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Evaluation of System Evolvability Based on Usable Excess

Complex, large-scale engineered systems are an integral part of modern society. The cost of these systems is often high, while their ability to react to emergent requirements can be low. This paper proposes evolvability, based on usable excess, as a possible metric to promote system longevity. An equation for the usability of excess, previously defined only in terms of quantity, is improved to include the attributes of type, location, and form as well as quantity. A methodology for evaluating a system's evolvability is also presented. Using an automated assembly line as an example, we show that system evolvability can be modeled as a function of usable excess. [DOI: 10.1115/1.4033989]

Keywords: evolvability, evolve, reconfigurability, reconfigure, system design, automated assembly line, excess, complex engineered systems

1 Introduction

In biological terms, evolvability is often defined as the ability of an organism to respond to circumstances that challenge its survival [1]. This response is generally a gradual, but permanent change to the species. Evolvability can also apply to some engineered systems, such as, complex, large-scale engineered systems, which are an important part of modern life. Examples of this type of system include communication networks, commercial aircraft, ocean vessels, telecommunication satellites, and military weapon systems. These systems are generally complex and expensive (in terms of development and production). Because of the large investment requirement, they must often remain in service for extended periods of time (as much as 50–100 years). During this extended service period, new requirements will likely emerge that may result in premature obsolescence. To improve decision making while designing engineered systems, this paper presents a method for evaluating system evolvability. This evaluation can be used as a design aid (e.g., numerical optimization) or selection criteria for complex, large-scale engineered systems.

A variety of terms are used in the literature when exploring how engineered systems change. These terms are used to differentiate between the focus of the work. A designer may be interested in focusing on a conceptual understanding of how the system changes versus a detailed analysis, applying methods and approaches at different stages of the design process, and changing the system in response to conflicting or future requirements. For example, research into transformation principles [2,3] was conducted to identify descriptive terminology that could be used to facilitate and improve concept generation. Work in changeable [4,5] and flexible systems [6–9] began to identify the mathematical formulations and models by which these problems could be explored. These efforts led to the differentiation between (i) reconfigurable changes which are repeatable and reversible [10–12] and (ii) adaptable changes [1,13] where the system was not required to return to its original state. While reconfigurability and adaptable do provide the ability to respond to unforeseen and unpredicted future requirements, the focus of these efforts was primarily to respond to conflicts within the boundary established by the original requirements. In response to these conflicting requirements, changes to the system were planned at the time of original design.

The evolvability-based methodology and metric introduced in this paper explore the ability of systems to change in response to a set of future needs, known or unknown. The actual change may be effected through any of the methodologies noted above. Evolvability helps engineered systems avoid premature obsolescence [14] by enabling changes to an improved state based on emergent requirements. *We define system evolvability as the ability of a system to improve based on emergent requirements after the system has been deployed.*

In addition to providing understanding in terms of the type of changes a system can experience (changeable, reconfigurable, flexible, adaptable, and transformable), the previous work has provided useful metrics and tools to assess and model a system's ability to change. Keese et al. [7] present an enhanced change modes and effects analysis tool (ECMEA) with increased consistency and ease of use over previous CMEA methods. The ECMEA provides a measure of a system's ability to change based on manufacturing changes. ECMEA considers potential changes, causes, effects, and affected components. Factors such as change-to-function ratio and change potential number are calculated to quantify the impact of the changes. Tilstra et al. [9] have developed a technique to measure and study a product's flexibility to evolve based on an high-definition design structure matrix, and a set of 24 previously developed flexibility guidelines [15,16]. A quantitative comparison of different products or design alternatives is made by determining adherence to each of the guidelines. Saleh and Hastings [8] present a technique for quantifying the adaptability and flexibility of space systems within the generalized information network analysis (GINA) methodology. The principal metric presented in their work is the cost-per-function ratio (defined as the ratio of lifetime cost to number of satisfied users). This ratio is used in conjunction other GINA factors (i.e., elasticity and mission modification) to determine the adaptability and flexibility of space systems. Siddiqi and de Weck [10] present several methods to model a reconfigurable system using Markov analysis and a metacontrol framework based on the concepts and tools of classical control analysis. The Markov approach allows for analyzing operational, reconfiguration, and failure states while the metacontrol framework focuses on the time-related aspects of reconfigurations.

These metrics and modeling techniques provide diverse and valuable insight into a product's ability to reconfigure or evolve. A different approach to the facilitators of evolvability, based on the work of Tackett et al., is taken in this paper. The evolvability analysis based on designed-in excess creates a chain of equations relating evolvability to design parameters and existing excess

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capabilities. We believe many of these techniques are compatible and can work together to provide a more rich and complete exploration of the principles that govern evolvability.

Evolvability is particularly desirable in complex, large-scale, engineered systems [12,17]. In addition to complex design challenges, the design teams involved in developing large-scale engineered systems often face challenges associated with team size and complexity [18]. These challenges generally lead to extended and costly development cycles [19–21]. Common, well-understood metrics and repeatable methodologies could help to mitigate issues associated with complexity of designs and team structures [22–24]. In 2010, the "NSF/NASA workshop on the design of large-scale complex engineered systems—from research to product realization" identified the need to create metrics for quantifying system evolvability, indicating that such metrics would enable more efficient design of complex systems [25]. The method presented in this paper allows system design teams to compare various concepts or designs based on evolvability.

Tackett et al. [26] have shown that the influence of adding excess capability to a system—as it affects evolvability—can be quantified. *Excess capability is defined as a resource, embodied by a system, which is not committed to any of the system's initial set of customer requirements.* Tackett et al. propose that evolvability is a function of the quantity of excess capability available in the system

$$E = f(q, x) \quad (1)$$

where

- E is the system evolvability
- x is a quantity of excess capability in the system
- q is an excess usability factor for quantity

It is important to note three significant issues related to the paper by Tackett et al. First, the usability factor (q)—as developed in Tackett et al.—is based only on the quantity of the excess capability. *However, excess capability is only valuable if the excess capability can be used to fulfill specific future requirements.* The usability of excess depends on more than just its quantity [27]. *Excess capability is said to be ideally usable if it is of the correct quantity, type, form, and location respect to a future need.* This paper addresses this limitation by incorporating the attributes of type, form, and location into the usability factor.

The paper by Tackett et al. requires a complete knowledge of the future needs to be evaluated. There is frequently a need to evaluate evolvability and excess capability when all future needs cannot be fully determined. The second issue is the inability to deal with unknown future needs. This paper presents a method to study the value of excess capability and the corresponding evolvability when future needs are not completely understood.

The third issue is that the paper by Tackett et al. does not present a method to evaluate the overall system evolvability. In the present paper, we provide such a method and demonstrate it for conditions when all future needs are known and when they are unknown.

In this paper, we build on the simplest form of Eq. (1), which was originally introduced in Ref. 26 and proceed to develop a new method for analyzing excess capability and evolvability that addresses all of the issues noted above. The simplest form of the work by Tackett et al. is shown in the following equation:

$$E = qx \quad (2)$$

Specifically, we extend Eq. (2) producing a more complete method for evaluating evolvability by incorporating usability factors for the *quantity*, *type*, *form*, and *location* of multiple excess capabilities into the equation.

This paper continues with a general discussion of the application of usable excess capability to meet new or changing requirements (Sec. 2). Then in Sec. 3, we describe the method for evaluating evolvability based on usable excess capability. The application of this method, to a relatively simple engineered system, is presented in Sec. 4. The final section (Sec. 5) contains our concluding remarks.

2 Usable Excess Capability Enables System Evolution

System evolution can be initiated by several means [10]. These means can be categorized into three groups:

(1) addition of a new requirement
(2) elimination of an unnecessary requirement
(3) exchange of requirements

Each of these groups is related to excess. When systems evolve by adding a new requirement, excess capability must be available to allow the new requirement to be added. When a requirement is removed, excess capability is made available for possible future use. When systems evolve by exchange of requirements, excess capability is made available as an intermediate step. The original requirement is removed, thus creating excess capability for the new requirement to be added. Excess capability is key to system evolution and as such is a potential parameter for evaluating evolvability [28]. Shown in Table 1 is a list of typical, but not comprehensive, types of excess capability and their associated parameters.

As an aid to understanding excess capability in a design, four simple examples are considered below. The first example demonstrates the use of excess capability that is designed in for a specific future need. The second example reviews a case where excess capability is available, but was not included to address a specific future need. The third example illustrates how excess capability is made available due to the infusion of new technology [29]. The last example deals with a change in requirements providing excess capability that can be used to meet a new requirement. A pickup truck is used as the basis for each of these examples.

2.1 Designed-In Excess Capability. Many pickup trucks are designed to accept an after-market tow hitch. However, the hitch is often not included in the original sale of the truck. The ability of the pickup truck to tow a trailer, after installation of the after-market hitch, is an example of designed-in excess capability. To add the tow hitch requires several types of excess capability such as payload, power, support structure, and excess space, to be available in specific locations. To facilitate this future change, the design team included all necessary quantities of excess in appropriate locations, including an attachment feature in the form of

Table 1 Typical types and parameters of excess

Type	Parameters
Volume, space	Length, width, height
Electrical power	Voltage, current, or amplitude, frequency and phase
Kinetic translation energy	Mass, velocity
Kinetic rotational energy	Moment of inertia, angular velocity
Potential energy	Mass, distance, length, or force, length, or Watts, or Joules
Pressure	Force, area
Torque	Force, moment arm length
Information, data transfer	bps, time, frequency
Electromechanical	Current, force, field strength
Chemical	Enthalpy of formation, reactivity, pH, net charge
Thermal	Specific heat, conductivity, density, enthalpy
Sound	Amplitude, frequency
Nuclear	Decay rate, radioactivity, density
Structural weight	Density, volume
Buoyant weight capacity	Volume, displacement
Volume flow	Volume, velocity

threaded holes. This example of designed-in excess for a future need is a common application of excess [11].

2.2 Available Excess Capability (Not Designed-In). Not all evolutions are anticipated by the system designers [30]. Unanticipated changes can often be addressed by in-service design changes; however, the costs of these changes may be prohibitive [31,32]. While the hitch, in the above example, was envisioned and designed in to the original design, attachment points and electrical connections for an electric brake controller are often not included in the vehicle. Such controllers are readily available and installation is fairly simple, provided adequate excess is available. To install the controller, several types of excess are required. There must be space in the engine compartment and in the cab to mount the main components. A small amount of excess space is required to run a bundle of electrical wires from the location under the hood to a connector near the hitch. Sufficient excess electrical power is also required to drive the additional brakes (on the trailer). In this case, the reconfiguration is not designed in but it can be accomplished, with little additional cost, by using existing excess.

2.3 Excess Made Available by New Technology Infusion. Excess can become available as a result of new technology infusion [33,34]. Consider the case of light emitting diodes (LEDs). In recent years, LEDs have become available as replacements for incandescent lights in many applications [35]. LEDs provide significant advantages in terms of power consumption and life in many automobile applications. In the case of the pick-up truck, the headlights, tail lights, and parking lights could be replaced by LEDs, resulting in excess electrical power for the system and extended life for the lights.

2.4 Excess Made Available by a Change in Requirements. A common example of creating and using excess capability results from a change in requirements. Unanticipated changes to requirements can often be dealt with by an adaptable or flexible system [6]. Consciously, changing a requirement can be an effective way of providing excess capability and achieving product evolvability. A pickup truck may be originally purchased for general hauling tasks. Let us consider that at some point during the service phase, there is a need to redeploy it as a snowplow and sand spreading truck. This is accomplished by redirecting the power and payload requirements to allow the addition of a snowplow and a sand spreader. While the original design team may not have foreseen this change, once the decision was made to eliminate the original cargo-carrying requirement, the new excess payload and power capabilities can be used for the new snowplow and sand spreader requirement.

3 Evaluation of Evolvability Based on Usable Excess Capability

Evolvability resulting from the addition of a new requirement is the focus of this paper. It requires specific types of capability (e.g., physical space, power, timing margin) to be in excess. Table 1 outlines common types of excess and their associated parameters. When all of the required excess capabilities are available, they may be used to enable the design evolution.

3.1 Usable Excess and Evolvability. The examples discussed in Sec. 2 illustrate that simply having an adequate quantity of excess is not sufficient for evolvability. In addition to quantity, excess capability must be appropriate in terms of type, form, and location. The quantity, type, form, and location of excess capability depend on the specific future need being considered. In order to evaluate the usability of excess, we must describe it in terms of factors that relate it to potential future needs [36]. For the purposes of this paper, we augment the usability factor (q), as noted in Eq. (2), to include the impact of type, form, and location of the excess capability. The resulting four usability factors are:

(1) quantity (q)
(2) type (t)
(3) form or configuration (f)
(4) location (l)

In this paper, we deal with normalized values of t, f, and l. The product qx is also normalized to ensure a normalized expression for evolvability (E). That is, the units of q are the reciprocal of the units of excess under consideration. Each of the factors is normalized with respect to the requirement of the future need. In normalized form, each of the usability factors range from 0 to 1, where 0 implies fully unusable (i.e., none of requirement met) and 1 implies fully usable (i.e., requirement completely met).

The usability factors (q, t, f, and l) and the quantity of excess capability (x) are the foundation of the method presented in this paper to determine the evolvability of a design. They are used to quantify the suitability of each excess capability as it relates to a future need. Calculating the evolvability of a system involves three evaluations: (i) evaluating the usability of the excess, (ii) evaluating the evolvability of the system to meet each future need, and (iii) evaluating the overall evolvability of the system to meet all future needs being considered.

The *quantity* usability factor (q) indicates the usability of the excess in terms of quantity. The product of the *quantity* usability factor (q) and the quantity of excess available is ratio from 0 to 1 indicating the portion of the future need that can be met by the excess capability being considered. Since excess beyond the requirement of the future need does not contribute the meeting the need, the ratio does not exceed 1. That is, excess capability, in quantities larger than that required by the future need, is not usable for that particular need

$$qx = \begin{cases} \dfrac{x_{\text{avail}}}{x_r}, & \text{if } x_a < x_r \\ 1, & \text{if } x_a \geq x_r \end{cases} \quad (3)$$

where x_a is the quantity of excess available in the system and x_r is the quantity of excess required by the future need under consideration. When no future need is specified, x_r is the maximum practical value of excess.

The *type* usability factor (t) is associated with the type of excess. It relates the type of excess capability available to the type of excess required for a particular need. For example, if a future need requires only excess space, then the *type* usability factors (t) for excess space are assigned a value of 1. For all other excess capabilities (e.g., power, payload, performance), the *type* usability factors (t) are assigned a value of 0 for that particular future need.

The form of excess capability is used to establish the *form* usability factor (f). It relates the form of the excess capability available to the form of the required excess. In the case of excess space, the *form* usability factor (f) refers to how well the shape of the available space matches the required shape. When the shape of the excess space matches the required shape, the *form* usability factor (f) is assigned a value of 1. All excess spaces, with incompatible forms, are assigned a *form* usability factor (f) less than 1, depending on their convertibility to the required shape. That is, f decreases as the effort or cost required to convert it to the required form increases. The form of other types of excess capability is analogous to shape. For example, the form of electrical power refers to its voltage and current characteristics (e.g., voltage, frequency, AC/DC).

The last factor to consider is the *location* usability factor (l), which addresses the fact that to be usable, excess capability must be available in the required location. It relates the location of the available excess capability to the required location. In the example of adding a trailer hitch to a pick-up truck, the excess space for the hitch was required to be in the rear of the truck under the bumper. Excess space that is in a location suitable for a hitch would receive a location usability value of 1. Excess space in other locations would receive a value less than 1 for l, depending on the adaptability of its location.

The usability of excess depends on all four usability factors (q, t, f, and l) and the quantity of excess capability (x). Nonzero values are needed for all factors, if the excess will be deemed usable at all. For this reason, we model the usability of excess as a product of normalized usability factors (as opposed to a sum). This product is referred to as the usable excess (U)

$$U_{ij} = (q_{ij}\ t_{ij}\ f_{ij}\ l_{ij})x_i \tag{4}$$

where U_{ij} is the usable excess associated with the ith excess capability as it relates to the jth need. The usability factors q_{ij}, t_{ij}, f_{ij}, and l_{ij} indicate the relevance of the quantity, type, form, and location of the ith excess capability to the jth need. When the future need requires only one excess capability, the usable excess is the evolvability (E) of the system to that future need (see Eq. (2)).

The evolvability of a system to meet a future need, which requires multiple excess capabilities, can be calculated based on the usable excess (U) of all required excess capabilities. Just as all four usability factors are required for an excess capability to be usable, all required excess capabilities must be included in the calculation of evolvability. If any required excess capability is missing, the system is deemed unable to evolve to meet that particular need. Therefore, the evolvability, for a particular need, is a product of all required excess capabilities

$$E_j = \prod_{i=1}^{n} U_{ij} \tag{5}$$

where E_j is the evolvability of a system as it relates to the jth future need, and i is an index for the set of n required excess capabilities for that need. Just as the usable excess (U_{ij}) is normalized (due to the normalization of qx, t, f, and l), the resulting evolvability is also normalized.

When only a partial understanding of future needs exists, usable excess can be designed in to improve the flexibility of a system. The highest average usable excesses (U_{ij}), across many possible future needs, identify the most frequently needed excess capabilities. If these most frequently utilized excess capabilities are included in the design, they will generally provide the system with more flexibility in the future.

For a system with more than one future need, an overall expression for evolvability is necessary. An approach to evaluate the overall evolvability of a system (E) to several needs is to average the evolvability of the system to the individual future needs (E_j)

$$E = \sum_{j=1}^{m} \frac{E_j}{m} \tag{6}$$

where j is an index for the m future needs. For cases where the evolvabilities of these needs should be aggregated differently to reflect the goals of a project, the design team could use one of various aggregation methods (e.g., weighted average) [37,38].

3.2 Application of Usable Excess (U), and Evolvability (E), to Three Categories of Future Needs.

There are three special cases that should be noted regarding Eqs. (4)–(6). They are:

(1) when future needs are known
(2) when future needs are not known, but can be generalized
(3) when future needs are not known, and cannot be generalized

These three cases are sometimes referred to in the literature as *known knowns, known unknowns, and unknown unknowns* [39]. They are described in more detail in Secs. 3.2.1, 3.2.2, and 3.2.3.

3.2.1 When Needs Are Known.

For the case where the excess capabilities are identified and the needs are known, functions can be established for the usability factors q, t, f, and l. Generally, the design teams will find that their experience in and understanding of their industry will greatly facilitate the development of normalized expressions for the usability factors.

For many cases, we use the superposition of three simple functions, the ramp, step, and impulse functions to determine normalized values for the usability factors (q, t, f, and l). A ramp function is appropriate when the value of a usability factor (t, f, or l) increases linearly with respect to the excess capability, with no minimum or maximum limits. It simply scales the value to a range of 0–1. The step function applies when there is a minimum or maximum requirement on the excess. The step occurs at the minimum or maximum excess value. An impulse function is a useful way to describe cases where a specific value of excess capability is required. All values other than the specific value are assigned a value of zero.

3.2.2 When Needs Are Unknown But Can Be Generalized.

In some cases, future needs are not identified and functions for q, t, f, and l are not explicitly known. When future needs are unknown, but can be generalized, functions can be developed that are useful for evaluating excess capability. For example, larger quantities of excess capability, located close to potential points of use, may be preferred. With these assumptions, the following equations can be applied to q, t, f, and l:

$q_{ij} = 1/x_{\text{i,max}}$ where q_{ij} is the inverse of the maximum practical value of excess capability. When multiplied by the available excess (x_i), the result is a normalized fraction of excess. When the product of q_{ij} and x_i is greater than 1, the result is set to 1, as noted in Eq. (3).

$t_{ij} = 1$ where a specific type is not a factor when considering generalized evolvability (all excess capabilities are considered). The values of q, f, and l determine the usability of the excess capability under consideration.

$f_{ij} = s_{\min}/s_{\max}$ where $s_{\min}$ and $s_{\max}$ are the minimum and maximum form dimensions of the excess (x_i) being considered. f characterizes the form of excess capability, where cubical or spherical forms have a larger value of f than plates or slender cylinders.

$l_{ij} = 1 - d/d_{\max}$ where d is the distance of the excess (x_i) from the required location of the excess and $d_{\max}$ is the maximum or worst case separation distance. l characterizes the location of excess capability, where larger values are assigned to l based on the proximity of the excess capability to the required location.

These equations are used to determine total system evolvability when future needs can be generalized.

3.2.3 When Needs Are Unknown and Cannot be Generalized.

In the case where the needs are unknown and cannot be generalized, usable excess cannot be determined. In this case, it may be appropriate to simply sum the quantities of excess capability. Previous work by Tackett et al. [26] examined this case. In their paper, the excess capability of a system was calculated as the sum of all the quantities of excess capability in the system. A possible issue arises from this approach; when the usability of excess capability is not considered, the evolvability will be inflated by excess capabilities that are unusable based on their quantity, type, form, or location.

3.3 Benefits of Quantifying Usable Excess and Evolvability.

Once quantified, excess capability and evolvability can benefit decision makers and design teams in several ways. For example, the overall evolvability of several candidate designs can be computed and compared, thus informing the decision making process. Once quantified, a range of numerical analyses can be carried out while considering evolvability, including optimization search methods, sensitivity analysis, and robust design. A major benefit of this quantification is that it enables a better understanding and management of the evolution that needs to occur in complex large-scale systems. In Sec. 4, an example is presented showing how this methodology can be used to compare two systems.

4 Automated Assembly Station Assessment

The following study of automated assembly stations illustrates how the relationships developed in Sec. 3 can be utilized to evaluate a system's ability to meet changing requirements. Automated assembly lines can be large complex engineering systems. They are generally composed of a number of stations linked by a main conveyor. The development of an assembly line requires a large development team, can cost millions of dollars to develop, and millions more to produce. Due to unpredictable market variations, these lines are extremely susceptible to costly in-service design changes and the possibility of premature obsolescence. The problem of creating and configuring assembly lines has been the focus of previous research [40,41]. Bryan et al. recognize this issue and have proposed a reconfiguration-planning tool to sequence a line between products once the configurations are known [42]. Spicer and Carlo have focused on the scalability of an assembly system due to production volume changes [43]. Their research does not include metrics or methodologies to evaluate the evolvability of an assembly line based on usable excess.

This section focuses on evaluating two different automated assembly stations for evolvability. Each automated assembly station takes a different approach to meeting the current and future design requirements. Evaluations of evolvability (E) and usable excess (U) allow comparisons and selections to be made between the two stations. To this end, we apply the equations outlined in Sec. 3 to each station utilizing the process outlined below:

(1) identify future needs
(2) identify all excess capabilities based on original requirements
(3) determine the usability factors q, t, f, and l
(4) determine the usable excess (U_{ij}) and the evolvability (E_j) of the system for each future need
(5) calculate overall system evolvability (E)

The resulting values for usable excess and evolvability are employed to evaluate the ability of each assembly station to meet future needs.

4.1 Automated Assembly Station Description. A brief description of the stations should facilitate our analysis (see Figs. 1 and 2). We examine two automated assembly stations: station 1 and station 2. The stations are designed to support products that are assembled by loading components unto a tray or mainframe (top–down operations). These stations can be used to assemble computer peripherals, such as hard disk drive memory units, keyboards, or printers. In this case, the stations are sized for hard disk drive memory unit assembly (measuring $54 \times 71 \times 8$ mm).

Figure 1 is an aerial view (layout) of the two assembly stations, mentioned above. Each station is composed of an incoming material or component tray (B), shown full in the upper left hand corner of the figure. This tray sits on a tray conveyor (A) that runs across the width of each station (shown in the upper portion of the figure). Empty trays are removed from the right side of the station (E). A horizontal actuator runs perpendicular to the tray conveyor (shown down the center of each station). Attached to the horizontal actuator is a vertical actuator (D). The main conveyor (F), shown across the lower portion of the figure, carries the product as it is assembled. Products being assembled are transported along the assembly line (between adjacent stations) by the main conveyor (F).

Three high-level requirements have been selected for this example:

(1) cycle time (throughput) ≤ 10.0 s
(2) floorspace $\leq 0.67\,\mathrm{m}^2$
(3) material resupply interval: ≥ 350 s

Cycle time is a measure of the rate at which units are produced (e.g., one every 10.0 s). With a maximum cycle time of 10.0 s, the material resupply requirement translates to a minimum of 35 pieces of material (components) in each component tray. The maximum allowable footprint for a station ($0.67\,\mathrm{m}^2$) is calculated based on the floorspace requirements of the factory and the number of stations anticipated in the line. These high-level requirements will be used to determine values for the usability factors (t, q, f, and l) for the excess capabilities in each station.

While the two stations are designed using a similar architecture, excess capability is different in each station. The value of this analysis is to provide a quantitative measure of evolvability based on those different excess capabilities.

4.2 Methodology Applied to Automated Station. The study includes two cases. The first case, presented in Secs. 4.2.1–4.2.5, demonstrates the evaluation of evolvability (E) and usable excess (U) when future needs are known. The second case, presented in Sec. 4.2.6, considers the case when future needs are unknown but can be generalized.

4.2.1 Step 1. Identify Known Future Needs. The first step of the process is to identify the future needs. Three specific future

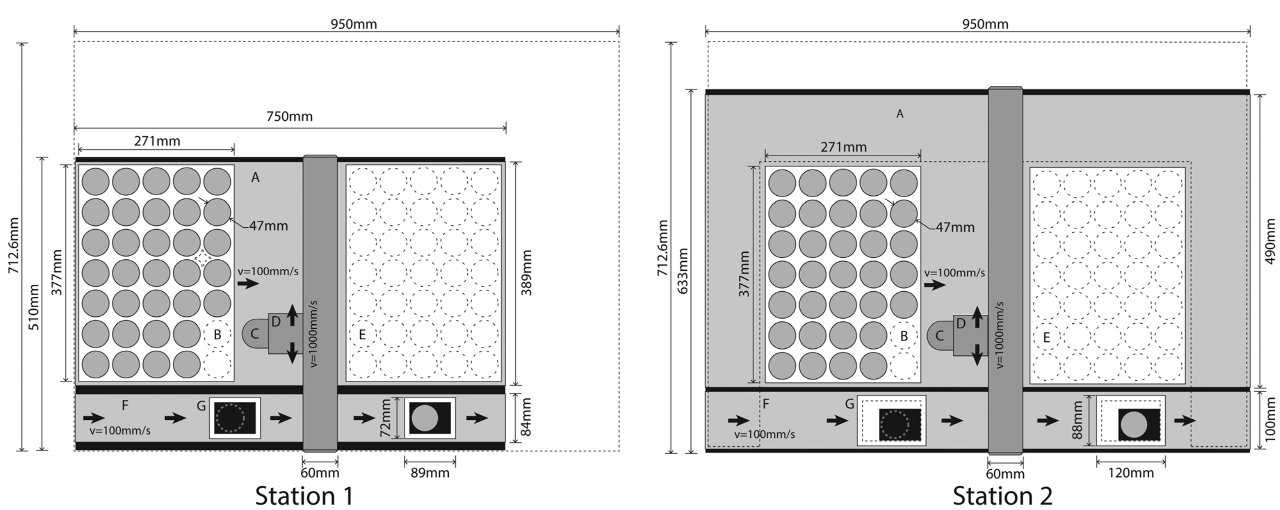

Fig. 1 Automated assembly station layouts. *A* = Tray conveyor, *B* = tray (incoming), *C* = end effector, *D* = vertical actuator, *E* = tray (empty), *F* = main conveyor, *G* = pallet.

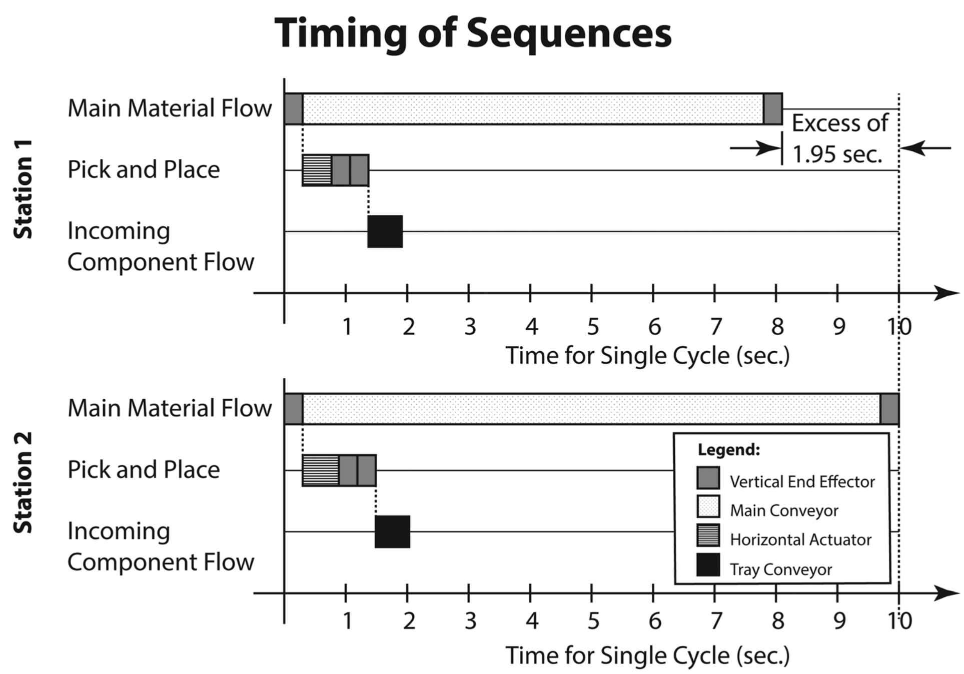

Fig. 2 Station timing layout

needs have been identified. Each station's evolvability is evaluated relative to each of these specific future needs

(1) decrease cycle time by 15%
(2) assemble a larger product (70 × 103 × 12 mm)
(3) increase the resupply interval by 30%

Like all computationally assisted methods, the method presented in this paper for determining evolvability depends on the existence of quantifiable values and models for each of the future needs. Nevertheless, some unquantified future needs can be quantified using established methods [44,45]. In many cases, decomposing the requirement into basic elements and then quantifying those basic elements can be helpful [46]. Another technique is to create a parametric function (or surrogate) that approximates the behavior based on the system design parameters. The future need is quantified by the required values of the surrogate. Future needs that are not quantified cannot be analyzed using the method presented in this paper.

4.2.2 Step 2. Identify Excess Capabilities. The second step is to determine all the quantities of excess capability. Recall that excess capability has been defined as a resource, embodied by a system, which is not committed to any of the system's initial design requirements. Based on the three high-level requirements and the designs outlined in Figs. 1 and 2, excess capability can be identified as shown in Table 2.

Excess capability can be viewed as excess space, excess move time, and excess cycle time. Excess space exists in only very limited quantities in station 1. However, station 2 has a relatively large quantity of excess space in the tray conveyor.

Cycle time is a function of the move times of the main conveyor, vertical actuator, horizontal actuator, and tray conveyor. These move times are calculated based on the distance moved and the speed of the actuator or conveyor. Figure 2 summarizes the move times and their relationship to each other for a complete station cycle. Note that the main conveyor move time is the longest and, as a result, the greatest contributor to the cycle time. The station cycle time is determined by summing the main conveyor move time and two vertical actuator move times. Station 1 has excess move time due to its cycle time being less than the requirement by 1.95 s. Station 2 has no excess main conveyor nor vertical actuator move time, since its cycle time just meets the 10.0 s requirement.

4.2.3 Step 3. Determine Usability Factors q, t, f, and l When Future Needs Are Known. Now that the excess capabilities have been identified, we determine the usability factors. The usability factors are related to both the future need and excess capability required to meet it. Table 3 shows the relationship between the identified needs and required excess capabilities. Excess capabilities not included in Table 3 have zero values for at least one usability factor (e.g., type is not appropriate resulting in $t = 0$). Hence, they are not usable for this future need.

As an example of this process, we consider the future need to assemble a larger product on the stations. This example is

Table 2 Excess capability available in each station

Excess capability	Station 1	Station 2
Pallet space	0.000 m^2	0.004 m^2
Tray space	0.041 m^2	0.041 m^2
Tray conveyor space	0.000 m^2	0.174 m^2
Main conveyor move time	1.842 s	0.001 s
Tray conveyor move time	9.511 s	9.511 s
Vertical actuator move time	0.074 s	0.000 s
Horizontal actuator move time	3.958 s	4.394 s
Station cycle time	1.950 s	0.000 s

Table 3 Future needs and the associated excess capabilities required

Need	Decrease Cycle Time	Assemble Larger Product	Increase Resupply Interval
Pallet space		0.003	
Tray conveyor space		0.069	0.038
Main conveyor move time	1.500		
Tray conveyor move time		0.158	0.147
Horizontal actuator move time		0.017	0.015

Table 4 Evolvability (E_j), and usability factors (t, q, f, l), with associated functions, calculated for the future need to assemble a larger product

	U	x	qx	t	f	l
Functions from Sec. 3.2.1			$x_{a,i}/x_{r,i}$	Impulse	Impulse	Ramp
Station 1						
Pallet space	0.000	0.000	0.000	1.000	0.000	1.000
Tray conveyor space	0.000	0.000	0.000	1.000	0.000	0.917
Tray conveyor move time	1.000	9.511	1.000	1.000	1.000	1.000
Horizontal actuator move time	1.000	3.596	1.000	1.000	1.000	1.000
Evolvability (E_j)	0.000					
Station 2						
Pallet space	1.000	0.004	1.000	1.000	1.000	1.000
Tray conveyor space	0.917	0.174	1.000	1.000	1.000	0.917
Tray conveyor move time	1.000	9.511	1.000	1.000	1.000	1.000
Horizontal actuator move time	1.000	4.394	1.000	1.000	1.000	1.000
Evolvability (E_j)	0.917					

analyzed for the case where the new product size is specified (from 54 × 71 × 8 mm to 70 × 103 × 12 mm).

As noted in Sec. 3.2.1, when needs are well understood, functions can be developed to evaluate the usability factors (q, t, f, and l). The types of functions used to determine the usability factors, for this example, are presented in the top portion of Table 4. Below each function are the resulting values of the usability factors.

4.2.4 Step 4. Determine Usable Excess and Evolvability to Each Future Need. The product of the four usability factors (q, t, f, and l) and the quantity of excess (x) are the value of usable excess (U) as they are applied to a specific need (see Eq. (4)). The evolvability is calculated (see Eq. (5)) by taking the product of all required usable excesses (U_{ij}). Again, we use the future need of assembling a larger product to illustrate this process. Using the values of q, t, f, and l presented in Table 4, the evolvability of each station to assemble a larger product can be determined. These results are also tabulated in Table 4.

As seen in Table 4, E_j for station 1 is 0. This indicates that station 1 is not evolvable to produce the larger product. While station 2 is not perfectly evolvable to assemble a larger product ($E_j \neq 1$), it is very close ($E_j = 0.917$). The reason for this is the location of excess space for the larger components. Ideally, this space would be in the conveyor tray ($l = 1$). However, there was no excess space in the conveyor tray, but there is excess space in the conveyor ($l = 0.917$). The corresponding location usability factor (l) can be calculated relatively easily based on its distance from the ideal location. Thus, the evolvability of station 2 to assemble a larger product is 0.917. When comparing two or more systems' ability to meet a specific future need, E_j should be used because it is specific to that need.

The values of usable excess (U) for each station indicate that the critical excess capabilities are excess space in the pallet and the tray conveyor. Station 1 has no excess space in either location, while station 2 has sufficient space, in a slightly less suitable location, to handle the larger product.

4.2.5 Step 5. Calculate Overall System Evolvability (E) Based on Known Future Needs. The process outlined in Secs. 4.2.3 and 4.2.4. (for the future need of assembling a larger product on the line) is repeated for each of the other two future needs. The values of E_j are then averaged to achieve an overall evolvability (E). The results are displayed in Table 5. Note that the overall evolvability (E) of the system is a function of each of the future needs (see Eq. (6)). Therefore, E should be used when comparing the evolvability of multiple systems to meet all future needs. And, E_j should be used in comparisons when considering only *one* specific future need.

The overall evolvability of the system is a function of the evolvability of the system to each of the future needs (see Eq. (6)). The process outlined in Secs. 4.2.3 and 4.2.4. (for the future need of assembling a larger product on the line) is repeated for each of the other two future needs. The values of E_j are then averaged to achieve an overall evolvability. The results are displayed in Table 5.

Based on the three identified future needs, each station exhibits evolvability for specific future needs, but neither station achieves an overall evolvability of 1.0. Specific required usable excess is missing in each station.

Because of its relatively smaller size, station 1 has excess cycle time, but lacks the required excess space. As a result, station 1 is more capable of evolving to improve cycle time, but incapable of evolving to assemble a larger product or increase the resupply interval.

Station 2 exhibits greater overall evolvability than station 1 (≈84%). Station 2 is more evolvable in terms of increasing assembled product size or increasing the resupply interval (increasing the number of parts in the tray), but incapable of decreasing its cycle time. The design of station 2 contains much more embedded excess space, but insufficient excess move time to compensate for its larger size. It excels in meeting needs that take advantage of designed-in excess. It provides an opportunity to change product sizes or to increase the resupply interval. A longer resupply interval could be a very important capability, particularly if cycle times are reduced due to main conveyor performance improvements. On the negative side, the station 2 design results in a permanent commitment to its larger overall size and associated cost.

Each station exhibits benefits in terms of evolvability. Decision makers can make a selection between station 1 and station 2 based on their judgment of which future needs are most probable. Designers can then use this information to identify possible changes and additions to improve evolvability by increasing specific usable excess capabilities.

Table 5 Overall evolvability (E)—both stations exhibit evolvability for at least one future need. However, station 2 scores better in terms of overall evolvability.

	Station 1 E_j	Station 2 E_j
Decrease cycle time	1.000	0.000
Assemble larger product	0.000	0.917
Increase resupply interval	0.000	0.917
Total (E)	0.333	0.611

Table 6 Evolvability, generalized usability factors (*t*, *q*, *f*, *l*), and associated functions calculated when future needs are unknown

			qx	t	f	l
Functions from Sec. 3.2.2	U	x	$x_{a,i}/x_{i,\max}$	Impulse	$s_{\min}/s_{\max}$	$1-d/d_{\max}$
Station 1						
Pallet space	0.000	0.000	0.000	1.000	0.760	1.000
Tray space	0.004	0.041	0.299	1.000	0.013	1.000
Tray conveyor space	0.000	0.000	0.000	1.000	0.000	1.000
Main conveyor move time	0.614	1.842	0.614	1.000	1.000	1.000
Tray conveyor move time	1.000	9.511	1.000	1.000	1.000	1.000
Vertical actuator move time	0.008	0.074	0.008	1.000	1.000	1.000
Horizontal actuator move time	1.000	3.959	1.000	1.000	1.000	1.000
Evolvability (E)	0.375					
Station 2						
Pallet space	0.418	0.004	0.615	1.000	0.680	1.000
Tray space	0.004	0.041	0.299	1.000	0.013	1.000
Tray conveyor space	0.714	0.174	1.000	1.000	0.714	1.000
Main conveyor move time	0.002	0.001	0.001	1.000	1.000	1.000
Tray conveyor move time	1.000	9.511	1.000	1.000	1.000	1.000
Vertical actuator move time	0.000	0.000	0.000	1.000	1.000	1.000
Horizontal actuator move time	1.000	4.394	1.000	1.000	1.000	1.000
Evolvability (E)	0.448					

To help calibrate the reader to these values of evolvability, consider the case of adding a tow hitch to a pickup (discussed in Sec. 2.1). In this case, all required types of excess capability were completely available in adequate quantities and in the correct form and location. As a result, the values of qx, t, f, and l are all equal to 1 and the corresponding value of evolvability (E) is also 1. Had any required excess capability been missing or in an incorrect location or form and could not be changed, the corresponding usability factor would have been 0 and the resulting evolvability would also be 0.

4.2.6 When Future Needs Are Unknown But Can Be Generalized. In practice, it is often difficult to provide a detailed description of all future needs. Nevertheless, the methodology presented in this paper is useful even when future needs can only be described in general terms. In such cases, the same five steps are followed. However, the usability factors (t, q, f, and l) determined in Sec. 4.2.3 are now determined using the generalized equations discussed in Sec. 3.2.2. This section generalizes excess for quantity as *larger being preferred over smaller,* for form as *lumped being preferred over dispersed*, and for location as *central locations being preferred over extremity locations*. Table 6 contains the results of this analysis. The functions are referenced at the top of the table, below the column headings. Results for the usability factors, usable excess (U), and evolvability (E) are included in the body of the table. As shown in Table 6, both stations exhibit usable excess. Station 1 has more usable excess move time (conveyor move time), while station 2 has more usable space excess.

With regard to evolvability, and just as in the case where the future needs are known, station 2 exhibits a greater evolvability than station 1. However, the difference in evolvability is reduced to ≈19%. This is due to the lack of a restriction on possible future needs. The excess move times available in station 1 and the excess space included in station 2 are more closely balanced, when no specific future needs are considered.

The decision makers and designers can use the information presented in Table 6 to investigate several aspects of the two designs being considered. In addition to the overall evolvability (E, shown at the bottom of each section of the table), the usability of the various excess capabilities (U) can be seen and compared in the second column of the table.

4.3 Summary of the Automated Assembly Case Study. In this simple example, we have shown that usable excess capability (U) and evolvability (E) can be quantified for an engineered system. This specific example is chosen: (i) to quickly illustrate how the five-step methodology can be used to evaluate a system's evolvability based on usable excess and (ii) to allow intuition to confirm the analysis results.

As the complexity of the system increases with a greater number of excess capabilities and future needs, the five-step methodology becomes more valuable because it captures conditions that cannot always be observed or deduced intuitively. As such, large teams involved in engineering complex systems can: (i) quantify and communicate needed aspects of evolvability and (ii) compare the strengths and weaknesses of alternatives based on repeatable calculations.

5 Conclusion

In this paper, we have introduced the concept of *usable excess* as a means to estimate system evolvability. The evaluation of usability is a meaningful and needed extension to the work of Tackett et al. [26] where all excess is regarded equally whether it is usable or not. The extension presented here evaluates available excess based on its quantity, type, form, and location.

The methodology presented in this paper provides system designers with an analytical tool to evaluate system evolvability relative to potential future needs (or a generalized form of future needs). With this methodology, we believe that teams working on complex projects may be able to quantify and communicate essential aspects of evolvability. A formal experiment to quantify these benefits would be a valuable element of future work. Further, we believe that the strengths and weaknesses of alternatives can be quantifiably analyzed, using these metrics as a tool.

We have demonstrated the methodology by comparing the designs of two different automated assembly stations. The example focused on examining excess space and performance, and their relationship to system evolvability. A summary of the case study (Sec. 4.3) describes how the presented method can benefit system designers.

We acknowledge that this paper has not addressed several practical issues. For example, the methodology is deterministic in nature; however, a nondeterministic extension is a worthy pursuit. Furthermore, we have only demonstrated the evolvability (E) and usable excess (U) as comparative measures, even though they can be used for a variety of purposes. Two addition applications are: (i) using the evolvability calculations could also be used in conjunction with other functions (e.g., cost or value functions) to provide the basis for an optimization problem, and (ii) employing the usability assessments, having been performed on several potential future needs, to identify frequently required excess capabilities, the inclusion of which may improve the system's survivability. Finally, even though it was proposed in Sec. 2 that the need for evolvability is motivated by three events, we only focused on one in this paper: the addition of a new requirement. While the methodology is applicable to the elimination of a requirement or the exchange of requirements, it has not been demonstrated in this paper.

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Nomenclature

E = system evolvability
f = excess usability factor for form
l = excess usability factor for location
m = number of future needs considered
n = number of excess capabilities considered
q = excess usability factor for quantity
t = excess usability factor for type
U = usable excess
x = quantity of excess capability in the system

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