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A Model for Quantifying System Evolvability Based on Excess and Capacity

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. In a different study, we examined 210 engineered systems and found that system excess and modularity allow a system to evolve while in service. Building on this observation, the present paper introduces mathematical relationships that map a system's excess to that system's ability to evolve. As introduced in this paper, this relationship is derived from elastic potential-energy theories. The use of the evolvability measure, and other related measures presented herein, are illustrated with simple examples and applied to the design of U.S. Navy nuclear aircraft carriers. Using these relationships, we show that the Navy's new Ford-class aircraft carrier is measurably more evolvable than the Nimitz-class carriers. While the ability for systems to evolve is based on excess and modularity, this paper is focused only on excess. The mapping between modularity and evolvability is the focus of another work by the authors. [DOI: 10.1115/1.4026648]

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1 Introduction

Large-scale engineered systems are essential to the modern, developed world. Yet, these systems are extremely challenging to design because they have complex internal interactions that couple numerous subsystems from disparate disciplines. *Design-phase evolution* takes such systems from embryonic ideas, to rough embodiments, to refined architectures. Research has explored how to maximize freedom throughout the design process, allowing for modifications to a system to occur with minimal rework or cost penalties [1–3]. However, large-scale engineered systems remain in service for extended periods of time, making it prohibitively difficult to predict all future operating scenarios and environments during the design process. 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.

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 [4]. This belief is supported by the literature, where system changes have been found to accomodate unexpected emergent behavior, changes to the goals of the system, emergent technologies, new missions, and resiliency [5–7]. Yet, while the need for service-phase evolution is soundly established, our understanding of how to best realize such capabilities is not fully developed [8]. Toward this goal, the Generational Variety Index [9] and work in high reliability organizations [10] explore how elements of an architecture change over time. 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 [11]. Flexibility in patents and products were studied by Keese et al., who generated 24 guidelines across the topic areas of modularity, parts reduction, spatial considerations, interface decoupling, and adjustability [12]. Use of these principles has been demonstrated when leveraged with change modes and effects analysis [13] for future evolvability [14] and with the definition of a high-definition design structure matrix (HD-DSMs) [15]. 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 [16].

A limitation of the above approaches is that they mainly serve to establish guidelines for a designer. More quantitative approaches typically try to capture the value associated with such a system or its complexity [17]. For example, Sandborn and Herald propose the use of Bayesian decision networks as a way of measuring system viability by aggregating system producibility, supportability, and evolvability [18]. 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 [19]. 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 [20]. Finally, an approach for calculating an evolvability advantage is introduced by Ref. [21] who use Epochs as static snapshots of the system. Monte Carlo simulations and Markov probability matrices are used to analyze the execution of "change mechanisms."

Motivated by these works, this paper introduces mathematical relationships capable of mapping a system's excess 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 dividend of evolutionary options while a system is in service. To further describe service-phase evolution, consider Fig. 1.

Figure 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

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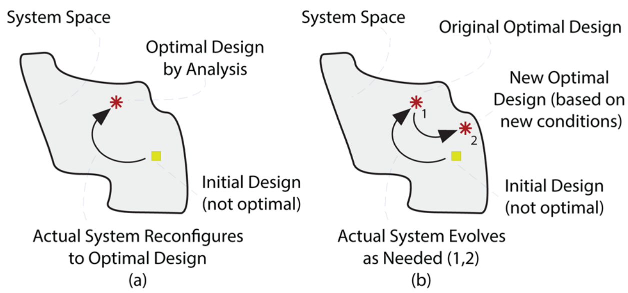

Fig. 1 System reconfigures once in (*a*) and evolves to needs in (*b*)

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 suboptimal. Having been designed to be reconfigurable, the initial system reconfigures to the desired optimal state. Figure 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.

Service-phase evolution, though historically rare, has been seen in some large-scale engineered systems. The Lockheed C-130 Hercules, for example, has been enormously successful because the versatility of its design gives it the ability to perform many different tasks. Designed in 1951 to meet the needs of the Korean War [22], 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 allowed the C-130 to remain in service for over 60 years. During these years, the aircraft has been 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. Importantly, the C-130 was not originally designed for these specific roles; rather, the standard C-130 was designed as a versatile platform, which allowed it to evolve to meet these roles as needed while in service [23,24].

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 [25–30], system robustness [31–35], or as proposed in this paper, in response to unforeseen needs. Whatever the strategy may be, the quantitative relationships developed in this paper allow system engineers to evaluate the degree to which a system is evolvable, and the benefit of system evolution.

The remainder of this paper is presented as follows: Sec. 2 presents an accepted theory upon which this paper's developments are built. Section 3 introduces the evolvability measures. Section 4 presents simple examples and a complex aircraft carrier example. Concluding remarks are provided in Sec. 5.

2 Technical Preliminaries

The mathematical relationships presented in this paper for mapping a system's excess 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 Sec. 3.

The relationships upon which mechanical behavior of materials is founded are almost entirely based on observations and experimental testing [36]. Furthermore, most engineering applications in mechanics of materials deal with large enough pieces of matter that average properties can be assumed [36]. Similarly, observation of factors that enable evolution in engineered systems was used in a previous study [37], where it was found that system excess and modularity enable a system to evolve while in service. In this paper, 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 paper – to describe evolvability – is Hooke's law. Based on observation and testing, Hooke's law states

$$F = k\delta \tag{1}$$

where F is the physical load experienced by an object, k is the elastic spring constant for that object, and δ is the deformation of that object. Clearly, Hooke's law is a first-order linear approximation of an output (F) to an input (δ) in the elastic region, where the variables related to force are usually displacement and force per unit area, rather than force itself [36]. Similarly, system capacity from excess to enable future evolution can be described as a force, where the variables related to capacity are gain per unit excess, and the input variable is excess. For this reason and for the purposes of this paper, capacity is analogous to force. This argument is reiterated in Sec. 3, where the simple representation of Hooke's law is used to quantify the capacity of excess 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

$$P_e = \int F d\delta = \int k\delta d\delta = \frac{1}{2}k\delta^2 \tag{2}$$

where the load experienced (F) is applied over the distance (δ). The object's elastic potential energy can then be used by the object to restore its shape. Similarly, systems with excess can evolve to new configurations using that excess – 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 Sec. 3, 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 $F = \partial P_e/\partial\delta$ can be used to quantify the capacity of excess to enable future evolution in a system.

3 Model Development

In a previous study [37], we examined 210 engineered systems and found that system excess and modularity allow a system to evolve while in service. Similar studies support this finding [12,38]. Building on these observations, this section introduces the mathematical relationships that map a system's excess to that system's capacity and ability to evolve.

3.1 New Developments. Two models are introduced in this paper: (i) a model to quantify the capacity of excess in a system, termed *capacity* and denoted as C; 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 (X) 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, \$).

Capacity (C) is the ability of a system to meet future performance objectives using existing system excess. In other words, *capacity* as used in this paper is the maximum force that can be exerted to enable future evolution.

Gain per unit excess (g_x) is defined as the capacity per unit of excess.

Evolvability (E) is defined as the potential (energy) for a system to evolve from one system configuration to another, using system excess, to meet specific new system objectives.

The general relationship between capacity (C) and excess (X) is

$$C = g_x X \tag{3}$$

where g_x represents the unit gain for excess. As represented, we believe *how much* the excess is valued is important. Consequently, this information is captured in the unit gain (g_x) described above, which describes the capacity/excess curve. The nature and determination of these gain parameters is described in Secs. 4.1.1 and 4.1.2. This general relationship of capacity connects excess to system objectives through gain parameters and stems from Hooke's law presented in Sec. 2. Limitations of this simple model are discussed in the concluding remarks.

Considering system evolvability as the potential (energy) enabling evolution, we believe that excess (X) resources can be used to achieve 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 capacity/excess curve (g_x). Therefore, the general relationship between system evolvability (E) and excess (X) is

$$E = \int_{x_l}^{x_u} g_x X dX \tag{4}$$

where x_l and x_u represent the lower and upper bounds of useful excess. In addition to modeling capacity, it is important to understand the potential a system has for future evolution, which is why quantifying system evolvability is worthwhile. Also, when the evolvability of a system is known the capacity can be evaluated by

$$C = \frac{\partial E}{\partial X} \tag{5}$$

From the developed relationships, it can be seen that four parameters (g_x, X, C, E) and two general equations (Eqs. (3) and (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 Sec. 4, to test the proposed relationships and illustrate their usefulness in evaluating system evolvability.

3.2 Model Use with Large-Scale Engineered Systems. In using the general relationships developed in this paper, one expansion that exists for large-scale engineered systems is that many factors are considered simultaneously. In the context of Eqs. (3) and (4), this means that multiple excess factors, for example, are evaluated $X = [X_1 X_2 \ldots X_{n_{fx}}]$, where n_{fx} 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 large-scale engineered system, there will be many excess factors to consider. When evaluating the capacity of multiple excess factors and multiple gains per unit capacity, the following equation may be used:

$$C = \sum_{i=1}^{n_{fx}} [g_{x_i} X_i] \tag{6}$$

where n_{fx} is the number of factors for excess, g_{x_i} is the ith gain per unit of excess, and X_i is the ith factor of excess. Likewise, the evolvability of a system when considering multiple factors is

$$E = \sum_{i=1}^{n_{fx}} \left[\int_{x_l}^{x_u} g_{x_i} X_i dX_i \right] \tag{7}$$

As seen in the equations, we assume uncoupled unit gain parameters for multiple factors. It would be useful in a future study to investigate coupled gain parameters.

Another challenge that exists when considering large-scale engineered systems 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 of leveraging available capacity will be termed *strategies* and the outcome from implementing a strategy will be termed *benefit*.

Benefit (B) is the conversion of capacity to meet a new configuration associated with a particular strategy using excess.

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 each strategy. For such scenarios the following relationship captures the complexity:

$$B_j = \sum_{j=1}^{n_{g_{x_j}}} \left[g_{x_{ij}} X_{ij} \right] \tag{8}$$

where $g_{x_{ij}}$ represents the ith factor of excess, and j represents the jth strategy. Also, $n_{g_{x_j}}$ is the number of strategies using excess.

However, to enact a strategy there is a cost in terms of excess. This cost will be called *depletion* and denoted as $D_{X_{ij}}$. The feasibility of implementing strategies can be tested by

$$X_{i\text{new}} = X_i - \sum_{j=1}^{n_{g_{x_j}}} \left[D_{X_{ij}} \right] \tag{9}$$

where $X_{i\text{new}}$ must be greater than or equal to zero for the strategies to be feasible.

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

$$E_{\text{new}} = \sum_{i=1}^{n_{fx}} \left[\int_{x_l}^{x_u} g_{x_i} X_{i\,\text{new}} dX_{i\,\text{new}} \right] \tag{10}$$

where $X_{i\text{new}}$ is the remaining excess in a system. Consequently, the conversion of system evolvability (energy) to carryout the selected strategies is

$$\Delta E = E - E_{\text{new}} \tag{11}$$

To better understand this equation and its implications, we must recognize that evolvability (E) is the potential (akin to potential energy) for a system that, if used, allows the system to evolve from one configuration to another to meet specific new system objectives. As such, ΔE represents the amount of energy needed to carryout a reconfiguration strategy (i.e., to evolve from one configuration to another). As shown in Eq. (11), E_{new} is also evaluated. It represents the potential of the system in its new configuration to evolve to yet another configuration.

Equation (11) implies that (i) systems must possess evolvability (potential) in order to evolve, (ii) when a system's potential is fully spent, it has no more potential to evolve, (iii) potential can be restored by reversing a previous evolution to gain excess, or by adding excess by some other means.

Notice that capacity (C) 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 large-scale engineered systems. Therefore, we demonstrate how values for multiple excess factors can be normalized in Sec. 4.2.

3.3 Establishing Gain Values. Similar to many engineering design methods, defining values for the various gain factors occurs with designer involvement. Building on the fundamental model presented in Sec. 2, it is known that the gain factors must be non-negative. This non-negativity constraint provides an absolute lower bound, and applies to all gains, excesses, capacities, and measures of evolvability. Using this information, gains can be determined individually (one at a time), or simultaneously. This section describes the rationale and procedure associated with each approach.

3.3.1 Defining Gains Individually. In this approach, the designer is interested in—and has adequate knowledge to be able to—define the gains one by one. For each excess factor, the designer must

(1) Define a value for $X_{\min}$—the smallest value of excess that provides any real benefit. This value may be zero, or it may be some positive number where anything below it has no practical benefit. This minimum excess must then be mapped to the corresponding amount of capacity ($C_{\min}$) that it enables.
(2) Define a value for $X_{\max}$—the largest value of excess that provides any real benefit. While the upper bound on this variable can theoretically be infinity, it is likely that there is some positive number where larger values of excess offer no additional benefit. This value of excess must then also be mapped to the corresponding amount of capability ($C_{\max}$) it enables.
(3) Determine the gain relationship between ($X_{\min}$, $C_{\min}$) and ($X_{\max}$, $C_{\max}$).
   (a) If the relationship is linear, then the gain factor is the slope of the line between these two points.
   (b) If the relationship if nonlinear, the rate of change (dC/dX) is identified by choosing or discovering one of various relationships that could exist along different regions of the excess axis. An equation for this relationship can then be determined using regression analysis or similar tools.

Assumptions associated with this approach are that a designer can define the maximum values of excess/capacity for each factor, and that the relationship between excess and capacity for each factor is understood or can be discovered. Choosing a gain in this manner is similar to selecting a spring by considering about how stiffness influences the displacement–force relationship.

3.3.2 Estimating gains simultaneously. When defining the gains simultaneously, it is assumed that the designer is starting with a baseline design concept. From this, an assumption can be made that the designer knows that the individual excess components are enough to achieve a certain capacity (in years) at the system level. As originally defined in Eq. (6), system capacity (C) is the summation of each excess factor (X_i) times its gain (g_{xi}). Therefore, the gain factors essentially serve as a mapping between constituent excess and top-level capacity. While an optimization problem could be formulated to find gains that meet the desired capacity, the only predefined constraint is that the gains must be non-negative. This could lead to an infinite number of gain configurations that minimize the objective function, but those gains may not be realistic. This limitation can be addressed by including additional pieces of information – in the form of additional constraints – to the problem formulation. Though a designer may not know the exact gain values that should be assigned, statements can be made regarding the:

(1) Rank ordering of the gains. This is akin to having some insight into the relative stiffness of springs within a system. When correctly defined, this leads to a set of inequality constraints.
(2) Realistic upper and lower bounds. If a desired total capacity is known, then an optimization problem can be constructed to solve for the gain values (g_{x_i}). associated with each gain parameter. This information could be gathered from prior versions of the complex system, or analogous complex systems.
(3) Statements about the excess needed in a system to accommodate various levels of capacity. For example, a designer could be asked a small series of questions where they have to define the necessary excess in a system to accommodate 5, 10, or 15 yr of capacity. This leads to additional information that reduces the feasible design space and can lead to more unique gain factors.

The result of this optimization process may still not be unique. Rather, an advantage of this approach is that the optimization procedure could be repeated a large number of times. This would allow for many different combinations of gains to be found, and the effect on capacity and evolvability potential could be explored. Building on this discussion of gain estimation or definition, Sec. 4 of the paper explores how the theory developed in this section can be applied in different examples.

4 Examples

In this section, we illustrate the use of the relationships developed in Sec. 3. The simple examples highlight the use of linear and nonlinear gains, and the complex example evaluates U.S. Navy nuclear aircraft carriers.

4.1 Simple Examples. This section demonstrates how to numerically evaluate the capacity (C) 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 (Eqs. (3) and (4)) can be extended beyond linear approximations by specifying nonconstant unit gains (g_x). Both constant and nonconstant unit gain scenarios are illustrated in this section.

4.1.1 Linear Scenario. Consider a small cargo transport vehicle, where the independent variables are chosen as g_x, and X. The vehicle excess (X) in cargo volume is 4 m^3, and the unit gain is 2 units of gain/m^3 excess. To quantify the capacity of the vehicle's excess to enable future evolution, we evaluate Eq. (3) as

$$C = g_x X = 2(4) = 8 \tag{12}$$

Likewise we evaluate the vehicle's evolvability using Eq. (4), where $x_l = 0$ and $x_u = 4$, as

$$E = \int_{x_l}^{x_u} g_x X dX = \frac{1}{2} g_x (x_2^2) - \frac{1}{2} g_x (x_1^2) = \frac{1}{2} 2(4^2) = 16 \tag{13}$$

Note that the evolvability units are (capacity·excess), which can be interpreted as capacity for a system's excess to enable future evolution times the excess.

Given the capacity and evolvability calculated above, we now consider the effect of using excess when evolving to other potential configurations. To do this, we will consider the ith excess factor and the jth strategy for using that excess as described when we

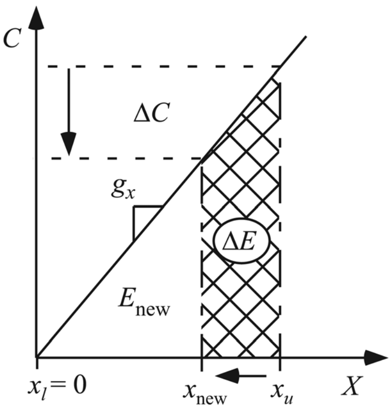

Fig. 2 A graphical representation of the change in capacity (*C*) and evolvability (*E*) with constant unit gain measures

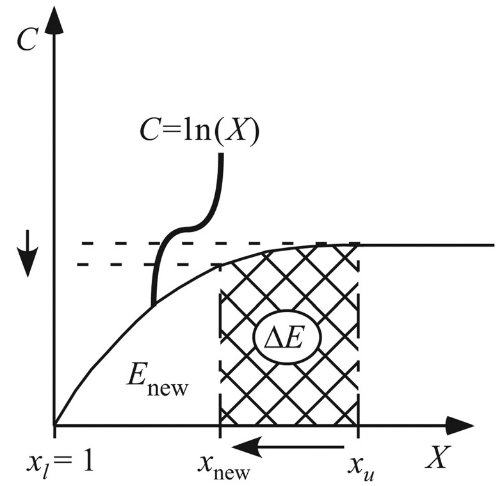

Fig. 3 A graphical representation of the change in capacity (*C*) and evolvability (*E*) with nonconstant unit gain measures

introduced Eqs. (8) and (9). For this simple example, let us consider only one excess factor; cargo volume. And let us assume two strategies for using that excess; strategy one is to add an air-conditioning unit to the vehicle, which will deplete the excess cargo volume from 4 m^3 to 3 m^3. The depletion for this strategy is formally $D_{X_{1,1}} = 1\text{m}^3$.

Strategy two, for using the excess cargo volume, is to add a tank for transporting liquids. Assume the tank would deplete the excess cargo volume by 2 m^3, thus $D_{X_{1,2}} = 2\text{m}^3$. The first evaluation is to compare the needed excess with the available excess per Eq. (9). As can be readily seen, there is sufficient excess to implement strategy one or two or both.

To continue the example, assume we decide to implement only the air-conditioning strategy. The new (remaining) excess is measured at $X_{\text{new}} = 3$ m^3. With this we can evaluate the remaining evolvability in the vehicle using Eq. (10); the result is $E_{\text{new}} = 9$ (capacity·excess). The change in evolvability (ΔE) to implement the chosen strategy is calculated using Eq. (11), and is shown to be 7 (capacity·excess).

Another evaluation that can be made is the benefit (B_j) of implementing any given strategy using Eq. (8). To evaluate adding the air-conditioning unit alone, we set $n_{g_{x_j}} = 1$ because only one strategy is under consideration. Additionally, it is assumed that $g_{x_{1,1}} = 14$ cooling units per m^3 of cooling volume. With these assumed parameters and the known required excess of $X_{1,1} = 1$ m^3, it follows that $B_1 = 14$.

The scenario of using a vehicle's cargo volume to evolve is represented in Fig. 2, where all the parameters from the general relationships Eqs. (3) and (4) are illustrated. In addition, we have shown and calculated the vehicle's evolvability ($E = 16$), which is the area under the curves from x_l to x_u, and the change in the vehicle's evolvability ($\Delta E = 7$) to gain 14 units of cooling benefit ($B_1 = 14$). Another important metric shown is the capacity of excess remaining to enable future evolution ($C = 8$) and its change (ΔC) of 8 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.

4.1.2 Nonlinear Scenario. The following illustration is a modification to the above cargo vehicle scenario, where the unit gain parameter is changed from constant to nonconstant, thus producing a nonlinear gain curve. Here, $g_x = \ln(X)/X$ units of gain per m^3 of cargo volume excess. This nonlinear gain 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 capacity of excess for future evolution. To evaluate the evolvability of the vehicle, we first evaluate the capacity using Eq. (3)

$$C = g_x X = \frac{\ln(X)}{X} X = \ln(X) = \ln(4) = 1.39 \tag{14}$$

We then evaluate the vehicle's evolvability using Eq. (4), where $x_l = 1$ and $x_u = 4$

$$\begin{aligned} E &= \int_{x_l}^{x_u} g_x X dX = \int_{x_l}^{x_u} \frac{\ln(X)}{X} X dX \\ &= (x_u \ln(x_u) - x_u) - (x_l \ln(x_l) - x_l) \\ &= (4\ln(4) - 4) - (1\ln(1) - 1) \\ &= 2.55(\text{capacity} \cdot \text{excess}) \end{aligned} \tag{15}$$

As in the previous example, we consider possible new configurations of the vehicle. A future configuration (or strategy) is proposed to improve the cargo vehicle's traction by adding mass to the system. The depletion of excess required to implement the strategy is 1.5 excess m^3, therefore $D_{1,1} = 1.5$ m^3. We evaluate the feasibility of implementing this strategy by using Eq. (9), where it is clearly deemed feasible. Next, we evaluate the benefit of implementing this strategy using Eq. (8). It is assumed that traction gain per unit excess volume used is 0.67 (that is, $g_{x_{1,1}} = 0.67$). Therefore

$$B_1 = g_{x_{ij}} X_{ij} = 0.67(1.5) = 1 \tag{16}$$

The impact of implementing this strategy can be further explored by calculating remaining capacity and evolvability in the system. Clearly, the remaining excess is $X_{\text{new}} = 2.5$ m^3. The remaining capacity, per Eq. (3) is $\ln(2.5) = 0.92$. Reevaluating Eq. (15) where $x_u = 2.5$ and $x_l = 1$, yields the new evolvability as $E_{\text{new}} = 0.79$ (capacity·excess).

This snap shot scenario is graphically represented in Fig. 3, where all the parameters from the general relationships Eqs. (3) and (4) are illustrated. In addition, we have shown and calculated the system's evolvability, the depletion in system evolvability to implement the proposed strategy ($\Delta E = 1.76$).

The two simple examples presented in this section, illustrate the basic workings of the theory developed in Sec. 3 and show how unit gain parameters (g_x) can be represented as constant and nonconstant through different gain curves. Two different gain functions (linear and natural log) were shown. One advantage of these relationships shown is the ability to numerically quantify system evolution interactions to aid decision making.

4.2 Complex Example. In this example, we consider two classes of nuclear aircraft carriers—the U.S. Navy's Nimitz and

Fig. 4 Nimitz-class nuclear aircraft carrier, USS John C. Stennis [39]

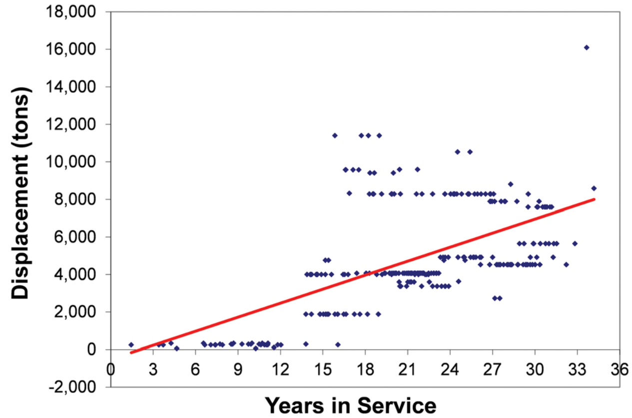

Fig. 5 Plot of service length as a function of displacement for all decommissioned Cruisers, Destroyers, Frigates, and Patrol Craft built after World War II. Adapted from Ref. [45]

Table 1 Excess factors for Nimitz-class aircraft carriers

Excess factor	Actual	Maximum	Normalized (%)
Displacement	91,440 LT	91,878 LT	0.48 [42]
Volume	14×10^6 ft^3	14.42×10^6 ft^3	3 [42]
Stability	46.82 ft	48.5 ft	3.57 [43]
Electrical power	192.71 MW	193.9 MW	0.618 [42]

Table 2 Excess factors for Ford-class aircraft carriers

Excess factor	Actual	Maximum	Normalized (%)
Displacement	100,000 LT	107,500 LT	7.5 [42]
Volume	14.7×10^6 ft^3	15.288×10^6 ft^3	4 [44]
Stability	44.67 ft	48.5 ft	8.57 [41]
Electrical power	392 MW	581.7 MW	48.4 [41]

Ford classes—and demonstrate how the relationships developed in this paper can be used to quantitatively evaluate their capacity (C) of excess for future evolution, and their evolvability (E). Fig. 4, shows a carrier from the Nimitz class.

Nuclear aircraft carriers are an example of large-scale engineered systems; they have long development cycles, are a significant capital investment, and must stay relevant in the changing landscape of modern warfare [40]. General design requirements for aircraft carriers include: the ability to launch and recover aircraft, operate for 50 yr, only refuel the nuclear core once, and project military power by operating in many different missions [41].

The U.S. Navy has recognized the growing demand for evolvable carriers to meet changing needs, environments, and technology, and have consequently started to implement evolvability into ships and defense systems to enable configuration changes while in service [40]. This provides the meaningful opportunity to apply the proposed models of evolvability in this paper to aircraft carriers.

To begin the process of applying this paper's developments to aircraft carriers, we identify the top-level excess factors used by the U.S. Navy to enable future evolution. For this example, this is done by searching the literature and other public records as a way of discovering realistic factors. Regarding ships and aircraft, Jonathan W. Greenert, the Chief of Naval Operations of the U.S. 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" [40]. In addition, a report written for the U.S. Department of Defense states that the limiting factors for new technology insertion into Nimitz-class carriers are weight, stability, and electrical power [42]. Based principally on these references, we simplify the top-level excess factors for aircraft carrier evolvability as

$X_1 =$ displacement
$X_2 =$ volume
$X_3 =$ stability
$X_4 =$ electrical power

To mitigate scaling problems, each of these factors is normalized by taking the maximum acceptable excess value minus the actual value, then dividing that quantity by the actual value. Tables 1 and 2 show the pertinent information. Note that the units LT refer to long tons, and that excess stability is measured by the distance from the keel to the center of gravity (ft) [43].

The next step in applying this paper's developments to aircraft carriers is to consider the gain factors (g_{xi}), which are measures of how much the excess is valued for each carrier class. To be useful, the gain factors must be mapped to the top-level objective for aircraft carriers, which based on the Navy vernacular is assumed to be desirable *service life allowance* for this example. The U.S. Navy uses various measures for determining the how long a carrier will stay in service [45]; one commonly used measure is service life allowance, which represents excess built into carriers to allow for future evolution while maintaining a service life requirements of 50 yr.

For example, the Nimitz-class is designed to have a service life allowance of 20 yr [45]. This means that if the Nimitz-class carrier is never functionally upgraded, the system could stay in service for an additional 20 yr beyond the expected 50 yr of service life. It is important to recognize that the Navy does not wish to actually keep a carrier in service for 70 yr, but it does wish to functionally upgrade carriers over the course of its 50 yr service so that the carrier can remain relevant. To that end, the excess service life capacity can be thought of as a sort of currency that can be drawn upon to upgrade functionality. Therefore, a portion (up to 20 yr) of the excess related to a 70 yr carrier is reserved for functional upgrades, while still meeting the 50 yr service life requirement.

To illustrate how gain factors can be determined, we show and describe Fig. 5, which is adapted from Ref. [45]. Figure 5 demonstrates that, for U.S. Navy vessels (not based on aircraft carriers alone) an excess capacity curve for service length (years in service) as a function of displacement (tons) can be derived from existing data. While a nonlinear fit can be easily identified and shown to be a better, Cable (the Director of Auxiliary and Special Mission Ship Design Division (SEA05D4) at Naval Sea Systems Command) indicates that the relatively poor linear fit shown in Fig. 5 ($R^2 = 0.35$) is sufficient to conclude there is a useful correlation between actual service life of Navy vessels and the vessels' excess displacement [45]. To remain consistent with the level of model fidelity described by Cable, which is a representation of the

Table 3 Top-level Nimitz-class carrier factors and gains

Displacement		Volume		Stability		Electrical power	
g_{x_1} (yr/%)	X_1%	g_{x_2} (yr/%)	X_2%	g_{x_3} (yr/%)	X_3%	g_{x_4} (yr/%)	X_4%
10.4	0.48	1.67	3	1.4	3.57	8.1	0.618

Table 4 Depletion in excess X_{ij} values for idea EMALS and STEAM as derived from Ref. [41,46].

Benefit: *discharge*/seconds	Displacement X_{1j} %	Volume X_{2j} %	Stability X_{3j} %	Electrical power X_{4j} %
EMALS$_{i1}$	0.241	0.0651	0.334	3.27
STEAM$_{i2}$	0.529	0.174	1	0

level of fidelity used by the Navy when making early-stage design decisions, we use this correlation as a guide to determine constant gain factors for this example.

Table 3 presents the gain factors and excess values for the Nimitz-class aircraft carrier. These factors were estimated for this example using the following relationship:

$$g_{x_i} = \frac{C}{n_{fx} X_i} \tag{17}$$

where $C = 20$ and $n_{fx} = 4$. The capacity of excess service life to enable future evolution is evaluated with values from Table 3 and using Eq. (6)

$$C = \left[10.4\left(\frac{\text{yr}}{\%\text{Disp.}}\right)(0.48(\%\text{Disp.})) + 1.67\left(\frac{\text{yr}}{\%\text{Vol.}}\right)(3(\%\text{Vol.})) + 1.4\left(\frac{\text{yr}}{\%\text{Stab.}}\right)(3.57(\%\text{Stab.})) + 8.1\left(\frac{\text{yr}}{\%\text{Elec.}}\right)(0.618(\%\text{Elec.}))\right] = 20(\text{yr}) \tag{18}$$

The evolvability of the system can be evaluated using Eq. (7), where the lower bound of excess is 0

$$\begin{aligned} E &= \frac{1}{2}\left[g_1(X_1)^2 + g_2(X_2)^2 + g_3(X_3)^2 + g_4(X_4)^2\right] \\ &= \frac{1}{2}\left[10.4(0.48)^2 + 1.67(3)^2 + 1.4(3.57)^2 + 8.1(0.618)^2\right] \\ &= 19.2(\text{yr}\cdot\%) \end{aligned} \tag{19}$$

The evaluation of capacity (C) and evolvability (E) is useful baseline measure that can be used to evaluate potential future configurations and understand their impact.

We now consider how the system's excess can be used to evolve to new configurations. More specifically, changes to the carriers aircraft catapult system are considered, as well their potential benefit (B_j) as a future configuration. Advancements in the area of energy storage, pulsed power, power conditioning, and controls have led to the development of the new ElectroMagnetic Aircraft Launch System (EMALS) [46]. The EMALS has many advantages over the conventional steam catapult (STEAM), including fewer personnel for operation and maintenance, more power, and reduced stress on aircraft frames from improved peak-to-mean acceleration ratio [41].

The current paper focuses on the benefit of aircraft launch systems through discharges per seconds (disc/s) when comparing launch systems. The EMALS can discharge every 15 s or 0.0667 (disc/s), and STEAM can discharge every 20 s or 0.05 (disc/s) [41]. 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 strategy considered here is to remove a STEAM and add an EMALS.

Implementing the strategy to remove a STEAM and add an EMALS will deplete some of the excess (service life allowance) that was built into the carriers. These depletions are derived from the literature and are listed in Table 4 [41,46]. Using this table, the feasibility of removing a STEAM and adding a EMALS to a Nimitz-class carrier is tested using Eq. (9)

$$X_{1\,\text{new}} = 0.48 - (0.241 - 0.529) = 0.768\% \tag{20}$$

$$X_{2\text{new}} = 3 - (0.0651 - 0.174) = 3.11\% \tag{21}$$

$$X_{3\text{new}} = 3.57 - (0.334 - 1) = 4.36\% \tag{22}$$

$$X_{4\text{new}} = 0.618 - (3.27 - 0) = -2.65\% \tag{23}$$

Equation (23) shows that $X_4\text{new} \le 0$ 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 [44]. 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 U.S. Navy to introduce a new aircraft carrier class [42].

We now analyze the new Ford-class aircraft carrier to compare two aircraft carrier classes and draw conclusions.

The gain measures for the Ford-class are calculated using Eq. (17) where excess service life capacity (C) is 30 year (yr). This means that if the Ford-class carrier is never functionally upgraded, the system could stay in service for an additional 30 yr beyond the expected 50 service life years. We pause now to consider why the gain factors between the two carrier classes are noticeably different as reported in Tables 3 and 5. Recall that the gain factors represent how much excess is valued for a particular

Table 5 Top-level Ford-class carrier factors and gains

Displacement		Volume		Stability		Electrical power	
g_{x_1} (yr/%)	X_1%	g_{x_2} (yr/%)	X_2%	g_{x_3} (yr/%)	X_3%	g_{x_4} (yr/%)	X_4%
1	7.5	1.87	4	0.89	8.57	0.155	48.4

Table 6 Gain parameter $g_{x_{ij}}$ for implementing (EMALS) and (STEAM) strategies into Ford-class carriers

	Displacement	Volume	Stability	Electrical power
	$g_{x_{1j}}((\text{disc/s})/\%)$	$g_{x_{2j}}((\text{disc/s})/\%)$	$g_{x_{3j}}((\text{disc/s})/\%)$	$g_{x_{4j}}((\text{disc/s})/\%)$
$_{i1}$	0.0693	0.256	0.0498	0.0051
$_{i2}$	0.0315	0.0957	0.0167	0

system. For the Nimitz-class carrier, any excess in displacement or electrical power is highly valued because of its scarcity in the design. For the Ford-class carrier, excess displacement and electrical power are not as scarce and therefore the value of excess is lower.

Based on the discussion of excess service life capacity for the Nimitz-class described above, we can see that excess service life capacity enables future evolution. Using Eqs. (6) and (7), and Table 5 values, the Ford-class capacity is evaluated as

$$C = \left[1\left(\frac{\text{yr}}{\%\text{Disp.}}\right)(7.5(\%\text{Disp.})) + 1.87\left(\frac{\text{yr}}{\%\text{Vol.}}\right)(4(\%\text{Vol.})) + 0.89\left(\frac{\text{yr}}{\%\text{Stab.}}\right)(8.57(\%\text{Stab.})) + 0.155\left(\frac{\text{yr}}{\%\text{Elec.}}\right)(48.4(\%\text{Elec.}))\right] = 30(\text{yr}) \quad (24)$$

The evolvability of the Ford-class system can be evaluated using Eq. (7)

$$\begin{aligned} E &= \frac{1}{2}\left[g_1(X_1)^2 + g_2(X_2)^2 + g_3(X_3)^2 + g_4(X_4)^2\right] \\ &= \frac{1}{2}\left[1(7.5)^2 + 1.87(4)^2 + 0.89(8.57)^2 + 0.155(48.4)^2\right] \\ &= 257.3(\text{yr}\cdot\%) \end{aligned} \quad (25)$$

The Ford-class carrier is designed with four EMALS. To consider a future catapult system configuration, we examine the strategy of adding an EMALS and STEAM to the Ford-class carrier. The feasibility of this idea is evaluated using Table 4 and Eq. (9)

$$X_{1\,\text{new}} = 7.5 - (0.241 + 0.529) = 6.73\% \quad (26)$$

$$X_{2\,\text{new}} = 4 - (0.0651 + 0.174) = 3.76\% \quad (27)$$

$$X_{3\text{new}} = 8.57 - (0.334 + 1) = 7.24\% \quad (28)$$

$$X_{4\text{new}} = 48.4 - (3.27 + 0) = 45.13\% \quad (29)$$

The above evaluations show that adding another EMALS and STEAM to the Ford-class is feasible ($X_{1_{\text{new}}} - X_{4_{\text{new}}} \geq 0$). 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.

Having established feasibility of the strategy, we now examine the benefit associated with it. We use Eq. (8) together with Tables 4 and 6 to calculate the benefit of adding an EMALS (B_1), and the benefit of adding a STEAM (B_2) as

$$\begin{aligned} B_1 &= [g_{x11}(X_{11}) + g_{x21}(X_{21}) + g_{x31}(X_{31}) + g_{x41}(X_{41})] \\ &= [.0693(.241) + .256(.0651) + .0498(.334) + .0051(3.27)] \\ &= 0.0667(\text{disc/s}) \end{aligned} \quad (30)$$

$$\begin{aligned} B_2 &= [.0315(.529) + .0957(.174) + .0167(1) + 0(0)] \\ &= 0.05(\text{disc/s}) \end{aligned} \quad (31)$$

The benefits carry units of 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 last step in applying this paper's developments to the Ford-class aircraft carrier is to evaluate the remaining evolvability after the strategy of adding EMALS and STEAM is implemented. We do this by evaluating Eq. (10) based on the remaining excess $X_{i\text{new}}$ and the gain factors g_{x_i} from Table 5

$$\begin{aligned} E &= \frac{1}{2}\left[g_1(X_{\text{new}_1})^2 + g_2(X_{\text{new}_2})^2 + g_3(X_{\text{new}_3})^2 + g_4(X_{\text{new}_4})^2\right] \\ E_{\text{new}} &= \frac{1}{2}\left[1(6.73)^2 + 1.87(3.76)^2 + .89(7.24)^2 + .155(45.13)^2\right] \\ &= 217 \end{aligned} \quad (32)$$

Thus, the change in E due to the depletion of excess is calculated as

$$\begin{aligned} \Delta E &= E - E_{\text{new}} \\ \Delta E &= 257.3(\text{yr}\cdot\%) - 217(\text{yr}\cdot\%) = 40.31(\text{yr}\cdot\%) \end{aligned} \quad (33)$$

Likewise, using Eq. (6)

$$C_{\text{new}} = 1\left(\frac{\text{yr}}{\%\text{Disp.}}\right)(6.73(\%\text{Disp.})) + 1.87\left(\frac{\text{yr}}{\%\text{Vol.}}\right)(3.76(\%\text{Vol.})) + 0.89\left(\frac{\text{yr}}{\%\text{Stab.}}\right)(7.24(\%\text{Stab.})) + 0.155\left(\frac{\text{yr}}{\%\text{Elec.}}\right)(45.13(\%\text{Elec.})) = 27.2(\text{yr}) \quad (34)$$

Finally, the reduction of excess service life (or capacity) can be calculated as

$$\begin{aligned} \Delta C &= C - C_{\text{new}} \\ \Delta C &= 30(\text{yr}) - 27.2(\text{yr}) = 2.8(\text{yr}) \end{aligned} \quad (35)$$

This means that the strategy to add one EMALS and one STEAM to the Ford-class carrier will cost the carrier 2.8 yr of its 30 yr service life allowance to evolve and stay relevant.

The intent of this example has been 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 [42], as well as the high evolvability of the Ford-class [44].

4.3 Exploring Gain Value Impact on Capacity and Evolvability. The results of Sec. 4.2 demonstrate the significant evolvability present in the Ford-class carrier design. However, while system excess is a measurable physical quantity, the values of the gains are subject to a designer's interpretation of how excess maps to capacity. This section exercises the proposed models for capacity and evolvability to explore how their values change when the gains are allowed to deviate slightly from their established values. If small changes to the gains yield large variability in capacity and evolvability, then (i) significant care and effort must be spent defining appropriate gain values and (ii) the insights drawn from the measures of capacity and evolvability may lack impact.

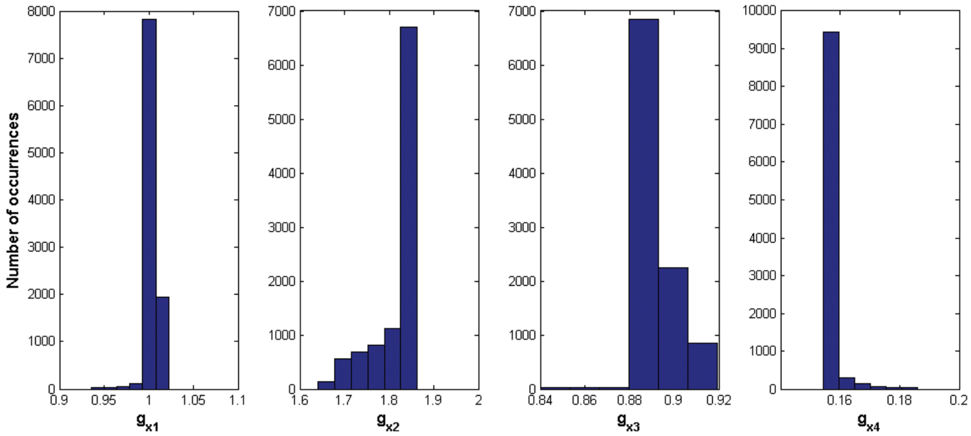

Fig. 6 Histogram of gain results

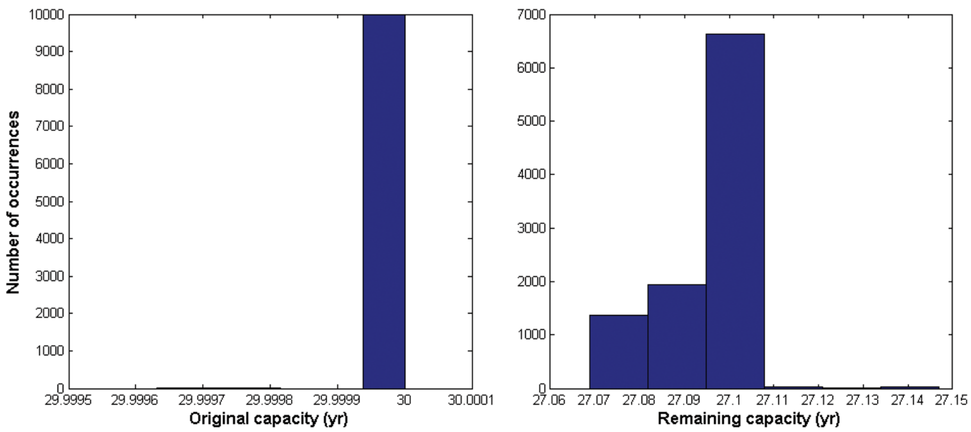

Fig. 7 Histogram of capacity due to gain variability

Exploring how the values of capacity and evolvability change because of uncertainty in the gain values is done through numerical simulation. To start, the gain values identified in Table 5 are used as baseline center-points. Since a designer may be unsure if this baseline value is correct, a 20% deviation in each direction is allowed. This deviation effectively creates a band of possible slopes linking capability and evolvability, as originally shown in Fig. 2. Since the Ford-class carrier is designed to have an additional 30 yr of extended service life, an optimization problem can be constructed to solve for gain value combinations that meet this criterion. As shown in Eq. (36), the optimization problem statement for the original Ford-class design is given by

$$\min_g J(g) = [30 - \sum_{i=1}^{4} g_i X_i]^2$$
$$\text{subject to}$$
$$0.8 \leq g_1 \leq 1.2$$
$$1.496 \leq g_2 \leq 2.244$$
$$0.712 \leq g_3 \leq 1.068$$
$$0.124 \leq g_4 \leq 0.186 \qquad (36)$$

where the gain factors, g, represent the variables of the optimization problem.

This optimization problem was solved 10,000 times using the fmincon function in Matlab to thoroughly sample the possible solution space. Random starting points were generated that fell within the side constraints established for the gains. Histograms of the resulting gain values are shown in Fig. 6, where the values are placed into six bins. For the factors of displacement and electrical power, there is very little variation in the gains. When deviation does occur for these factors, the gains for these factors tend to increase (greater than 1 and 0.155, respectively). More variation in the gain results are seen for the factors of volume and stability. Here, variations in the gain associated with volume tend to yield smaller answers, while the gains associated with stability tend to increase.

The impact of gain variability on capacity and evolvability is shown in Figs. 7 and 8. For these figures, an additional EMALS catapult has been added to the system. The left hand plot of Fig. 7 shows that for nearly all of the 10,000 optimizations were able to identify gains that approximately met the 30 yr capacity for extended service life with the original values of excess. The results on the right of Fig. 7 show the remaining capacity (in years) after adding the EMALS catapult. The mean for these 10,000 cases is 27.092 yr with a standard deviation of 0.0096 yr.

The results on the left of Fig. 8 show that gain variability does introduce slight variation for evolvability. For the 10,000 simulations, the mean original evolvability was 258.088 (yr·%) with a standard deviation of 3.7245 (yr·%). Improving the performance of the carrier by adding the EMALS catapult draws from this evolvability budget, reducing it to a mean of 217.69 (yr·%) with a standard deviation of 3.2196 (yr·%). An interesting outcome of this result is that a change in the gains tends to increase both the system's original evolvability and remaining evolvability.

As discussed in Sec. 3.3, finding gain values can be aided if the designer can make statements about relationships between remaining excess and different values of extended service life. It is expected that adding these additional constraints will further constraint the gain design space. To test this expectation, the

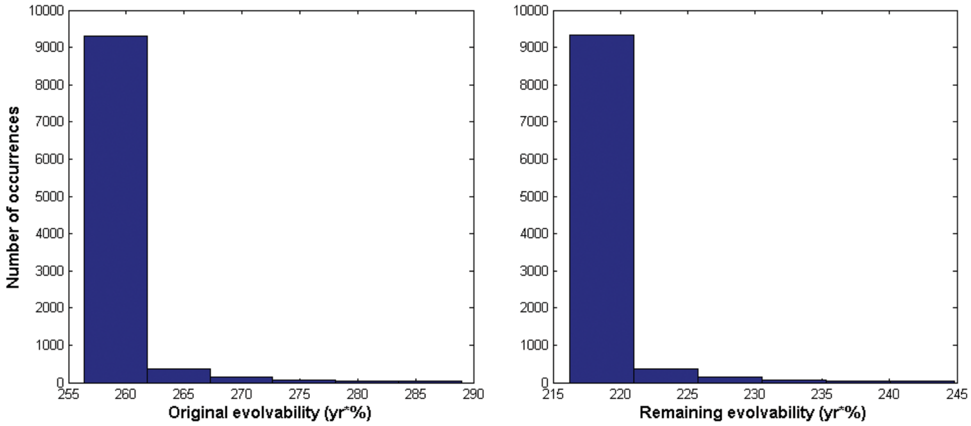

Fig. 8 Histogram of evolvability due to gain variability

Table 7 Gain values with the inequality constraint introduced

Gain	g_{x1}	g_{x2}	g_{x3}	g_{x4}
Mean (yr/%)	0.8442	1.5679	1.0658	0.1707
Std. dev. (yr/%)	0.0078	0.0098	0.0166	0.0016

Table 8 Capacity and evolvability values with the inequality constraint introduced

	C_{orig}	C_{rem}	E_{orig}	E_{rem}
Mean (yr/%)	30.0	26.99	275.37	231.98
Std. dev. (yr/%)	1.2×10^{-8}	0.0108	1.4475	1.3372

constraint in Eq. (37) was added to the optimization problem, where the coefficients in front of the gains represent the remaining excess for each of the four factors when 10 yr of extended service life remains

$$10 \leq (2.1)g_{x1} + (0.95)g_{x2} + (3.42)g_{x3} + (19.25)g_{x4} \tag{37}$$

Results from 10,000 optimizations with the additional inequality constraint show that the resulting gain values are more tightly constrained. As shown in Table 7, gain g_{x3} is often fixed at the upper bound of its allowed range. The results in Table 8 show the impact of this constraint on capacity and evolvability (note that orig = original, and rem = remaining). The capacity scores are unaffected, and the standard deviations have shrunk for both original and remaining capacity. Both evolvability results, however, have experienced a positive shift due to gain g_{x3} being at the upper end of its range. While a score in the range of 275.37 (yr·%) was found for original evolvability in the first simulation, this result occurred only a very small percentage of the time.

Evolvability potential, however, is most effective as a relative measure. Despite the positive shift in mean (and reduction in standard deviation), the overall difference of the means between the two simulations are relatively close. For the simulation without the inequality constraint, the difference in evolvability potential after making the change to the system was 40.398 (yr·%). In the simulation with the inequality constraint, this difference was 43.39 (yr·%). When used to compare the impact of different solution strategies, this small difference should not have a significant role in influencing the overall decision.

5 Concluding Remarks

Uncertainties in future operations and environments in large-scale engineered systems lead to problems in system safety, life, and value [47]. The literature within this area has identified ways in which to overcome uncertainty, such as system flexibility, adaptability, upgradeability, maintainability, modularity, reconfigurability, and transformation [11]. In this paper, it is illustrated that such problems in large-scale engineered systems can be minimized through quantifying and using system evolvability. Mathematical models of capacity 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 capacity and evolvability relationships presented herein. Ultimately, the analytical models in this paper are tools to help designers and decision makers better understand evolvability in systems, enabling systems to be strategically designed with evolvability.

The models for system evolvability, as developed in this paper, were used to evaluate current aircraft carrier systems, and future configurations of those systems. Two classes of carriers were examined; the Nimitz class and the Ford class. The Nimitz-class carriers were shown to have an evolvability of $E = 19.2$ (yr·%) and a capacity of excess service life at $C = 20$ (yr), while the Ford-class carriers were shown to have $E = 257.3$ (yr·%) and $C = 30$ (yr). Both carrier classes were considered based on future configurations with EMALS and steam catapult systems. The Nimitz-class carriers were shown to 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, however, was shown to have sufficient evolvability to added EMALS and a steam catapult in a future configuration. This future configuration is beneficial because it allows the Ford-class carrier to launch an additional aircraft every 8.6 s, over the current configuration. As described in the paper, this future configuration depletes the Ford-class evolvability by 40.3 (yr·%), which equates to a depletion of 2.8 excess service life years. Note that this depletion in excess service life years is calculated by evaluating $\Delta C = C(X_{1-4}) - C(X_{1_{\text{new}}-4_{\text{new}}})$.

The models developed in this paper characterize the relationships between evolvability, capacity, gains, and excess in systems. We recognize that these relationships require further validation and additional higher fidelity development. Nevertheless, the relationships as presented in this paper are a useful step in being able to model evolvability, which opens the door to considering evolvability as a formal quantitative characteristic that can be optimized. Future research can apply the developed models to different scenarios using multi-objective optimization to better understand the compromises of system evolvability. Additionally, an in-depth study of capacity/benefit curves and unit gain parameters (capacity/excess) would be beneficial. Finally, further research should include a measure of time required to evolve or system availability for upgrade. The need for this is clear when considering aircraft carriers; 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.

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Nomenclature

B = measure of benefit from converting to new configuration
C = measure of capacity for future evolution due to excess
D = measure of how much excess is depleted to implement a strategy
E = measure of a system's evolvability
g_x = gain per unit excess
n_{fx} = number of excess factors
$n_{g_{x_j}}$ = number of strategies using excess
X = measure of excess in a system

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