconds (disc/s) when comparing launch systems. The EMALS can discharge every 15 seconds or 0.0667 (disc/s), and STEAM can discharge every 20 seconds or 0.05 (disc/s) [80]. It is important to note that the discharge per seconds measure is based on the system's capabilities and not on actual launch per seconds of aircraft from aircraft carriers. The Nimitz-class currently has four steam catapults; thus, the idea is to remove a STEAM and add an EMALS.

Using the demand in excess listed in Table 2.2 of the two launch systems, the feasibility of removing a STEAM and adding a EMALS to a Nimitz-class carrier is tested using Equation 2.9

Table 2.3: Four Top-level Ford-class Aircraft Carrier Factors in Excess Percentage and Gain Parameters

Utility:	Displacement		Volume		Stability		Electrical Power	
Excess Service Life (yr)	$g_{c_1}(\frac{yr}{\%})$	$C_1\%$	$g_{c_2}(\frac{yr}{\%})$	$C_2\%$	$g_{c_3}(\frac{yr}{\%})$	$C_3\%$	$g_{c_4}(\frac{yr}{\%})$	$C_4\%$
Ford-class	1	7.5	1.87	4	0.89	8.57	0.155	48.4

$$C_{1\,\text{new}} = 0.48 - (0.241 - 0.529) = 0.768\% \tag{2.15}$$

$$C_{2\,\text{new}} = 3 - (0.0651 - 0.174) = 3.11\% \tag{2.16}$$

$$C_{3\,\text{new}} = 3.57 - (0.334 - 1) = 4.36\% \tag{2.17}$$

$$C_{4\,\text{new}} = 0.618 - (3.27 - 0) = -2.65\% \tag{2.18}$$

Equation 2.18 shows that $C_{4\,\text{new}} \leq 0$ and this idea is therefore infeasible. This is due to the amount of excess electrical power needed for the EMALS. The Nimitz-class still has some evolvability, albeit not the evolvability required for a future configuration with the EMALS.

The last carrier of the Nimitz-class carriers was commissioned in 2009, and must service until 2059 in order to meet its expected service life [81]. This presents a key problem; Nimitz-class carriers currently do not have the ability to evolve to the new EMALS. Moreover, this shows that the Nimitz-class carriers could be unable to evolve to changing threats of modern warfare. In addition, the steam catapults on the Nimitz-class carriers can generate enough power to launch an aircraft; however, this power is in the form of steam and, as of yet, the Nimitz-class carriers do not have the ability to convert and store the needed electrical power for EMALS. These suggestions are supported by the proposed models and are leading issues for the US Navy to introduce a new aircraft carrier class [82].

The gain measures for the Ford-class are calculated using a utility of excess to enable future evolution of 30 excess service life years (yr), meaning that if the Ford-class carrier environment does not change, the system could stay in service for an additional 30 years beyond the expected 50 service life years. The value of 30 excess service life years for the Ford-class is used because of the increase excess in the system, and is based on US Navy service life allowance calculations [2].

Table 2.4: Gain Parameters $g_{c_{ij}}$ for Ideas EMALS and STEAM

Benefit: Discharge per Sec.	Displacement $g_{c_{1j}}(\frac{\text{(disc/s)}}{\%})$	Volume $g_{c_{2j}}(\frac{\text{(disc/s)}}{\%})$	Stability $g_{c_{3j}}(\frac{\text{(disc/s)}}{\%})$	Electrical Power $g_{c_{4j}}(\frac{\text{(disc/s)}}{\%})$
EMALS_{i1}	0.0693	0.256	0.0498	0.0051
STEAM_{i2}	0.0315	0.0957	0.0167	0

In Table 2.3, the Ford-class excess percentage and gain measures are presented. Using Equation 2.6 and 2.7, and Table 2.3 values, the Ford-class utility for evolution is $U = 30$ (yr) and evolvability is $E = 257.3$ (yr·%).

The Ford-class carrier is designed with four EMALS, so a future configuration for the Ford-class is above that considered for the Nimitz-class. This future configuration is to evolve by adding an EMALS and STEAM to the Ford-class carrier. The feasibility of this idea is evaluated using Table 2.2 and Equation 2.9.

$$C_{1\,\text{new}} = 7.5 - (0.241 + 0.529) = 6.73\% \tag{2.19}$$

$$C_{2\,\text{new}} = 4 - (0.0651 + 0.174) = 3.76\% \tag{2.20}$$

$$C_{3\,\text{new}} = 8.57 - (0.334 + 1) = 7.24\% \tag{2.21}$$

$$C_{4\,\text{new}} = 48.4 - (3.27 + 0) = 45.13\% \tag{2.22}$$

The above evaluations show that adding another EMALS and STEAM to the Ford-class is feasible ($C_{(1-4)\,\text{new}} \geq 0$). In summary, the Ford-class aircraft carrier has the evolvability to enable a future configuration above and beyond the Nimitz-class with added STEAM and EMALS catapults.

The gain measures (see Table 2.4) for these separate systems are calculated by using the benefit of discharge per second and the demand in excess for each system in Table 2.2. The benefit of these launch systems (adding EMALS and STEAM) are then evaluated using Table 2.2, Table

2.4, and Equation 2.8

$$
\begin{aligned}
B_1 &= [g_{c11}(C_{11}) + g_{c21}(C_{21}) + g_{c31}(C_{31}) + g_{c41}(C_{41})] \\
&= [.0693(.241) + .256(.0651) + .0498(.334) + .0051(3.27)] \\
&= 0.0667 \qquad (2.23) \\
B_2 &= [.0315(.529) + .0957(.174) + .0167(1) + 0(0)] \\
&= 0.05 \qquad (2.24)
\end{aligned}
$$

The benefit of the feasible ideas are $B_1 = 0.0667$ (discharge per seconds) and $B_2 = 0.05$ (discharge per seconds), which means that the discharge per seconds with the two systems could be increased by 0.1167 (discharge per seconds). All nuclear aircraft carriers have four catapults to one landing strip, demonstrating the importance of catapults and the ability to quickly launch aircraft, and implying that a future configuration with added EMALS and STEAM might be important.

The remaining evolvability is evaluated using Equation 2.11, as well as the gain measure of excess service life for the Ford-class g_{c_i}, and the remaining excess $C_{i\,\text{new}}$:

$$
\begin{aligned}
E_{\text{new}} &= \frac{1}{2}[1(6.73)^2 + 1.87(3.76)^2 + .89(7.24)^2 + .155(45.13)^2] \\
&= 217 \qquad (2.25)
\end{aligned}
$$

Thus, $E_{\text{new}} = 217$ (yr·%) and using Equation 2.6, $U_{\text{new}} = 27.2$ (yr). The significance of these results are presented in concluding remarks.

The intent of this example is to demonstrate that the proposed models are useful in quantitatively evaluating system evolvability and future configurations. One point of validation regarding the proposed models' usefulness is the ability to quantitatively communicate what has qualitatively been written about the Nimitz-class carrier's inability for further evolution to EMALS [82], as well as the high evolvability of the Ford-class [81]. When comparing the two launch systems, the EMALS is a better choice in every factor, except electrical power demand.

The Ford-class excess electrical power is calculated to be 48.4% compared to the Nimitz-Class, which is 0.618%. This highlights the increased importance of electrical power for new technology configuration, such as dynamic armor, new radars, and directed-energy weapons, which all have high demands of electrical power. In addition, this illustrates how the Ford-class aircraft carrier is the most evolvable design and meets the objective set by the US Navy CNO to design platforms that "effectively incorporate new payloads [configurations] through their service life" [79].

In conclusion, this practical example has demonstrated a method for using the developed models with nuclear aircraft carrier designs and future configurations. We have also been able to quantitatively evaluate the benefit of future configurations. This example further illustrates use of the developed relationships for quantifying a system's evolvability and the trade-offs of future configurations, utility, excess percentages, and gain parameters.

2.5 Concluding Remarks

Uncertainties in future operations and environments in CES lead to problems in system safety, life, and value [3]. The literature within this area has identified ways in which to overcome uncertainty, such as system flexibility, adaptability, upgradeability, maintainability, modularity, reconfigurability, and transformation [59]. In this thesis, it is illustrated that such problems in CES can be minimized through quantifying and using system evolvability. Mathematical models of utility and evolvability were presented as ways to describe service-phase evolution. Observation and testing have proven useful in developing most engineering relationships, and are the methods used to develop the utility and evolvability relationships presented herein. Ultimately, the analytical models in this thesis are tools to help designers and decision makers better understand evolvability in systems, enabling systems to be strategically designed with evolvability.

Utility and evolvability were used as performance criteria for aircraft carrier designs, and future configurations were evaluated with the relationships developed. In the simple and complex examples, the use of the evolvability and utility equations were demonstrated. In the complex example, it was shown that the Nimitz-class carriers have an evolvability of $E = 19.2$ (yr·%) and a utility of excess service life at $U = 20$ (yr). However, the Nimitz-class carrier does not have sufficient evolvability for a future configuration with the new EMALS, which dramatically diminishes its value now and in the future. The Ford-class carrier has an evolvability of $E = 257.3$ (yr·%) and a utility of excess service life of $U = 30$ (yr). It was shown that, different from the Nimitz-class carrier, the Ford-class carrier has the evolvability necessary for a future configuration with an added EMALS and steam catapult. The benefit of this future configuration was an increase in catapult system discharge per seconds of 0.1167. This future configuration comes at an evolvability demand from the system of 40.3 (yr·%), which is 2.8 excess service life years. The complex example of aircraft carriers displays the ability to mathematically represent utility and evolvability within CES. Maintaining the war fighting effectiveness of a vessel is a primary reason for updating its technology. However, a vessel that spends most of its time dockside having its technology updated, may have world-beating capabilities, but have limited availability to exercise those capabilities. Therefore, further research should include a measure of time required to evolve or system availability for upgrade.

The developed models in this thesis further communicate the relationships between evolvability, utility, gains, excess, and modularity in systems, which opens the door to using the measures with optimization algorithms. Future research can apply the developed models to different scenarios using multi-objective optimization to better understand the compromises of system evolvability. Clearly, Equation 2.3–2.7 assume additive (first-order) relationships between excess and modularity in systems. Although further validation of these relationships is needed, we believe that they are a useful step in being able to model evolvability, with the possibility of a higher degree of fidelity in the future. Additionally, an in-depth study of utility curves and unit gain parameters (utility/excess and utility/modularity) would be beneficial. Further research could look at discrete utility curves, step function utility curves, delta function utility curves, and the nature of coupled gain parameters for systems with multiple factors.

CHAPTER 3. CONCLUSION AND FUTURE WORK

Four main tasks are involved in the overall perspective of this research: (i) empirical study of service-phase evolution in existing engineered systems; (ii) measure and model service-phase evolution for emergent needs; (iii) assessment of measurement quality; and (iv) connecting the discovered measures of evolvability with value-driven design. This thesis is an initial effort to understand service-phase evolution through studying 210 engineered systems (see appendix A) and to develop a quantitative model of service-phase evolution (see Chapter 2).

3.1 Conclusion

In conclusion, the pioneering efforts of this thesis lay a foundation for understanding and quantifying system evolution. Additionally, it brings understanding of how system evolvability can enable complex engineered systems (CES) to evolve in response to unanticipated needs, operating conditions, and market competition while in service. The results of these innovative relationships (see Chapter 2), developed from trusted engineering theories (Hooke's law and elastic potential energy), provide correlations of applicability and benefits from these theories.

As discussed earlier in this thesis, modern society is dependent on CES for its way of life. With the present environment of growing complexity in CES, today's CES are at risk of becoming less evolvable in service. Ultimately, with results such as less system agility, more expensive satellite, weapon system development and deployment costs, US citizens would greatly benefit from a stronger national engineering workforce that is more fully equipped to design and sustain CES. This thesis has laid a foundation for improving the ability to design evolvable systems that avoid such unwanted cost increases to society.

3.2 Future Work

3.2.1 Model Validation

We acknowledge that model validation is a difficult task, leading some to say that "all models are wrong, but some models are useful" [85]. Sargent [86] dictates that validating model quality can be done concurrently with model development. Therefore, the next task needed in this research is further model validation, developing confidence that the models created in Chapter 2 produce sound insight and data [87].

Future research, can focus on assessing model quality by building tests and criteria that compare how the models correlate with the results shown in real systems. This will allow the establishment of applicability domains and ranges of accuracy [88]. From these factors, it will be possible to understand both when and where the models can be used. Another important plan would be to extend these tests to hypothetical systems that can be created by a research team as a means of providing a control mechanism by which model quality can be judged.

Next, future research can include updating the models as more examples of evolvable systems are examined. The objective of this is to determine if the: 1) theories and assumptions underlying the models are correct, and 2) the model's representation of the mathematical and causal relationships are "reasonable" for the intended purpose of the model [86]. Successfully validating these models will require consensus of the research team, as it is generally understood that the creator of the model is the most qualified to judge whether an assumption is met "closely enough" [86]. To help in this process, examples should be purposely held-out [89] to assess the quality of the generated measures.

3.2.2 Value-Driven Design

Recent research has shown that requirement-driven processes [90] have led to staggering cost overruns and schedule delays [18, 91]. In value-driven design (VDD), no requirements are applied at the system, sub-system, or component levels [14]. Rather, scalar objective functions are passed to lower levels, creating self-contained design problems. Future research might consider introducing a representation of a value function facilitating the decision between system replacement (rejecting the new degraded performance) or evolving the system to achieve desired performance (arriving at a quantifiable measure of value requires synthesizing the knowledge and information gained from this thesis). Creating the value function involves: (i) selecting key system attributes, (ii) establishing relationships between subsystem attributes and system attributes, (iii) establishing a structure of the value model, and (iv) deriving the value-based objective functions for the subsystems.

This thesis has provided insight into key enablers of service-phase evolution and how evolution physically impacts the component-subsystem-system relationship. The remaining challenge is integrating this information into a value model and exercising the model to understand how different evolution strategies impact overall system value. First, one might explore how the parameters affecting System Space movement can be represented in a value-driven design framework, by constraining how the system changes configuration states, through studying how to compose the value-based objective functions at the component/sub-system level.

Additionally, exploring how system longevity and narrowness of task impact the value of an evolvable system can be beneficial. In constructing the system-level value function, one might begin by experimenting with real options theory to calculate the net present value (NPV) of the system [92–94]. NPV has been applied in VDD for technology comparison, competitive markets, and system maintenance. Additional approaches toward creating a value model can also be explored [47, 95].

Lastly, research efforts should further expand the value function to include aspects of reliability. The objective of this task would be two-fold: (i) exploring solution robustness of different architecture/transformation combinations; and (ii) exploring how the ability to evolve in-service influences system value in the presence of system failure. In doing so, the combination of these three steps will fully establish and exercise the developed value function.

REFERENCES

[1] Steckler, K., 2009. Pearl harbor salute http://outontheporch.org/tag/pearl-harbor/, May 28. vii, 24, 67

[2] Cable, C., 2011. "Demistifying service life." In *ASNE Flagship*. vii, 24, 26, 27, 29, 69

[3] Bloebaum, C. L., and McGowan, A. R., 2012. "The design of large-scale complex engineered systems: Present challenges and future promise." In *Proceedings of the 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, IN, AIAA-2012-5571*. 1, 2, 32

[4] Boeing, 2012. 787 dreamliner program fact sheet www.boeing.com/commerical/787family/programfacts.html, retrieved February 1. 1

[5] Peacock, L., 1999. "Mighty hercules: The first four decades." In *Royal Air Force Benevolent Fund Enterprises*. 1

[6] Bloebaum, C. L., McGowan, A. R., Lightfoot, M. C., Collopy, P. D., and Hazelrigg, G., 2012. "NSF/NASA workshop on the design of large-scale complex engineered systems - from research to product realization." In *Proceedings of the 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, IN, AIAA-2012-5572*. 1, 2, 3, 12

[7] Lewis, K., and Collopy, P. D., 2012. "The role of engineering design in large-scale complex systems." In *Proceedings of the 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, IN, AIAA-2012-5573*. 1

[8] Defense-Acquisitions, March 29, 2012. Assessments of selected weapon programs Tech. rep., GAO-12-400SP. Washington, D.C. 1

[9] DepartmentofDefenese, June 14, 2012. Joint strike fighter: DOD actions needed to further enhance restructuring and address affordability risks Tech. rep., GAO-12-437. Washington, D.C. 1

[10] Larson, B. H., Mattson, C. A., and McLain, T. W., 2012. "A method of predicting multidisciplinary system behavior for validating design decisions research in engineering design." *Research in Engineering Design,* **Submitted February 2011**, p. Revisions requested June 2011. 1, 4

[11] Brown, O., and Eremenko, P., 2006. "The value proposition for fractionated space architectures." In *Space 2006, San Jose, CA, AIAA-2006-7506*. 2

[12] Ferguson, S., Lewis, K., Siddiqi, A., and de Weck, O., 2007. "Flexible and reconfigurable systems: Nomenclature and review." In *ASME Design Engineering Technical Conferences, Design Automation Conference, Las Vegas, NV, DETC2007/DAC-35745*. 2, 14, 46

[13] Collopy P. D., Bloebaum, C. L. M. B., and Green, L. L., 2012. "The distinct and interrelated roles of value-driven design, multidisciplinary design optimization, and decision analysis." In *Proceedings of the 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, IN, AIAA-2012-5575*. 2

[14] Collopy, P. D., and Hollingsworth, P. M., 2011. "Value-driven design." *AIAA Journal of Aircraft,* **(48)3**, pp. 749–759. 2, 11, 35

[15] Becz, S., Pinto, A., Zeidner, L. E., Khire, R., Bazaszuk, A., and Reeve, H. M., 2010. "Design system for managing complexity in aerospace systems." In *Proceedings of the 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX, AIAA-2010-9223*. 2

[16] ElMaraghy, W., ElMaraghy, H., Tomiyama, T., and Monostori, L., 2012. "Complexity in engineering design and manufacturing." *CIRP Annals - Manufacturing Technology,* **61(2)**, pp. 793–814. 2

[17] Jarke, M., Loucopoulos, P., Lyytinen, K., Mylopoilos, J., and Robinson, W., 2010. "The brave new world of design requirements: Four key principles." *Advanced Information Systems Engineering: Lecture Notes in Computer Science,* **6051**, pp. 470–482. 2

[18] Deshmukh, A., and Collopy, P., 2010. "Fundamental research into the design of large-scale complex systems." In *13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference. Fort Worth, Texas, AIAA-2010-9320*. 2, 35

[19] Simpson, T. W., Siddique, Z., and Jiao, J., 2006. *Product Platform and Product Family Design: Methods and Applications*. Springer. 2, 7

[20] Nadadur, G., Kim, W., Thomson, A. R., Parkinson, M. B., and Simpson, T. W., 2012. "Strategic product design for multiple global markets." In *ASME Design Engineering Technical Conference, Chicago, IL, DETC2012-70723*. 4

[21] Gawer, A., 2009. *Platforms, Markets and Innovations*. Edward Elgar Publishing Limited. 4

[22] Agte, J., de Weck, O., Sobieszczanski-Sobieski, J., Arendsen, P., Morris, A., and Spieck, M., 2010. "MDO: Assessment and direction for advancement - an opinion of one international group." *Structural and Multidisciplinary Optimization,* **40(1)**, pp. 17–33. 4

[23] Verbraeck, A., and Valentin, E. C., 2008. "Design guidelines for simulation building blocks." In *In Proceedings of the 2008 Winter Simulation Conference, Modeling Methodology II: Component-based Simulation*. 4

[24] Fritzson, P. A., 2004. *Principles of Object-Oriented Modeling and Simulation with Modelica.*, 2.1 ed. IEEE Press. 4

[25] Olewnik, A., and Lewis, K., 2006. "A decision support framework for flexible system design." *Journal of Engineering Design,* **17(1)**, pp. 75–97. 4

[26] Siddiqi, A., and de Weck, O. L., 2008. "Modeling methods and conceptual design principles for reconfigurable systems." *Journal of Mechanical Design,* **130(10)**, pp. 101–112. 4, 7, 14

[27] Lewis, P. K., and Mattson, C. A., 2012. "A method for developing systems that traverse the pareto frontiers of multiple system concepts through modularity." *Structural and Multidiscipilnary Optimization,* **45(4)**, pp. 467–478. 4, 14

[28] Holland, M. D., Ferguson, S., Tilstra, A. H., Seepersad, C. C., and Wood, K. L., 2012. "Linking system transformation to performance gains in the design of unmanned aerial vehicles." *Structural and Multidisciplinary Optimization,* **under review**. 4

[29] Lewis, P. K., Murray, V. R., and Mattson, C. A., 2011. "A design optimization strategy for creating devices that traverse the Pareto frontier over time." *Structural and Multidisciplinary Optimization,* **43(2)**, pp. 191–204 DOI 10.1007/s00158-010-0555-1. 4, 10, 14

[30] Siddiqi, A., de Weck, O. L., and Iagnemma, K., 2006. "Reconfigurability in planetary surface vehicles: Modeling approaches and case study." *Journal of the British Interplanetary Society,* **59**. 4

[31] Ulrich, K., and Eppinger, S., 2011. *Product Design and Development.*, 5 ed. McGraw-Hill, New York. 5, 7

[32] Wasserman, G. S., 2003. *Reliability Verification, Testing, and Analysis in Engineering Design*. Marcel Dekker. 5

[33] Lee, I., Choi, K. K., and Zhao, L., 2011. "Sampling-based RBDO using the stochastic sensitivity analysis and dynamic kriging method." *Structural and Multidisciplinary Optimization,* **44(3)**, pp. 299–317. 5

[34] Gershenson, J. K., Prasad, G. J., and Zhang, Y., 2004. "Product modularity: Measures and design methods." *Journal of Engineering Design,* **15(1)**, pp. 33–51. 7

[35] Martin, E., and Crossley, W., 2002. "Multiobjective aircraft design to investigate potential geometric morphing features." In *AIAA Aircraft Technology, Integration, and Operations (ATIO), Los Angeles, CA, AIAA-2002-5859*. 7

[36] Holtta-Otto, K., 2005. *Modular Product Platform Design*. Helsinki University of Technology. 7

[37] Pate, D. J., Patterson, M. D., and German, B. J., 2011. "Methods for optimizing a family of reconfigurable aircraft." In *11th AIAA ATIO Conference, including the AIAA Balloon Systems Conference and 19th AIAA Lighter-Than, Virginia Beach, VA*. 7

[38] Patterson, M. D., Pate, D. J., and German, B. J., 2011. "Performance flexibility of a reconfigurable family of uavs." In *11th AIAA ATIO Conference, including the AIAA Balloon Systems Conference and 19th AIAA Lighter-Than, Virginia Beach, VA*. 7

[39] Bizony, P., 2011. *The Space Shuttle: Celebrating Thirty Years of NASA's First Space Plane*. Minneapolis, MN. 8

[40] Heppenheimer, T., 1999. *A. The Space Shuttle Decision: NASA's Search for a Reusable Space Vehicle*. Washington, DC. 8

[41] Dooling, D., 2012. Spacelab joined diverse scientists and disciplines on 28 shuttle missions, retrieved February 1,. 8

[42] Washington, G. N., and Silverberg, L. M., 1997. "Uniform damping and stiffness control of distributed systems." In *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 119. 8

[43] Beard, J., 1993. "Technology: How static could improve satellite signals." In *New Scientist*. Issue 1866. 8

[44] Lopez-Mesa, B., and Bylund, N., 2011. "A study of the use of concept selection methods from inside a company." *Research in Engineering Design,* **22(1)**, pp. 7–27. 9

[45] Hansen, T. F., 2003. "Is modularity necessary for evolvability? remarks on the relationship between pleiotropy and evolvability." *Bio Systems,* **69(2-3)**, pp. 83–94. 9

[46] Fitzgerald, M. E., Ross, A. M., and Rhodes, D. H., 2011. "A method using epoch-era analysis to identify valuable changeability in system design." In *9th Conference on Systems Engineering Research, Los Angeles, CA.* 9

[47] Ross, A., and Rhodes, D., 2008. "Using natural value-centric time scales for conceptualizing system timelines through epoch-era analysis." In *INCOSE International Symposium 2008, Utrecht, the Netherlands.* 9, 36

[48] Rader, A. A., Ross, A. M., and Rhodes, D. H., 2010. "A methodological comparison of monte carlo methods and epoch-era analysis for system assessment in uncertain environments." In *4th Annual IEEE Systems Conference, San Diego, CA.* 9

[49] F.A.S., 2012. Federation of american scientists f-14 tomcat online: [http://www.fas.org/programs/ssp/man/uswpns/air/fighter/f14.html]. 9, 47

[50] Bowman, M. W., 1999. *Lockheed C-130 Hercules*. Crowood Press. 9

[51] Francillon, R. J., 1987. *Lockheed Aircraft since 1913*. Naval Institute. 9

[52] Smith, P. C., 2001. *Lockheed C-130 Hercules: The World's Favourite Military Transport*. Airlife Press. 9

[53] Lewis, P. K., Murray, V. R., and Mattson, C. A., 2010. "Identification of modular product platforms and modules that account for changing consumer needs." In *6th AIAA Multidisciplinary Design Optimization Specialist Conference*. 10

[54] Lewis, P. K., Murray, V. R., and Mattson, C. A., 2010. "Handling changing needs by designing products that modulate from one s-Pareto optimal design to another." *Structural and Multidisciplinary Optimization,* **Submitted August 18**. 10

[55] Hanisch, C., and Munz, G., 2008. "Evolvability and the intangibles." *Assembly Automation,* **28(3)**, pp. 194–199. 12

[56] Madni, A. M., 2012. "Adaptable platform-based engineering: Key enablers and outlook for the future." *Systems Engineering,* **15(1)**, pp. 95–107. 12

[57] Urken, A. B., Nimz, A., and Schuck, T. M., 2012. "Designing evolvable systems in a framework of robust, resilient and sustainable engineering analysis." *Advanced Engineering Informatics,* **26(3)**, pp. 553–562. 12

[58] Simpson, T. W., and Martins, J. R. R. A., 2011. "Multidisciplinary design optimization for complex engineered systems: Report from a national science foundation workshop." *Journal of Mechanical Design,* **133(10)**, p. 101002. 12

[59] Beesemyer, J. C., Ross, A. M., and Rhodes, D. H., 2012. "An empirical investigation of system changes to frame links between design decisions and ilities." In *Conference on Systems Engineering Research*. 13, 32

[60] Keese, D. A., Tilstra, A. H., Seepersad, C. C., and Wood, K. L., 2007. "Emporically-derived principles for designing products with flexibility for future evolution." In *Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Las Vegas, NV, DETC2007-35695.* 13, 15

[61] Keese, D., Takawale, N. P., Seepersad, C. C., and Wood, K. L., 2006. "An enhanced change modes and effects analysis (cmea) tool for measuring product flexibility with applications to consumer products." In *Proceedings of ASME 2006 International Design Engineering Technical Conferences, Philadelphia, PA, DETC2006-99478.* 13

[62] Tilstra, A. H., Backlund, P. B., Seepersad, C. C., and Wood, K. L., 2008. "Industrial case studies in product flexibility for future evolution: An application and evaluation of design guilelines." In *Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, New York, NY, DETC2008-49370.* 13

[63] Tilstra, A. H., Seepersad, C. C., and Wood, K. L., 2009. "Analysis of product flexibility for future evolution based on design guilelines and a high-defintion design structure matrix." In *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, San Diego, CA, DETC2009-87118.* 13

[64] VanBeek, T. J., and Tomiyama, T., 2012. "Structured workflow approach to support evolvability." *Advanced Engineering Informatics,* **26(3)**, pp. 487–501. 13

[65] Sandborn, P. A., and Herald, T. E., 2003. "Optimum technology insertion into systems based on the assessment of viability." *IEEE Transactions on Components and Packaging Technologies,* **26(4)**, pp. 734–738. 13

[66] Suh, E., de Weck, O. L., and Chang, D., 2007. "Flexible product platforms: Framework and case study." *Research in Engineering Design,* **18(2)**, pp. 67–89. 13

[67] Suh, E., Furst, M. R., Mihalyov, K. J., and de Weck, O. L., 2010. "Technology infusion for complex systems: A framework and case study." *Systems Engineering,* **13(2)**, pp. 186–203. 13

[68] Fulcoly, D. O., Ross, A. M., and Rhodes, D. H., 2012. "Evaluating system change options and timing using the epoch syncopation framework." In *Conference on Systems Engineering Research*. 13

[69] Ferguson, S., and Lewis, K., 2006. "Effective development of reconfigurable systems using linear state-feedback control." *AIAA Journal,* **44(4)**, pp. 868–878. 14

[70] Ferguson, S., Tilstra, A., Seepersad, C. C., and Wood, K. L., 2009. "Development of a changeable airfoil optimization model for use in the multidisciplinary design of unmanned aerial vehicles." In *ASME Design Engineering Technical Conference, Design Automation Conference, San Diego, CA, DETC2009-87482*. 14

[71] Morrise, J. S., Mattson, C. A., Lewis, P. K., and Magleby, S. P., 2011. "A method for designing collaborative products for poverty alleviation." In *ASME Design Engineering Technical Conference, Design Automation Conference, Washington, DC DETC2011-47409*. 14

[72] Sullivan, E., Tortorice, M., and Ferguson, S., 2010. "Using design reconfigurability to mitigate the effects of uncontrolled system variations." In *13th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Fort Worth, TX, AIAA-2010-9185*. 14

[73] Chmarra, M. K., Arts, L., and Tomiyama, T., 2008. "Towards adaptable architecture." In *ASME Design Engineering Technical Conference, Design Automation Conference, New York, NY, DETC2008-49971*. 14

[74] Arts, L., Chmarra, M. K., and Tomiyama, T., 2008. "Modularization method for adaptable products." In *ASME International Design Engineering Technical Conference and Computers and Information in Engineering Conference, New York, NY, DETC2008-49338.* 14

[75] Spencer, A. J. M., 2004. *Continuum Mechanics*. Dover Publications, Inc. 14, 15

[76] Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., and Sierakowski, R., 2009. "Innovation in design through transformation: A fundamental study of transformation principles." *Journal of Mechanical Design,* **131(8)**, p. 081010. 15

[77] Mattson, C. A., and Magleby, S. P., 2001. "The influence of product modularity during concept selection of consumer products." In *Proceedings of the ASME DETC'01, ASME 2001 Design Engineering Technical Conferences, and Computers and Information in Engineering Conference*, no. DETC2001/DTM21712. 16, 20

[78] Messac, A., 1996. "Physical programming: Effective optimization for computational design." *AIAA Journal,* **34(1)**, pp. 149–158. 24

[79] Greenert, J. W., 2012. "Payloads over platforms: Charting a new course." *Proceedings Magazine,* **138/7/1,313**. 25, 32

[80] Schank, J., Smith, G., Alkire, B., Arena, M. V., Birkler, J., Chiesa, J., Keating, E., and Schmidt, L., 2005. *Modernizing the U.S. Aircraft Carrier Fleet: Accelerating CVN 21 Production Versus Mid-Life Refueling*. RAND Corporation. 25, 26, 28, 68

[81] Moran, W., Moore, T., and McNamee, E., 2012. "A 'leap ahead' for the 21st-century navy." *Proceedings Magazine,* **138/9/1,315**. 25, 26, 29, 31, 68

[82] Howard, W., 2002. Future of the aircraft carrier Tech. rep., Defense Science Board Task Force. 25, 26, 29, 31, 67, 68

[83] Wolfson, D., 2004. "A solution to the inherent list on nimitz class aircraft carriers." Master's thesis, Massachusetts Institute of Technology, June. 26, 68

[84] Doyle, M. R., Samuel, D. J., Conway, T., and Klimowski, R. R., 1995. "Electromagnetic aircraft launch system-EMALS." *Magnetics, IEEE Transactions on,* **31(1)**, Jan, pp. 528–533. 28

[85] Box, G. E. P., and Draper, N. H., 1987. "Empirical model-buliding and response surfaces." In *Wiley, New York, NY*. 35

[86] Sargent, R. G., 2010. "Verification and validation of simulation models." In *Proceedings of the 2010 Winter Simulation Conference, Baltimore, MD., 978-1-4244-9568-9*. 35

[87] Macal, C. M., 2005. "Model verification and validation." In *Threat Anticipation: Social Science Methods and Models, Chicago, IL, April 7-9*. 35

[88] Malak, R. J., and Paredis, C. J. J., 2007. "Validating behavioral models for reuse." *Research in Engineering Design,* **18**, pp. 111–128. 35

[89] Kalwani, M. U., Meyer, R. J., and Morrison, D. G., 1994. "Benchmarks for discrete choice models." *Journal of Marketing Research,* **31(1)**, pp. 65–75. 35

[90] Yi, S. I., Shin, J. K., and Park, G. J., 2008. "Comparison of MDO methods with mathematical examples." *Structural and Multidisciplinary Optimization,* **(35)5**, pp. 391–402. 35

[91] Collopy, P. D., 2007. "Adverse impact of extensive attribute requirements on the design of complex systems." In *AIAA-2007-7820*. 35

[92] Hollingsworth, P. M., 2004. "Requirements controlled design: A method for discovery of discontinuous system boundaries in the requirements hyperspace." PhD thesis, Georgia Tech. 36

[93] Ross, A. M., and Hastings, D. E., 2006. "Assessing changeability in aerospace systems architecting and design using dynamic multi-attribute tradespace exploration." In *AIAA Space 2006, San Jose, CA, AIAA-2006-7255*. 36

[94] Briceno, S., and Mavris, D., 2005. "Strategic decision-making: Applications of game theory in a systems approach to commercial engine selection." In *AIAA 5th ATIO and 16th Lighter-than-Air Systems Technology and Balloon Systems Conference, Arlington, VA, AIAA-2005-7428*. 36

[95] Abbas, A. E., and Howard, R. A., 2009. *Foundations of Decision Analysis*. Prentice-Hall. 36

[96] Zaloga, S. J., 2006. *HMMWV Humvee 1980-2005: US Army Tactical Vehicle*. Osprey Publishing. 45

[97] Green, M., 2005. *Humvee at War*. Zenith Press. 45

[98] associated Press, 2006. Report: Added armor causing humvees to roll over Tech. rep., June 11, 2006. 45

[99] Saleh, J. H., Mark, G., and Jordan, N. C., 2009. "Flexibility: A multi-disciplinary literature review and a research agenda for designing flexible engineering systems." *Journal of Engineering Design,* **20(3)**, pp. 307–323. 47

[100] Friedman, N., 1983. *U.S. AIRCRAFT CARRIERS An Illustrated Design History*. Naval Institute Press. 67, 68

[101] , 2012. United states navy fact file: Aircraft carriers - cvn, October. 67, 68

[102] Malone, M. L., 2001. "An alternate method for the determination of aircraft carrier limiting displacement for strength." Master's thesis, Massachusetts Institute of Technology, June. 68

[103] Birkler, J., Mattock, M., Schank, J., Smith, G., Timson, F., Chiesa, J., Woodyard, B., MacKinnon, M., and Rushworth, D., 1998. *The U.S. Aircraft Carrier Industrial base: force structure, cost, schedule, and technology issues for CVN 77*. RAND Corporation. 68

[104] Koenig, P., Nalchajian, D., and Hootman, J., 2008. "Ship service life and naval force structure." In *American Society of Naval Engineers, ASNE symposium Engineering the Total Ship, Tysons Corner, Va., 23-25 Sept.* 69

APPENDIX A. EMPIRICAL STUDY OF 210 ENGINEERED SYSTEMS

As a foundation, a large variety of existing engineered systems are studied in search of patterns and principles that govern successful service-phase system evolution. It is believed that this empirical study will help develop an understanding of system evolvability in an effective way that capitalizes on existing system successes and failures.

The plan of this section is to understand how and why existing engineered systems leverage service-phase evolution in response to emergent needs. More importantly, this section aims to draw insights and conclusions about why certain CES are more effective at evolving than others.

A few of the studied systems are mentioned in Chapter 1 (e.g., the C-130, the Space Shuttle, GE products, smart phones, and the F-117). In total, 210 products were examined of varying complexity from disparate industries. Ultimately, significant insights can be drawn from successful and unsuccessful evolution in systems. The Humvee (HMMWV) [96, 97] is one example of a system that has undergone successful generational evolution, but has struggled to meet the demands of service-phase evolution. Designed primarily for personnel and light cargo transport behind front lines, the conflict in the Middle East saw these systems serving as elements of an occupying force. In urban warfare environments where the entire area is a combat zone, Humvees were used in roles they were never designed for. Unable to protect their passengers from close-range automatic weapons fire and rocket-propelled grenades, the U.S. military began upgrading current vehicles with armor kits. By adding thousands of pounds of steel to the chassis of the vehicle, "upgraded" Humvees have experienced excessive mechanical and wear problems, rollovers, and continued susceptibility to insurgent attack [97, 98].

The previously listed systems and the example of the Humvee demonstrate how an inductive approach facilitates an empirical study of service-phase evolution (see Figure A.1). Having preliminarily studied existing small and large-scale engineered systems and patents, ideas for achieving service-phase evolution exist; however, they have not been formalized. In addition, key

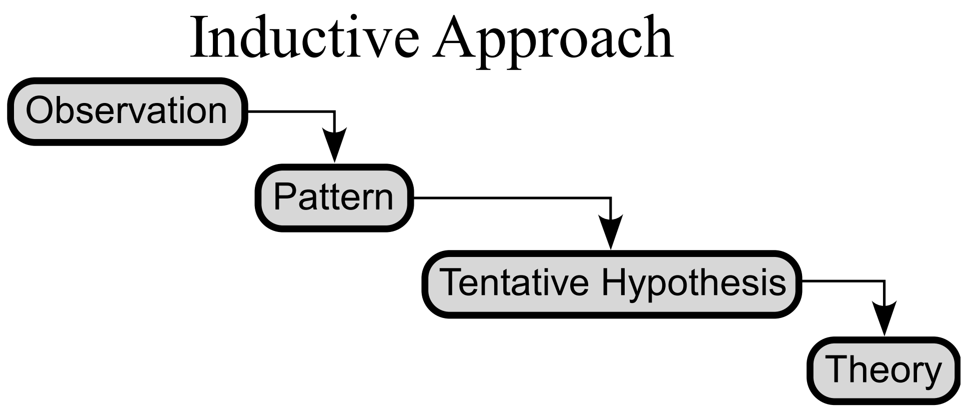

Figure A.1: Inductive approach for discovering system evolvability factors

features of service-phase evolution, such as modularity or adaptability [12], are identified. As part of this study, natural systems as they evolve generationally were not studied. On the other hand, we were able to draw insights from systems that have failed to evolve, leading to a discontinuation of use.

One specific industry that has many different complex engineering systems is defense - with an array of systems ranging in diversity from land, water, air, and space defense. As preliminary work, we have considered military aircrafts designed and used by the US, and have looked at the ways these aircrafts utilize service-phase evolution. A very small portion of the collected data is shown in Tables A.1, A.2, and A.3.

Table A.1: US Fighter Jet Aircraft

Fighter Jets				
Name (Year Introduced)	F-16 (1978)	F-18 (1983)	F-22 (2005)	F-35 (est 2016)
Years from First Flight to Introduction*	4	5	8	10
Number of Variants Introduced	6	19	4	5

*we use this as a preliminary (and rudimentary) measure of development complexity

From Tables A.1, A.2, and A.3, a general downward trend is evident in the number of aircraft variants introduced. In addition, the time in years between first flight and the introduction of that aircraft into military service is considered to be preliminary measures of system complexity.

Table A.2: US Bomber Aircraft

Bombers				
Name (Year Introduced)	B-36 (1949)	B-52 (1955)	B-1 (1986)	B-2 (1997)
Years from First Flight to Introduction	3	3	12	8
Number of Variants Introduced	21	14	3	0

Table A.3: US Cargo Aircraft

Cargo Carriers				
Name (Year Introduced)	C-131 (1950)	C-130 (1957)	C-5 (1970)	C-17 (1993)
Years from First Flight to Introduction	1	3	2	2
Number of Variants Introduced	42	52	6	3

In this sense, there seems to be a general upward trend in system complexity. For the aircraft that have evolved into numerous variants, key features of flexibility in architecture are observed that allows for modularity of components and the design of features that allow the users to reconfigure the system for changes in preferences, concepts, models, and environments [99]. Features like the F-14's variable sweep wing are examples of a reconfigurable aspect allowing aircraft to operate at different preferences and in various environments [49].

Additionally, for fighter jets there has been an increase in the development time (characterized by time between first flight and introduction) of the aircraft. This is largely influenced by the increased complexity of modern fighter jets. Furthermore, there are relatively low and steady development times for cargo aircraft. This is largely influenced by the architecture of cargo aircraft. One interesting observation is that the two aircrafts with the most variations are cargo aircraft that were designed in the 40's and 50's and were in service for more than 40 years. This is why the C-130 facilitates service-phase evolution so well; it is not only a cargo aircraft, but has also been able to reconfigure into a bomber and reconnaissance aircraft.

The evaluated 210 engineered systems range in complexity from a bicycle to the international space station. The observed trends in market demand and the amount of system complexity found in those markets have been evaluated. For instance, the highest human demand is found in water treatment, food systems, and shelter infrastructure. Within these markets there are complex engineering systems, such as farm equipment, canals, dams, and skyscrapers. Other areas in society defined by highly complex systems include: healthcare, defense, transportation, communication, and energy, to name a few. The collection of engineered systems can be seen below in Table A.4 and A.5, where 173 engineered systems evolvability attributes are detailed.

Table A.4: Engineered Systems with Evolvability Attributes

#	Engineered System	Evolvability Attribute	Market
1	Panama Canal	Reconfigurable gates, changeable water level, and large lock volume allows the system to evolve for different ship sizes and changes in ocean elevation.	Transport
2	Falkirk wheel	Lock volume allows the system to evolve for different ship sizes.	Transport
3	World's largest water pump, New Orleans	Modular components like propeller blades and gears, along with extra horsepower in the motor allows the system to evolve through new components and changing water pump demands, respectively.	Food
4	Kifco water reel	Extendable, retractable water tube reel allows the system to evolve for different environments.	Food
5	Chapin backpack crop sprayer	Interchangeable components allow the system to change components, but not necessarily evolve while in service.	Food
6	Tractor 3 point hitch crop sprayer	Ability to attach this system to a tractor or the modularity of the tractor allows the system to evolve to meet new operating environments.	Food
7	Tractor trailer for crop spraying	Reconfigurable arms allow for two operating environments spraying crops and collapsed for storage.	Food
8	Agricultural aircraft	Many agricultural aircraft were not designed for agricultural use, but have evolved for these operating conditions. The ability of these aircraft to evolve to agricultural aircraft has been through adding agricultural components (chemical holders and sprayers) and having system robustness to operate in these new conditions.	Food
9	Amphorae wave plant block	Repeating geometry that can interlock allows the components to be connected, stacked, or arranged to evolve this vertical garden for the needed environment, operations, and requirements.	Food

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
10	Hydroponics	The ability to change the light source and nutrition in hydroponics allows for evolution in the system for customer needs.	Food
11	Big Bud 747, largest farm tractor	An excessive amount of horsepower and weight allows this system to evolve to operating conditions that normal tractors cannot operate in.	Food
12	8030 series John Deere tractor	The modular nature of tractors facilitates different components to be attached for many different operations. This allows tractors to evolve to many different operating conditions.	Food
13	John Deere cultivator	T-style hitch allows the system to be a modular component for tractors in new operations.	Food
14	John Deere plow	T-style hitch allows the system to be a modular component for tractors in new operations.	Food
15	Farm planter	Modular farm equipment allows a single tractor to meet many different requirements through system modularity.	Food
16	Farm harvester	Modular farm equipment allows a single tractor to meet many different requirements through system modularity.	Food
17	Farm mower	Modular farm equipment allows a single tractor to meet many different requirements through system modularity.	Food
18	Farm baler	Modular farm equipment allows a single tractor to meet many different requirements through system modularity.	Food
19	Food sorting machines	The modular and reconfigurable nature of this system allows it to change capacity and functionality.	Food
20	Cow milking equipment	The ability to expand the system capacity when needed allows this system to evolve.	Food
21	Food processing equipment	The modular and reconfigurable nature of this system allows it to change capacity and functionality.	Food
22	Food silo	This system is built with excess capacity of storage to allow it to meet varying demands.	Food
23	Fishing trawlers	Adjustable netting for different fishing conditions.	Food

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
24	Fishing seiners	Upgradable equipment allows for increased capacity as operations demand.	Food
25	Large fishing vessels	Incorporates many different operations of fishing into one vessel (floating fish factory) through the capacity to catch, gut, clean, and freeze fish. Vessel can evolve by having the needed resources (e.g., power, volume, displacement) to incorporate such capacities.	Food
26	Food freezer	Modular component that can be added to a fishing vessel.	Food
27	Fish separator	Modular component that can be added to a fishing vessel.	Food
28	Itaipu Dam	Reconfigurable gates and modular components that can be updated allow this dam to evolve for changing conditions.	Water
29	Three Gorges Dam	Reconfigurable gates and modular components that can be updated allow this dam to evolve for changing conditions.	Water
30	Water tower	The static volume and constant system output pressure (gravitational force) can be seen as reasons why this type of system has not been able to evolve to new system requirements.	Water
31	Rain water hog	This modular water storage system allows new modules to be added as needed.	Water
32	Modular tanks	Versatile liquid storage through modular tanks enables easy system adaption to changing needs.	Water
33	Mod tanks	Uniform modules that easily interface with each other allow easy configuration changes of the system for new requirements.	Water
34	Canal	Canals with reconfiguring water ways allows for changes in water flow (changing environment), but traditional canals are very static in operation, which led to failure in operation or flooding.	Water
35	Levees	Levees are used to hold back excess water and therefore need to be able to meet the requirements of evolving weather patterns. If they are not built with excess capacity, they can fail to evolve to system requirements and system failure can occur, like the levee failures in New Orleans with hurricane Katrina.	Water

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
36	Modular piping	Standard interfaces allow piping to be evolvable for many different scenarios.	Water
37	AdEdge modular water filter	AdEdge Modular systems are available in a variety of flow rates and configurations to meet needs from 10 to 120 gallons per minute. Modular systems are primarily used on applications with relatively small flow rates, limited space, and the lowest cost treatment option is preferred without sacrificing performance.	Water
38	Water filter	Self contained water filter modules allow adaption of new modules for changing requirements.	Water
39	Septic tank	Tanks are modular in nature, which allows easy interchanging and upgrading of the system.	Water
40	Sewer treatment plants	Robust system capabilities allow the system to operate in a wide range of system operations.	Water
41	Modular appliances	Modular kitchen appliances allow users to reconfigure their kitchen to their personal preference.	Shelter
42	Scaffolding	The expandable and collapsible nature of this system allows it to transform to the needed configuration.	Shelter
43	Win Tech modular	The true flexibility of the modular building system is that adopting a standard module design allows for a building to be either extended or reduced in size over a period of time and the layout modified to suit changing requirements.	Shelter
44	Drop box Inc.	Using the existing module of a shipping container, Drop box Inc. will customize a shipping container for individual user needs (e.g., housing, store, restrooms).	Shelter
45	Express modular	Use of modular home construction can provide the highest quality while providing the greatest value, making it easy to be successful in building new custom homes.	Shelter
46	Mobile home	While the requirements of shelter are pretty standard, mobile homes are a system that can be used in many different environments or locations.	Shelter

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
47	Modular pocket knife	Switch - Your Tool, Your Way: Switch is the ultimate modular pocketknife, with 18 different attachments so users can mix and match most frequently used tools.	Shelter
48	Black & Decker tool system	The Matrix system tool from Black & Decker is a good find. The design features a single base power unit with a variety of head attachments that let users go from drilling, sanding, routering, and sawing by just popping on a new head.	Shelter
49	Northerntools modular welding table	The innovative design lets users clamp anywhere on the table using the slots or the holes for faster, more efficient fixturing and job layout.	Shelter
50	Reconfiguring aircraft	Modular aircraft design seeks to achieve this by connecting different modules together in a flexible and changeable way. Morphing aircraft achieve similar changes to configuration by reversible changes to the structural units. Re-configurable aircraft are effectively a sub-set of modular aircraft and have changes made by exercising one of a pre-planned series of possible changes to give a limited number of variants of the original design.	Transport
51	Droop nose aircraft	The droop-nose configuration is a distinctive feature of some supersonic aircraft, most notably both Concorde and the Tu-144. When these aircraft were in service, the pilot would lower the nose to improve visibility of the runway and taxiways. When in flight, the nose would be raised.	Transport
52	AD1 aircraft	The Ames-Dryden (AD)-1 was a research aircraft designed to investigate the concept of an oblique (or pivoting) wing. The oblique wing could be rotated on its center pivot so that it could be set at its most efficient angle for the speed at which the airplane was flying.	Transport
53	Hot air balloon	The hot air balloon was one of the first air vehicles. However, due to the system being unable to evolve further, hot air balloons are only a novel air transport vehicle, and have not been able to evolve to the new demands in air transport vehicles.	Transport

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
54	Modular airship system	A modular airship system capable of assembling and disassembling two or more modular airships while in flight. The assembled modular airships providing improved lift and loft characteristics, while the disassembled modular airships provide for improved ground handling, storage, and transport. The modular airship comprises a coupling device to couple two or more modular airships together while in flight.	Transport
55	Lockheed Martin blimp	This high altitude airship allows for evolution in surveillance, telecommunications, and weather observer in this new platform.	Transport
56	Boeing V-22 Osprey	The Bell Boeing V-22 Osprey is an American multi-mission, military, tilt rotor aircraft with both a vertical takeoff and landing (VTOL), and short takeoff and landing (STOL) capability. It is designed to combine the functionality of a conventional helicopter with the long-range, high-speed cruise performance of a turboprop aircraft.	Transport
57	Submarine	While a submarine has the ability to evolve through new technology insertion, they are a limited system when it comes to system evolution in operations.	Transport
58	River Hawk Fast Sea Frames	River Hawk builds fast sea frames that can be outfitted as required and reconfigured as mission, threat, and technology change.	Transport
59	N55 boat	The modular boat is constructed from a space lattice system of stainless acid resistant steel, which combines optimal strength with low weight. Half-octahedral tanks are built into the deck that connects the two floats. In combination with polycarbonate lids, they provide flexible space for different functions and items: ladder, anchor, seats, tables, stowage, compass, battery containers, etc. These functions can be fastened and moved around as desired.	Transport
60	Cruise ships	Low evolvability is found in cruise ships which could be due to minimal changes in operating needs.	Transport
61	Ferries	Low evolvability is found in ferries which might be due to low variation in operating environments.	Transport

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
62	Humvee (HMMWV)	The High Mobility Multipurpose Wheeled Vehicle (HMMWV), commonly known as the Humvee is highly evolvable due to the reconfigurable, interchangeable nature of its design.	Transport
63	Space Camper Van	The concept of the Space Camper puts everything a full blown much larger camper has into a T5 transporter, and reconfigures the layout so that it can be repurposed for use in multiple roles.	Transport
64	Folding camper trailers	These systems are both modular (can be towed as a module) and reconfigurable (camping configuration and transportation configuration) to allow the system to evolve for all operating conditions.	Transport
65	Reconfigurable simulator	The Reconfigurable Vehicle Simulator (RVS) has evolved to support the Infantry Brigade Combat Team, Airborne, Rangers and Special Forces units as well as Improvised Explosive Device-Defeat (IED-D) training.	Transport
66	Automated Carwash	There are many different shapes and sizes of cars on the road. Therefore, automated carwash systems must be adaptable for the evolving shapes and sizes of cars.	Transport
67	Emergency response vehicles	Ambulances and fire trucks are built with system capacity to meet the demands of the many different scenarios they must respond too.	Transport
68	Semi-truck	The standard interface of a semi-truck and trailer allows this system to incorporate many different trailers for many different operations.	Transport
69	Fork-lift	Interchangeable forks, adjustable fork position, and excess weight of a fork-lift allow it to transport and move a wide range of cargo.	Transport
70	Portable bicycle	A collapsible bike allows for two configurations: riding and transportation.	Transport
71	Modular bicycle	This modular bike can be easily coupled with a second bicycle. For a great and secure tandem side-by-side manner the bicycles can be fixed together with three main joints: the front steering, the back joint-which is sited at the back wheel of the inner frame, and the front joint that is positioned at the front of the outer frame.	Transport

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
72	Zigo bicycle	The Zigo is a modular bicycle that allows users to carry a team of kids in the Child Pod up front, unlike other bikes that have the child sitting behind. In this manner, users can keep a good eye on their children while riding. After reaching the desired place, the detachable Child Pod can be removed and transformed into a stroller in about 30 seconds.	Transport
73	Motorcycle attachments	Motorcycle side carts, trailers, and interchangeable components allow these systems to evolve for new system requirements.	Transport
74	Scooter	In many developing countries, scooters have evolved for many diverse operations, like tuk tuks in Cambodia or a vehicle for a family of four in China.	Transport
75	Cool Rider personal transporter	A personal transport vehicle with multiple configurations for operation.	Transport
76	Toyota Winglet	A personal transport vehicle with a simple stand on interface that can accommodate many different shapes and sizes of people.	Transport
77	Segway	A personal transport vehicle with a simple stand on interface that can accommodate many different shapes and sizes of people.	Transport
78	Trains	The modular design of train cars allows for easy configuration changes of the train modules when needed.	Transport
79	Highways	Highways are a very static system in that they cannot move. But the way in which highways are used can evolve like changing the flow of cars to meet rush hour needs.	Transport
80	Roads	Roads are a very static system in that they can not move. However, the way in which roads are used can evolve, like changing the flow of cars to meet rush hour needs.	Transport
81	Moveable bridges	A moveable bridge is a bridge that moves to allow passage (usually) for boats or barges. An advantage of making bridges moveable is the lower price, due to the absence of high piers and long approaches. The principal disadvantage is that the traffic on the bridge must be halted when it is opened for passages.	Transport

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
82	Manned Maneuvering Unit	The unit featured redundancy to protect against failure of individual systems.	Transport
83	Mars rovers	The Mars rovers must be some of the most evolvable engineered systems because once they leave earth they must evolve on their own to the environment, conditions, and operations of Mars. Some features include energy storage capacity and adaptability for surface environments.	Transport
84	Space Exploration Vehicle (SEV)	The Space Exploration Vehicle (SEV) is a modular multi-mission vehicle concept developed by NASA. Modular space suits and a truck design vehicle facilitate a wide range of missions.	Transport
85	Rockets	Most rockets are designed for a one time use. However, the Space Shuttle Solid Rocket Boosters (SRBs) were reusable, which led to evolution of components for new missions.	Transport
86	Modular oil drilling rig	Flexibility is at the heart of the modular rig concept. Whether in its mobilization or its operations, everything is built to allow maximum flexibility in order to cut costs.	Energy
87	Tankers	Large cargo capacity within tankers for oil or natural gas transport allow these systems to evolve for changing cargo demand.	Energy
88	Oil platform module	Oil rig platforms are made into large modules that are then relocated to off-shore drilling sites. Modularity of these systems allows for easier transportation and assembly.	Energy
89	Oil pipeline transport	Interchangeable pipe diameters and variable flow rates allow pipeline transportation of goods to adjust to the needed output.	Energy
90	Modular petroleum refining	A modular refinery is one whose parts or equipment are constructed in modules designed to be transported quickly and easily anywhere in the world and comes in a variety of sizes with capacities that range from 500 to 20,000 barrels per day.	Energy

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
91	6FA Heavy Duty Gas Turbine	Featuring a compact layout, fuel flexibility, and strategic configuration options, the 6FA gas turbine excels in a variety of applications for decentralized power generators, industrial businesses, and district heating users.	Energy
92	MW191 Gas Turbine	MW191 type engine frame has proven to be a low maintenance, reliable, and highly serviceable turbine. The MHI MW101/MW191 type gas turbine fleet has accumulated an impressive number of operating hours and is highly appreciated for its reliability and availability in extreme operating environments.	Energy
93	Turbine blades	Modular turbine blades and standardized interfaces allow for easy maintenance and upgrade of existing blades.	Energy
94	Modular wind turbine	Modular components in this large wind turbine allow for ease in transportation and assembly of the system.	Energy
95	Modular Wind Energy blade	Wind energy turbine blades are a modular design for improved logistics, site assembly, bonding, and erection of blades.	Energy
96	Hydro generator	Interchanging of components allows generators to evolve through new technology insertion.	Energy
97	Solar generator	Solar generators have the ability to meet new system demands through integration of added solar panels.	Energy
98	Energy storage	Energy storage is accomplished by devices or physical media that store energy to perform useful operation at a later time.	Energy
99	Overhead power lines	Towers that hold power lines are built with multiple connection points for the evolving needs of additional power lines.	Energy
100	Power converters	A power converter is an electrical or electro-mechanical device for converting electrical energy. This could be as simple as a transformer to change the voltage of AC power, but also includes far more complex systems.	Energy
101	Reebok deck	Expandable, collapsible, and reconfigurable components on this system allow it to evolve for user preferences in height and functionality.	Health

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
102	Modular GYM	Modular gyms allow users to choose from five components to custom the ideal gym experience. It accommodates up to four users at one time and allows for equipment to be added/removed to adapt to user preferences and needs.	Health
103	Home GYM	Home gyms are adaptable for many uses for many different people. Users can use home gyms for convenience, without having to travel far. The home gym is convenient to their location. Many home gyms provide various exercises without having to change machines.	Health
104	Bow flex	The design of the Bow flex provides multiple uses in one product. It can serve as a pull up, push up, sit up, lifting, etc. machine for individual exercise.	Health
105	Modular X-ray	Compensation curves on this x-ray exposure time control can reconfigure to account for variable effects on x-ray film.	Health
106	Arcomat table	This table reconfigures to allow for different positioning for patients.	Health
107	Reconfigurable healthcare table	Reconfigurable healthcare items can change to meet different requirements. Articulated arms can provide different motions for healthcare equipment and provide optimal services.	Health
108	CT scanner	CT scanners are reconfigurable to meet many different orientations and positions. The movable support frame, scanning axis, x-ray detectors, mounts, etc. can all adapt to fit needs for vertical or horizontal situations.	Health
109	MRI	The upgradability of software and some hardware allows these systems to evolve to new needs.	Health
110	Blood work machine	These machines can reconfigure to meet various configurations, each being optimized for a certain environment, such as home, travel, or a dialysis center.	Health
111	AED	A standard interface of sticky pads to the human body allows this system to function on any human.	Health

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
112	Modular AED	Interchangeable components allow the system to change components and evolve through new technology insertion.	Health
113	Anesthesiology machine	These machines can evolve to meet four primary functions. Some traditional machines only meet one need for a doctor; however anesthesiology machines can work to meet multiple needs at once.	Health
114	Acuson V219 Ultrasound Probe Transducer	Varying ultrasound prodes allow the system to evolve for new or improved operation.	Health
115	Dynamic clean room	Conveyors found in these clean room are reconfigurable to become ramps, tables, slides, etc. The flexible design allows for width, incline, decline, turn, etc. changes. These clean room products are maintenance free, energy efficient and cost effective to repair.	Health
116	Clean room	Modular conveyors are reconfigurable by removing, inserting, or exchanging modules of different shapes and sizes. These conveyors are clean room ready, which make them ideal for most FDA specifications.	Health
117	Lab room	Modular lab rooms can be easily assembled, moved, modified, and re-erected as needs change. Various modular workspaces provide different construction needs for specific lab requirements.	Health
118	Modular conveyor	Conveyors are a necessity for plants and therefore, need to be flexible and adaptable for different scenarios and user needs. Reconfigurable modular conveyors evolve to unite the requirements and preferences of controllers and engineers. Older conveyors have a limited amount of fixed dimensions and standard abilities, while newer modular conveyors can be put together to achieve different desired results.	Health
119	Reconfigurable manufacturing system	Meet the needs of global markets and can adjust to fluctuations in product demand, specifications, and changing technology needs.	Health
120	Wheelchair	Varying styles of wheelchairs can adapt to meet the needs of individual users.	Health

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
121	Army tank	Army tanks can evolve to meet certain needs depending on the environment. The Patria AMV modular vehicle can adapt to various types of land and water conditions and is equipped for multiple (at least four) variants.	Defense
122	XM8 Gun	The XM8 is a modular assault weapon with different barrels and modules that can be changed out quickly depending on different situations. There are four variants: baseline carbine, compact carbine, sharpshooter variant, and automatic rifle.	Defense
123	Bomb Robot	This evolvable system is delicate enough to disarm a bomb instead of detonating, it is inexpensive, and can mend itself.	Defense
124	Off-road vehicle	This system can evolve through new component addition and a robust design that allows it to operate in many different environments.	Defense
125	Wireless communication	Reconfigurable antenna have switch configurations that can be modified to adapt to changes in the environment. Different patterns can lead to improved capacities for antenna and wireless communication.	Defense
126	Reconfigurable communication	Technology today has evolved digital hardware to act as a type of reconfigurable communication powerful enough to perform multiple operations. High performance signal processing has become more available. By using a reconfigurable architecture, a single hardware platform can be used for different applications with different processing needs.	Defense
127	Missile	Missiles are reconfigurable in flight by changing certain vehicle dynamics. In-flight reconfiguration allows to adaptability to threats and reduces launch time without impairing the missiles function or reliability.	Defense
128	AASM missile	This air-to-ground modular weapon can integrate different types of guidance units and different types of bombs.	Defense
129	XC-120 aircraft	This aircraft used removable cargo pods attached below the fuselage instead of an internal compartment, and had landing gear that could be raised/lowered in a scissor like fashion to simplify and quicken the load/unloading procedures.	Defense

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
130	Fieseler Fi 333	The very tall braced undercarriage of this transport aircraft was made unretract able and designed to evolve to fit varying sizes of cargo without the strain of heavy cargo.	Defense
131	Harrier aircraft	Can evolve to meet needs of both vertical/short takeoff and landing operations. Started as a jet to operate from car parks or forest clearings, then later adapted for larger uses, such as from aircraft carriers. It can serve as a naval strike or air defense fighter.	Defense
132	Variable sweep wing	Reconfigurable wing aircraft enable multiple system operation capabilities and environments.	Defense
133	EMALS	Evolves to meet needs of more hostile environments and able to operate from an aircraft carrier at sea instead of only on land. Can adapt to meet needs in different environments.	Defense
134	Reconfigurable UAV	This system takes advantage of reconfigurability to be able to operate as a single UAV system that can operate in the many needed environments and conditions.	Defense
135	HADA reconfigurable UAV	The objective of the "Helicopter ADaptive Aircraft" (HADA) is the development of a reconfigurable Unmanned Air Vehicle (UAV) that performs both as a helicopter for take-off, landing and hovering flight, but that "morphs" in flight to a conventional fixed wing configuration for cruise flight.	Defense
136	Modular UAV	Interchangeable components allow the system to change components and evolve for different missions.	Defense
137	Defense Submarine	The Virginia Class defense submarine design uses Technology insertion to implement advanced technologies as they become available. Evolves to meet new technologies periodically without needing complex and expensive redesigning.	Defense
138	Offshore base	Provides support for military operations when other land bases are not available.	Defense

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
139	Hover craft	Hover crafts are evolvable to meet needs of different vehicle aspects (boating, flying). Also, the fuel economy of hover craft is better than a boat.	Defense
140	Hover wing	This Hover wing is able to fly due to a set of unusual aerodynamics. It can change to meet the needs of a boat (on water) a hovercraft (above water) and then act as a plane (in air). The wings can be extended for these different scenarios.	Defense
141	Battleships	Ship design margins compensate for growth in the system and allow the addition of new technology insertion into the system.	Defense
142	Modular network design	A fundamental concept related to hierarchy is modularity. Large network design projects and large networks in general consist of different areas and modules.	Defense
143	Evolvable Internet hardware	Network routing platforms and Internet firewalls of the next decade will be radically different than the platforms of today. They will contain modular components that can be dynamically reconfigured over the Internet.	Comm
144	Telephone	Traditional telephones have the ability to have reconfigurable hardware, providing flexibility, time efficiency, etc.	Comm
145	Cell phone	Mobile phones have the ability to have reconfigurable hardware, such as field programmable gate arrays, provide flexibility in developing new features quickly and reduce time to go to the public market.	Comm
146	Package	Packaging materials can be reconfigurable to be used for bulk shipments or individual shipments for the same products. This saves in cost of packaging materials and waste.	Comm
147	Intel Server	Modular servers can evolve for many different communication needs, helping with time management, flexibility, value, etc.	Comm
148	Robots	Robots can transform/evolve into vehicles (similar to the idea of Transformers). Example: Humvee Biloid. Robots can also evolve to assist in battlefield situations (e.g., Battlefield Extraction-Assist Robot).	Other

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
149	Modular products	Modular products, such as buildings, data venter, cars, furniture, etc. allow for multiple uses with the same product. Modular furniture, for example can be reconfigured from a floor design, to a couch, to a bed, to a table, just by rearranging moveable parts.	Other
150	Mobile Launcher Platform	Operates as both a support system for Space Shuttles transportation as well as a launch platform. Is able to evolve to meet needs of different scenarios and Space Shuttles.	Transport
151	Enterprise Space Shuttle	Six Space Shuttles were used for manned space flights from 1981 to 2011. Special mission requirements necessitated service-phase evolution that lead to orbiter add-ons including orbital laboratories, boosters for launching payloads farther into space, logistics modules, and Canadarm. Missions included manned space flight, scientific experiments, space station docking, spacewalks, and satellite launching and repair. Additionally, the orbital laboratory Spacelab was itself evolvable, using a modular architecture to support special missions.	Transport
152	Columbia Space Shuttle		Transport
153	Challenger Space Shuttle		Transport
154	Discovery Space Shuttle		Transport
155	Atlantis Space Shuttle		Transport
156	Endeavour Space Shuttle		Transport
157	Spacelab	Spacelab was a reusable laboratory used on certain spaceflights flown by theSpace Shuttle. The laboratory comprised multiple components, including a pressurized module, an unpressurized carrier and other related hardware housed in the Shuttle's cargo bay. The components were arranged in various configurations to meet the needs of each spaceflight.	Transport
158	International Space Station	The ISS is a modular structure whose first component was launched in 1998. The ISS consists of pressurised modules, external trusses, solar arrays and other components.	Shelter

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
159	Hubble space telescope	Hubble is the only telescope designed to be serviced in space by astronauts. Between 1993 and 2002, four missions repaired, upgraded, and replaced systems on the telescope. One final servicing mission, completed in 2009 by Space Shuttle Atlantis. The telescope is now expected to function until at least 2013.	other
160	Freedom Littoral combat ship (LCS)	The LCS designs add the capabilities of a small assault transport with a flight deck and hangar large enough to base two SH-60 Seahawk helicopters, the capability to recover and launch small boats from a stern ramp, and enough cargo volume and payload to deliver a small assault force with armoured fighting vehicles to a roll-on/roll-off port facility. The LCS concept emphasizes speed, flexible mission module space and a shallow draft.	Defense
161	Independence Littoral combat ship (LCS)		Defense
162	USS Enterprise (CVN-65)	The USS Enterprise was the first nuclear aircraft carrier ever built, and as such, had areas of over design due to a lack of knowledge. These over designed features aided this warship in becoming the longest serviced warship in the US Navy of 51 years. In addition, it has evolved to meet many new threats and missions.	Defense
163	USS Nimitz (CVN-68)	Over the lifespan of the Nimitiz-class many new technologies have been successfully integrated into the design of these vessels. However, with the technical advances made in the past decade the ability of the Navy to make improvements to this class of ship has become more limited. Some of the biggest problems facing the Nimitz-class are the limited electrical power generation capability and the upgrade-driven increase in ship weight and erosion of the center-of-gravity margin needed to maintain ship stability.	Defense
164	USS Dwight D. Eisenhower (CVN-69)		Defense
165	USS Carl Vinson (CVN-70)		Defense
166	USS Theodore Roosevelt (CVN-71)		Defense
167	USS Abraham Lincoln (CVN-72)		Defense
168	USS George Washington (CVN-73)		Defense

Table A.4: (continued)

#	Engineered System	Evolvability Attribute	Market
169	USS John C. Stennis (CVN-74)		Defense
170	USS Harry S. Truman (CVN-75)		Defense
171	USS Ronald Reagan (CVN-76)		Defense
172	USS George H.W. Bush (CVN-77)		Defense
173	USS Gerald R. Ford (CVN-78)	Increased capacity of electrical power generation, ship stability, margin for additional ship weight, and reconfigurable room infrastructure are some of the new design changes to the Ford-class carriers. These features allow this system to evolution for many missions and new threats.	Defense

For additional engineered systems (174-210) see Table A.5 below.

In sum, excess in engineered systems (be it cargo capacity (volume), engine power, or any other form of excess) aids in the evolution of engineered systems. Moreover, a system's ability to add, remove, or rearrange modules allows the system to change over time. These two measure of system evolvability differ by the system having excess or being modular. Therefore, we simplify the evolvability attributes of the 173 engineered systems (Table A.4) to Excess and Modularity.

Table A.5: List of United States Aircraft from 1930's to Present

Aircraft	First Flight (FF)	Years between FF to Intro	Introduction	Retired	Variations	#
Fighter jets						
F-35	15-Dec-06	10	2016		5	174
F-22	7-Sep-97	8	15-Dec-05		4	175
F-117	18-Jun-81	2	15-Oct-83	22-Apr-08	0	176
F-18	18-Nov-78	5	7-Jan-83		19	177
F-16	2-Feb-74	4	17-Aug-78		6	178
F-15	27-Jul-72	4	9-Jan-76		9	179
F-14	12/21/1970	4	Sep-74	10-Mar-06	3	180
F-8	25-Mar-55	3	Mar-57	1976	27	181
F-11	30-Jul-54	2	1956	1961	4	182
F-101	29-Sep-54	3	May-57	Jun-05	19	183
F-102	24-Oct-53	3	Apr-56	1979	9	184
F-84	28-Feb-46	1	Nov-47	mid-1960s	18	185
P-38	27-Jan-39	2	1941	1965	6	186
Bombers						
B-2	17-Jul-89	8	Apr-97		0	187
B-1	23-Dec-74	12	1-Oct-86		3	188
B-70	21-Sep-64			4-Feb-69	5	189
B-58	11-Nov-56	4	15-Mar-60	31-Jan-70	8	190
B-57	20-Jul-53	1	1954		16	191
B-52	15-Apr-52	3	Feb-55		14	192
B-45	3/17/1947	1	4/22/1948	1959	5	193
B-50	25-Jun-47	1	1948	1965	14	194
B-47	17-Dec-47	4	Jun-51	1969	28	195
B-36	8-Aug-46	3	1949	12-Feb-59	21	196
B-29	21-Sep-42	2	8-May-44	21-Jun-60	2	197
B-24	29-Dec-39	2	1941	1968	29	198
B-17	28-Jul-35	3	Apr-38	1968	15	199
Reconnaissance						
SR-71	22-Dec-64	2	1966	1998	3	200
U-2	1-Aug-55	2	1957		18	201
Cargo						
C-17	15-Sep-91	2	14-Jul-93		3	202
KC-10	12 July 1980	1	March 1981			203
C-5	30-Jun-68	2	Jun-70		6	204
C-135	17-Aug-56	1	Jun-57		8	205
C-130	23-Aug-54	3	Dec-57		52	206
C-131	1949	1	1950	1990	42	207
C-123	14-Oct-49	1	1950	1980	18	208
C-125	1-Aug-49	1	1950	1955	4	209
DC-3	17-Dec-35	1	1936	1942	19	210

APPENDIX B. NUCLEAR AIRCRAFT CARRIER EXCESS VALUES

Figure B.1: Display of hull dimension of nuclear aircraft carriers (USS John C. Stennis [1])

Excess Displacement

As ships age, they get heavier due to new paint, barnacles, and the addition of new equipment. A "Service Life Allowance" of 7.5% weight margin (displacement) on aircraft carriers is now required [82]. The excess displacement percentage (%) is calculated by [a ship's displacement limit (capacity) minus actual displacement] divided by the ship's displacement limit. The displacement limit (combat) is 91,878 long tons (LT) and actual displacement is 91,440 (LT) [100]. The Nimitz-class carriers have ≈1% weight margin remaining [82]. The Ford-class displacement limit is ≈107,500 (LT) and actual displacement is ≈100,000 (LT) [82, 101].

Excess Volume

Aircraft carrier overall volume is normally static; however, the percentage of unused volume in a carrier can change. The Nimitz-class volume is the Length at WaterLine (LWL) 1,040 (ft) times the beam at WaterLine (WL) 134 (ft) times the hull depth (keel to flight deck) 100.5 (ft), equals the volume at 14 E^6 (ft^3) [100]. A ≈3% unused volume margin is used for the Nimitz-class [82]. The Ford-class volume is the length 1,092 (ft) times the beam 134 (ft) times the hull depth ≈100.5 (ft), equals the volume at 14.7 E^6 (ft^3) [80, 101]. An ≈4% unused volume margin is used for the Ford-class (because of the flexible infrastructure [81]).

Excess Stability

A maximum center of gravity limit (KG_{limit}) for Nimitz-class stability is 48.5 (ft) and actual (KG) is 46.83 (ft) [83, 102]. Compared to the Nimitz-class, the Ford-class has ≈5% restored stability at a (KG) of 44.67 (ft) [80]. Also, the same (KG_{limit}) as the Nimitz-class (48.5 (ft)) is used for the Ford-class. Excess stability percentage (%) is calculated by [(KG_{limit}) minus (KG)] divided by (KG_{limit}).

Excess Electrical Power

Maximum power output for aircraft carriers is listed in units of shaft horsepower; it is assumed that all shaft horsepower can be converted into electrical power for calculations of the output in Mega Watts. Nuclear aircraft carriers are not all-electrical ships, but this is used for the purpose of excess percentages calculations. The Nimitz-class maximum electrical power output is 193.9 (MW) [100, 103] and the electric power margin is exhausted [82]. Therefore, An average electrical power demand of ≈192.7 (MW) (≈0.6% electrical power margin) is used. The Ford-class maximum electrical power output is three times that of the Nimitz-class at 581.7 (MW) [80]. The Ford-class average electrical power demand is greater because of electric auxiliary systems at ≈391.9 (MW) [80]. Excess electrical power percentage (%) is calculated by [max electrical power output minus average electrical power demand] divided by max electrical power output.

Service Life Allowance

There are many different ways to represent data, trends, and information through functions. Three different gain functions (linear, natural log, and Gaussian distribution) were shown in Chapter 2. To further clarify how unit gains (g_c and g_m) may be represented, one method used by the US Navy is "Service Life Allowance" calculations. According to Koenig et al., "the process of evolution is a key factor in distinguishing different alternative future plans, and ship service life [is] one of the principal evolutionary mechanisms" [104]. Alternatively, "Service Life Allowance" is above and beyond service life measures [2]. We point out that methods for determining gain parameters could be curve fits to known data, extrapolation, interpolation, and linear approximation. A general rule of thumb is to use a curve fit on trusted data; if data is not available, linear approximation can be useful, and then later, curve fits to collected data or related data can be used.