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Defining and Using the New "ilities"

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Abstract. The nature of system properties, sometimes called the new "ilities" are discussed, and defined, with particular attention to the differences between the ilities, formalized specification for the ilities, as well as relationships between the ilities. Examples are given including generalized statements about the "ility" of a system, as well as specification statements for requirements definition and verification.

Introduction

Much confusion abounds in the systems engineering community about the nature of "ilities." "ilities" have been around for a while, in particular the classical "RMA ilities" of *reliability*, *maintainability*, and *availability*. These classical "ilities" relate to the satisfactory performance of a system from a quality perspective, over the operational life of the system. The "new ilities" include a very long list of additional system qualities. Table 1 below lists some examples of the new "ilities" cited in various literature (ESD_Symposium_Committee 2001)[1].

Table 1 Example listing of "ilities" cited in various literature

accessibility	extensibility	repairability
accountability	fail-safe	repeatability
adaptability	flexibility	reproducibility
administrability	installability	reusability
affordability	interchangeability	robustness
agility	interoperability	safety
auditability	learnability	scalability
availability	maintainability	seamlessness
changeability	manageability	serviceability (a.k.a. supportability)
compliant with standards	mobility	securability
composability	modifiability	simplicity
configurability	modularity	stability
credibility	nomadicity	survivability
customizability	operability	sustainability
degradability	portability	tailorability
demonstrability	predictability	testability
dependability	quality	timeliness
deployability	reconfigurability	understandability
distributability	recoverability	usability
durability	relevance	
evolvability	reliability	

[1] Table compiled from Wikipedia "ilities" entry April 24, 2008 and MIT Engineering Systems Working Paper Series ESD-WP-2002-1, though there are many, many more "ilities" out there and this list does not claim completeness.

A primary source of confusion in utilizing these "ilities" as requirements on systems is a lack of agreement of definition for these terms. The "ilities" are system properties, that is, they describe some essential quality of the system that describes, or results from, the form or function of the system and typically relates to qualities above and beyond the cost, schedule, and performance expectations for the system development and operation.

The proliferation of "ilities" partly relates to the fact that any verb or adjective can be conjugated, albeit awkwardly, with *–ability*, sometimes shorten as *–ility*, resulting in a new ility. Usually these ilities describe additional qualities beyond the essential form or function needs for the system. For example, suppose one desired a cooler that satisfies the following basic needs:

Basic Needs for a "cooler"

1. Keep food cool for longer than 2 hours
2. Enclose at least 2 cubic feet of volume
3. Is lightweight to minimize additional weight-bearing needs
4. Costs no more than $20

Suppose now that a consumer desires also for the cooler to be able to have more volume than originally desired. The cooler must be able to perform the "scaling" function in terms of volume. Therefore the consumer desires a cooler that is *scaleable in volume beyond 2 cubic feet*. Perhaps the manufacturer also realizes that appearances matter and that it would be desirable for consumers to be able to change the appearance on case by case basis. The ability for the consumer to customize the cooler's appearance means the cooler should have *customizability in appearance* for the customer.

Even though the example is simple, one can readily see that an infinite number of potential "ilities" can be levied on the system, especially since many of these so-called "ilities" are in fact just additional function or formal requirements.

Essential differences between "ilities"

In order to clearly specify "ilities" as required characteristics for a system being developed or operated, it is critical to be able to formulate unambiguous statements regarding the meaning for the "ility" in the context of the system, as well as the metrics that can be used for verification.

Structural versus Operational "ilities"

One key differentiator between "ilities" relates to whether it describes a form-related aspect of the system, or a function-related aspect of the system. The former type of "ilities" can be measured using *structural metrics*, and are properties of the system architecture, or form, often completely independent of the system context or intended use (Giachetti, Martinez et al. 2003)[2]. The latter type of "ilities" can be measured using *operational metrics*, and are properties of the system in use, or over time, and may be dependent on the context in which the system operates.

[2] Giachetti et al. discusses the difference between structural and operational metrics, as well as potential for misapplication and misinterpretation of using the incorrect type.

An example of a structural ility is *modularity*. An example of an operational ility is *survivability*. Some ilities cross between the two, such as *flexibility*.

Ilities describing types of "changes"

It turns out that many of the ilities actually relate to changes in function or form of the system over time. The growing attention to the new ilities likely reflects a growing desire for systems that can change their form or function over time to meet changing needs in changing environments. (Ross 2006) describes some of these ilities as types of *changeability* for a system.

The following is an excerpt from (Ross, Rhodes et al. 2008):

Changeability Defined

As changeability grows in importance as a consideration in the engineering of systems, there is a critical need to have a more rigorous and quantified definition. In this section of the paper an enhanced definition of system changeability is described, which characterizes the elements of changeability. Change can be defined as the transition over time of a system to an altered state. If a system remains the same at time i and time i+1, then it has not changed. The inevitability of the effects of time on systems and environments results in a constant stream of change, both of the system itself and of its environment.

A change event can be characterized with three elements: (1) the agent of change, (2) the mechanism of change, and (3) the effect of change. Figure 1 illustrates these three elements. The *agent of change* is the instigator, or force, for the change. The role of change agent can be intentional or implied, but always requires the ability to set a change in motion. The *mechanism of change* describes the path taken in order to reach state 2 from state 1, including any costs, both time and money, incurred. The *effect of change* is the actual difference between the origin and destination states. A system that is black in time period one and gray in time period two has had its color changed. The change agent could be Nature, which can impart physical erosion due to wind, water, or sun, or could be a person with paint can and brush. The change mechanism could be the erosion or painting process, costing no money, but taking a long time, or costing some amount of money, but taking a shorter amount of time. Figure 1 shows the three aspects of change that must be defined to specify a change.

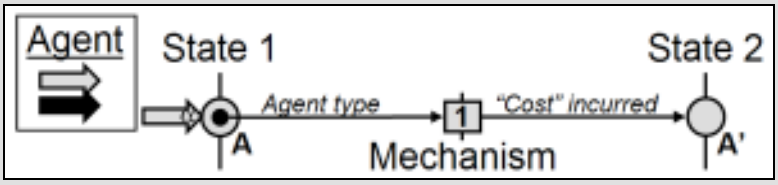

Figure 1. Change defined as state transition. Change specifications must include descriptions of change effect (difference between state 1 and state 2), change mechanism including "cost," and the change agent instigating the change.

The change described in Figure 1 is a simple case where there is only one particular change. In the *agent-mechanism-effect representation*, a particular change is represented by a *path*. The changeability of a system is determined by how easily it can undergo various changes. Figure 2 shows an example of an expanded view with multiple change paths enumerated.

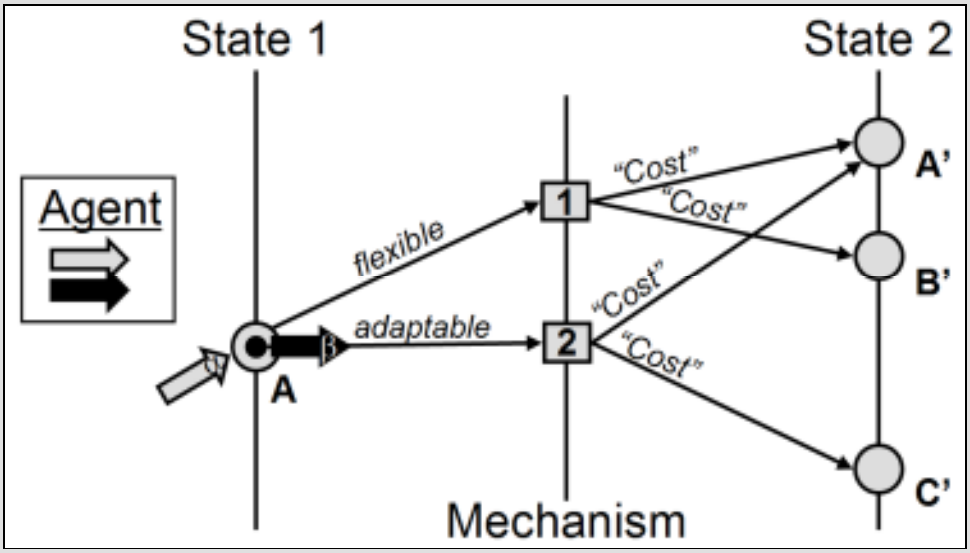

Figure 2. Multiple system changes depicted using the agents, mechanisms, and effects representation.

Table I enumerates the example agents, mechanisms, and effects shown in Figure 2. For a particular system, many agents, mechanisms, and end states may be possible.

Table I. Agents, mechanisms, effects, and paths shown in Figure 2.

Element	Description	As Illustrated in Figure 2
Change Agent	*The force instigator for the change to occur, for example humans, software, Mother Nature, etc.*	α, β
Change Mechanism	*The particular path the system must take in order to transition from its prior to its post state, including conditions, resources, and constraints*	1, 2
Change Effect	*The difference in states before and after a change has taken place.*	A'-A, B'-A, C'-A
Potential Paths	*The potential paths for the system to change from one state to another.*	α:A-1-A', α:A-1-B' β:A-2-A', β:A-2-C'

Change Agents.

One of the three elements of a change is the *change agent*. As defined above, the agent is the force instigator for the change to occur. Examples of change agents include humans, software, Mother Nature, etc. Intent is not required for a change agent, but the ability to set in motion a change mechanism is required. When characterizing an agent it is useful to think in terms of the steps required to put into motion a particular action.

Working backwards from most to least necessary, three capabilities can be used to differentiate the most to least sophisticated of change agents: 1) impact, 2) decision making, and 3) observation. Impact is the actual ability to set into motion a change mechanism. A physical impetus, such as a bat hitting a ball, or a social impetus, such as a manager tasking an employee, are examples of impact. Decision-making is the ability to process information in a structured

manner in order to determine a course of action, presumably regarding whether to exert impact. Having decision-making ability allows for the incorporation of intent into actions. Observation is the ability to gather relevant information in order to conduct effective decision-making, and can increase the likelihood of making good decisions. It is important to realize that change can occur with only impact present, but intentional change usually occurs with decision-making, and the most effective intentional change usually occurs with all three abilities present. Adding "intelligence" to a change agent is equivalent to adding the decision-making and possibly observation abilities. The three abilities are loosely based on the analysis in [Hall, 1985], which differentiates between human and machine capabilities Psychomotor (Impact), Intellectual (Decision making), and Sensory/Perceptual (Observation).

The location of a change agent is a useful taxonomic distinction to be made when classifying change. If the change agent is external to the system, then the change under consideration is a *flexible*-type change. If the change agent is internal to the system, then the change under consideration is an *adaptable*-type change. Note that depending on the particular change being considered, a single system can be both flexible and adaptable. The definition of the system boundary must be explicitly defined in order to remove ambiguity when discussing whether a change should be considered as flexible or adaptable. Figure 3 summarizes these two change classification types.

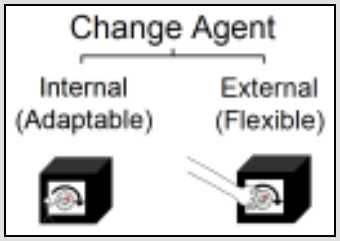

Figure 3. Change agent location (internal or external) for distinguishing between Adaptability and Flexibility.

Change Effects.

Another element of change to define is *change effect*. The change effect is the difference in states before and after a change has taken place, and often it is the effect that is first noticed to indicate a change has occurred. The changeability of a system can be classified into three categories of effects: *robustness*, *scalability*, and *modifiability*, which are proposed as a set from a parameter-based description of a system.

A system can be described in terms of sets of parameters, which capture physical, functional, and other performance aspects. *Robustness* is the ability to remain "constant" in parameters in spite of system internal and external changes. *Scalability* is the ability to change the level of a parameter. *Modifiability* is the ability to change the membership of the parameter set. The intent of the definitions is to balance generalizeability with precursor definitions. The definition of scalability thus presented would encompass concepts such as scaling up the number of satellites in a constellation (example parameter=number of satellites), the size of car chassis (example parameter=diameter or mass), and the number of users for the system (example parameter=required data bandwidth).

As an example, consider the following parameter set for a car, which includes both function and form: {number of wheels, color of vehicle, quietness of cabin}. Suppose a design

under consideration has the following particular parameter values: {4, “red,” “moderately quiet”}. The possible ranges for these parameters, from lowest to highest, include: {[3, 4, 6, 8]; [“black”, “red”, “blue”]; [“very quiet”, “moderately quiet”, “little quiet”, “not quiet”]}. If the current system can maintain its {4, “red,” “moderately quiet”} in spite of its operating environment changing, such as due to driving on unpaved roads and past construction sites, then it is robust in these parameters to those particular environments. The more environments to which it is insensitive, the more robust the system.

If the system changes from having 4 wheels to having 6 wheels, then it has made a scalable change, and likewise if it changes from being “moderately quiet” to being “very quiet” or from being “red” to being “blue.” If the system parameterization set is changed to be {number of wheels, color of vehicle, quietness of cabin, fraction cabin open} then it has undergone a modifiable change, enabling it to display a new function and/or form. In this example, the system is now designed to consider the amount of openness in the cabin. Figure 4 summarizes the three change effect types: robust, scaleable, and modifiable.

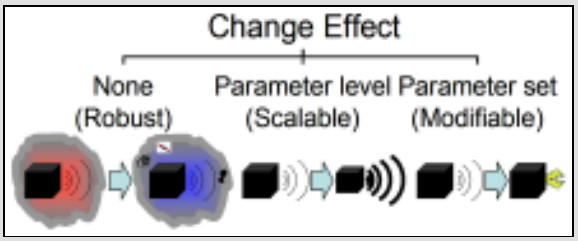

Figure 4. Change effect for distinguishing between Robustness, Scalability, and Modifiability.

Concepts such as modularity and integrality have been intentionally excluded from discussion on effects. Architectural concepts such as these are means to achieving ends (the effects) and should be considered separately. It is anticipated that modularity and other architectural approaches (networks, hierarchies, etc.) have costs and benefits, application dependent, and may or may not impact the change effects on a system. The next section, mechanisms, will discuss the “cost” for change as an important consideration for determining whether a system is actually changeable. Due to the context-dependent costs and benefits for particular architectural choices, these choices do not always increase or decrease the robustness, scalability, or modifiability of a system in straightforward manner. For example, modularity may increase one aspect of scalability of a system, due to lower costs for adding more components, but it may decrease other aspects of scalability of the system due to increased development costs for setting up the modularity in the first place.

Change Mechanisms.

Another element of change to define is *change mechanism*. The mechanism is the path the system must take in order to transition from its prior to its post state. A change path details the necessary components to bring about the change, including conditions, resources, and constraints for the change.

As an analogy, consider the problem of bringing a basketball down court from one basket to the other by a player. (This simple example could represent the problem of relocating a satellite, for instance.) The change agent is the player, the system is the ball, and the change effect is on the location of the ball. Many possible paths can be taken by the player, each

incurring a "cost" in terms of time and effort to change the location state of the ball. Depending on the circumstances (e.g., location of opposing and supporting teams, time of the game, penalty status of the player) the player may choose different paths in order to bring about the same change. More generally, systems likewise have many potential change mechanisms for bringing about different change effects. The more change paths available for a system to follow, the more changeable the system. Just as the "cost" for following a path played a role in determining the best course of action for the basketball player, so too does the potential path cost for a system determine its apparent changeability for a given decision maker. Over time the cost of a given path may change, especially as the context changes. The existence of paths may be objectively determined, but assessing whether a path at a point in time is reasonable to follow is subjectively decided by individuals based on their preferences and circumstances, including available resources. Figure 5 gives a notional example multiple paths with differing costs connecting the same prior and post states for change.

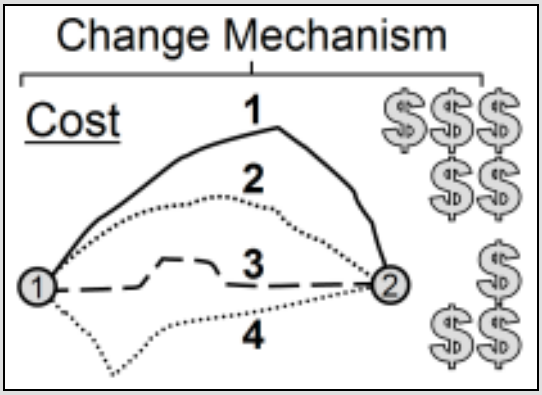

Figure 5. Change mechanism as paths for change for determining degree of changeability of a system.

Implications of definition.

As described, the changeability of a system is determined by the number of acceptable change paths that can be taken by a system. The number of acceptable change paths is determined both by the possible number of end states and the number of change mechanisms available (number of possible effects and number of possible mechanisms). The agent origin serves only taxonomic value in classifying whether a particular change is system-internally or externally motivated. In terms of affecting changeability, the change agent distinction can be used as descriptors on change mechanisms. For example, final assembly of a car could be done by a robot or a team of people. Even though both utilize the "put subassemblies mechanically together" mechanism, these two methods could be distinguished as particular ways to assemble the car, and thereby count as two mechanisms.

Refining the acceptable path counting further, two axes can be defined: number of change end states (specified vs. open-ended) and number of change mechanisms (countable vs. uncountable). These ranges correspond to finite vs. infinite numbers. Figure 6 below shows four possible cases in which a system can fall: (1) countable end states with specified mechanisms, (2) countable end states with open-ended mechanisms, (3) uncountable end states with specified mechanisms, and (4) uncountable end states with open-ended mechanisms. The purpose of Figure 6 is to point out the differing degrees of changeability that can occur in a system. The

remainder of the paper will discuss an approach to the case of quantifying possibly large, but finite numbers of mechanisms and end states in order to quantitatively assess the changeability of systems on a common basis (lower left quadrant of Figure 6).

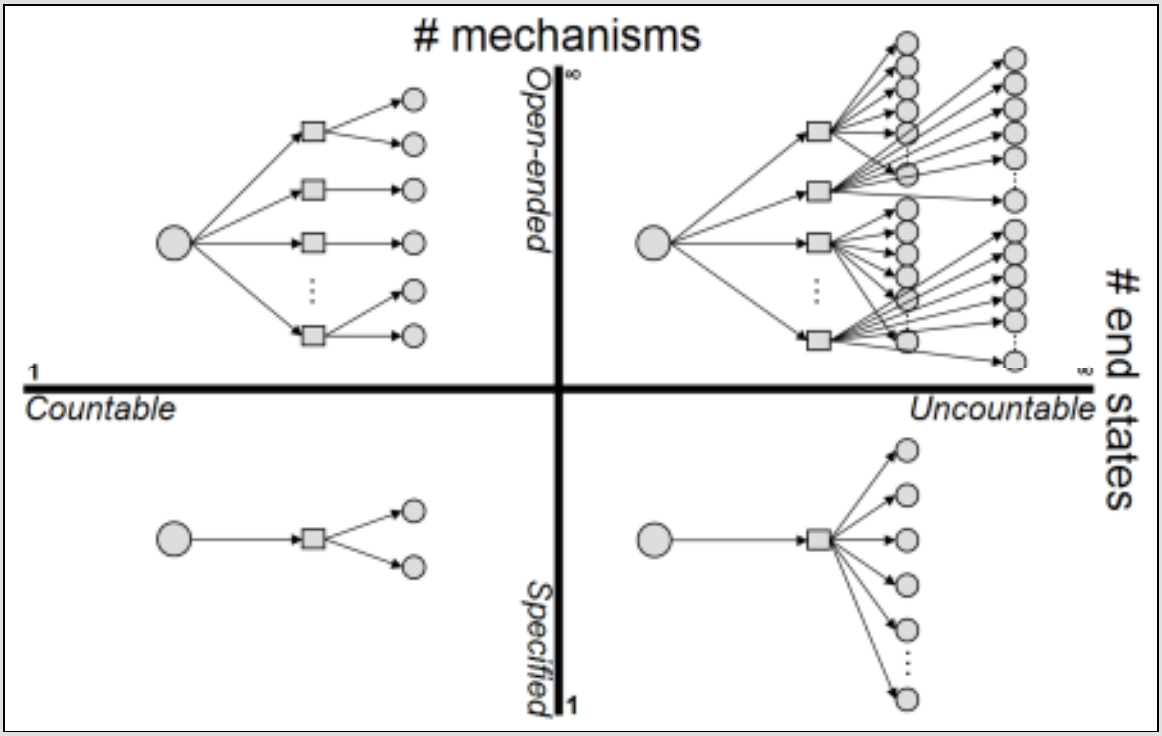

Figure 6. Two axes for counting change paths: number of mechanisms and number of end states, both on finite to infinite scales.

The meanings of flexibility, adaptability, scalability, modifiability, and robustness have been clarified so that a more rigorous consideration can be applied to system specification, evaluation, and verification. Subsequent sections of the paper will describe quantification approaches to these ilities so that a decision maker requesting "flexibility" in the system can move from an abstract notion to a quantifiable and verifiable system specification.

The ilities described by the change taxonomy is not exhaustively complete, for example it excludes agility, which is one of the four central changeability ilities in [Fricke and Schulz, 2005]. The reason is that agility is the ability of a system to make a change quickly. In this way, agility is a modifier describing the nature of the change, just as flexibility and adaptability describe the location of the change agent. An agile system is one that can make many types of changes "quickly," though the subjective assessment of "quickness" will vary from decision maker to decision maker, just as "cost" acceptability for following change paths. [Dove, 2005] defines agility in a similar manner to changeability, encompassing adaptability, flexibility, and robustness, along with notions of ease of change in terms of both dollars and time.

Implications for Design.

Given the motivation of a value-centric definition of changeability and robustness, the implications for design become clear. Designers must no longer only consider the aspects of a design that meet today's needs and requirements, but rather keep an eye to the future by building

in change mechanisms into a system to allow for change. Designers can parameterize the system both in terms of design parameters as well as path enablers, the former intended to create value and the latter intended to lower the cost or create the possibility for following a change path. In order to explicitly address the desire of a system customer to have "flexibility" it is necessary to push back and inquire for more information about the desired change effect, as desiring "flexibility" alone is an imprecise request.

In order to write requirements and evaluate systems on that basis, it is necessary to conduct four steps:

Step 1. Determine each decision maker's willingness to pay for change, meaning set the initial acceptability "cost" threshold.

Step 2. For a particular change ability desired, specify the origin of the change agent: internal (adaptable-type), or external (flexible-type) to the system boundary. Discussions around this issue will focus whether the system needs agents built in, or from without in order to cause the change to occur.

Step 3. For the same change ability specified in step 2, specify the desired change effect: change in level of a parameter (scalable-type), change in parameter set (modifiable-type) and in what parameter. For example, one could specify "scalable change in number of satellites," or "scalable change in total bandwidth." If the desire is for "no change" (robust-type), then robust in what parameter to what type of disturbance (e.g. environments, preferences, constraints, etc.). For example, one could specify "robust in output voltage to changes in temperature," or "robust in response time to changes in atmospheric conditions and fuel costs."

Step 4. Once the change capability is specified in terms of change agent location and change effect on which parameters, then dynamic tradespace analysis can be performed to determine the outdegree functions of various designs. The filtered outdegree of a design, which is a measure of its apparent changeability, can be assessed, with only mechanisms that match the specified change type counted toward the outdegree. For example, if a decision maker desires the system to be flexibly scaleable in image resolution, then only change mechanisms that result in a change in level of image resolution performance will be counted towards the calculation of the outdegree of designs in the tradespace network. In this way the specific flexibility (in terms of scaling image resolution) can be evaluated and compared against requirements. Desiring "flexibility" in a general sense is meaningless from a design perspective, since it is an inherently ambiguous term, and must be further specified in order to be quantifiable and testable as a design goal.

Guiding designers, in addition to the concrete definitions in this paper, are the heuristics and guiding principles in [Fricke and Schulz, 2005], which lists three basic principles and six extending principles for designing for changeability. These principles are techniques that will allow designers to creatively develop change mechanisms that will more likely be acceptable to decision makers.

The complete paper, *Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining System Lifecycle Value by Ross, A.M., Rhodes, D.H., and Hastings, D.E., Systems Engineering, Vol. 11, No. 4. December 2008*, can be found online at http://seari.mit.edu.

Formulating ility statements

The following statement is the structure of a formalized operational ility statement:

The system shall be	_____	_____	in	_____	for less than	_____.
	(change agent type) flexibly or adaptably	(change effects) scalable, modifiable		(system parameter)		(resources)

Explicit in this statement is an acceptable level of expended resources, i.e. "cost", incurred for executing the operational ility, meaning following a particular change path. Since the cost for executing a change path often occurs during the operation of the system, the parties willing to spend the resources for the change may not be the same as the parties paying for the system acquisition. This mismatch often results in an undervaluing of operational ilities by system acquirers. Differences in the funding for system development and operation also separate the costs and benefits for operational ilities, especially since the "hooks" for the operational ilities are often built-in up-front, while the benefits are realized later. The implication is that the costs for the "ilities" may be easier to account for and are paid in advance, while the benefits are accrued later and the execution cost is paid from a different "pot of money."

Example:

The system shall be flexibly scalable in storage volume for less than $10/cu. ft.
The system shall be flexibly scalable in number of satellites for less than $100M per satellite.
The system shall be flexibly modifiable in visible user interface features for less than 30 seconds per hiding/revealing features.

Potential sources of confusion

Often in definitions in the literature and common use, flexibility and adaptability are used as catch-all ilities. They often also include the *intent* for the change as well. For example, adaptability has been defined as changing the system in response to changes in its environment. The implied intent is that the system senses changes in its environment and is changed or changes itself to somehow "do better" in this new regime. It turns out that generally speaking, adaptive systems, which change themselves in response to feedback from their environments, may not actually make the correct change to "do better." Sometimes they do worse. Any generalizeable definition needs to remove any implicit or explicit assumptions. The definition of adaptability given in this paper uses it solely as a modifier describing the origin of the location of the change agent instigating the change on the system.

It is important to here clarify that the changeability "ilities" only make sense if the change agent *intends* to alter the system. If a system is changed by its environment, often people do not use flexible to describe the change that has occurred. Some ilities, however, do not require intent. Structural ilities do not require intent, for example a system can be modular, whether or not any agent intends for it to be so. The same is true of classically robust systems, which minimize environmental variations effects on system parameters, regardless of the system agent's intent for doing so. Operational ilities that achieve their ability through passive means are similar to

structural ilities. For example, if a system achieves survivability through passive means, such as hardening and redundancy, the system does not require intent to achieve survivability; it is a property of the structural choices made prior to operation. Active achievement of an ility is similar to operational ilities and therefore requires the intent of the change agent in order to occur. For example, using avoidance to achieve survivability requires the intent of the change agent to intentionally execute the avoidance maneuver in order to achieve survivability. A maneuver done without intent may result in the survival of the system, but it will more likely be attributed to "luck" rather than due to it being a survivable system.

Table 2 New "ilities" orientation matrix

"ility" Name	Change Agent	Agent Intent Required?	Change Effect*	System Stressor	Primary Execution Resource Type	Structural/ Operational†
Changeability	any	yes			money, time	both
Flexibility	outside	yes	alteration		money, time	both
Adaptability	inside	yes	alteration		money, time	both
Scalability	any	yes	level of system parameter	changing contexts	money, time	operational
Modifiability	any	yes	set of system parameters	changing contexts	money, time	operational
Robustness	any	no	no apparent change in system parameters	changing contexts (environments)	money	operational
Survivability	any	yes/no	minimized long term change in system parameter	finite disturbances	time, money	operational
Agility	any	yes	alteration	changing contexts	time	operational
Sustainability	any	yes	maintain system parameters	changing contexts	money, time	operational
Evolvability	any	yes	change system parameters	changing system generation	time, money	both
Modularity	outside	no	system set of parameters	changing contexts	money, time	structural
Reconfigurability	any	yes	system set of parameters	changing system configuration	time, money	operational

*the particular "system parameters" of interest must be explicitly specified for the formal ility specification statement.
†structural ilities can be measured independent of time; operational ilities can only be measured in a dynamic context, those that are "both" have aspects that can be specified as structural or operational.

Eliciting the reason behind a desired ility

There are at least several kinds of ilities, as discussed prior.

1. An ility that relates to changes in the system "essential form/function" (e.g. scalability)
2. An ility that relates to the quality of the system "essential form/function" over time (e.g. reliability)

3. An ility that relates to an additional new "ability" for the system (e.g. repairability)
4. An ility that relates to the structure of the system (e.g. modularity)

The true reason why a person states a desire for an ility is because he or she desires the underlying enabled feature from the ility, rather than the ility itself. For example, a user might request a "flexible" system, when in fact what he desires is a system that can be changed (assumedly in a favorable manner in response to changes in needs or contexts to achieve a successful form/function at a later point in time). The value of the ility is not in having the ility in and of itself, but rather in having the ability to reach desired end states for the system at a later point in time. (Note that this comment indicts against the ilities that relate to structural properties of a system, such as modularity. Why do people desire modularity? Modularity may not have value in and of itself, but rather may be desired because it decreases the cost to change the system, or enables isolation of changeability and stability within a system architecture.)

Conclusion

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