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Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities)

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Abstract. *The ilities are properties of engineering systems that often manifest and determine value after a system is put into initial use (e.g. resilience, interoperability, flexibility). Rather than being primary functional requirements, these properties concern wider system impacts with respect to time and stakeholders. Over the past decade there has been increasing attention to ilities in industry, government and academia. Our research suggests that investigating ilities in sets may be more meaningful than study of single ilities in isolation. Some ilities are closely related and do in fact form semantic sets. Here, we use two methods to investigate over twenty ilities in terms of their prevalence and their interrelationships. We look for trends related to ilities of interest in relation to system type and an understanding of their collective use. First, we conducted a prevalence analysis of 22 ilities using both the internet as well as the Compendex/Inspec database as a source. We found over 1,275,000 scientific articles published between 1884 and 2010 and over 1.9 billion hits on the internet, exposing a clear prevalence-based ranking of ilities. Two questions we seek to address are: why and how are the ilities related to one another, and what can we do with this information. Initial steps to answer the first question include a 2-tupel-correlation matrix analysis that exposes the strongest relationships amongst ilities based on concurrent usage. Moreover, we conducted some preliminary experiments that indicate that a hierarchy of ilities with a few major groupings may be most useful. The overall objective for this research is to develop a formal framework and prescriptive guidance for effectively incorporating sets of ilities into the design of complex engineering systems.*

Keywords. *Ilities, lifecycle, system properties, systems engineering.*

1 Introduction

The *ilities* are desired properties of systems, such as flexibility or maintainability (usually but not always ending in "ility") that often manifest themselves after a system has been put to initial use. These properties are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders than embodied in those primary functional requirements (de Weck et al., 2011). The ilities do not include factors that are always present, including size and weight (even if described using a word ending in "ility")[1].

Interest in the ilities such as safety, reliability and others has a long history, but traditionally these system properties have not enjoyed the same focus as other engineering properties that are more easily tested in a laboratory or field setting. Furthermore when ilities were important they were often treated in isolation. In this paper we seek to uncover relationships amongst ilities, particularly between those that are closely related and may therefore correlate and form semantic sets, and those that may lead to tradeoffs in system design.

The investigation in this paper is two-fold: (1) a quantitative review of citation frequency over time (prevalence) and association in literature (co-occurrence) leading to implied networked interrelationships amongst ilities; (2) preliminary work into eliciting a means-ends hierarchical relationship amongst ilities (explicit consideration of interrelationships) through interviews and stakeholder engagement.

2 Prevalence Analysis

In recent research we compiled a list of twenty ilities frequently encountered in our work on Engineering Systems. This is not a complete list and larger sets of ilities could be considered in the future. For each of the twenty ilities, we collected data allowing us to rank these lifecycle properties based on how frequently they are mentioned in the printed scientific literature and on the Internet[2]. Fig. 1 shows the result of this initial analysis. The black vertical bars indicate the number of scientific papers (in thousands) that mention a particular ility in its title or abstract. The gray vertical bars show the number of Google search engine hits (in millions) obtained for each ility[3]. Results from the scientific database and number of Internet hits are strikingly similar, with the notable exception of *sustainability*. The top four ilities are, in order, *quality*, *reliability, safety* and *flexibility*. Quality and safety are so important in part because they have received much attention since the beginning of modern engineering practice starting in the late 19th century.

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[1] In Computer Science, ilities are often discussed as non-functional requirements.

[2] We searched the Engineering Village database (http://www.engineeringvillage.com), which contains both INSPEC and Compendex, two of the most comprehensive sources of scientific papers on engineering dating back to 1884. Articles were included where the name of the 'ility' was included in the title or abstract of the paper.

[3] While there are limitations to Google search data, the results in Fig. 1 are relatively robust to such concerns. Different terms, use of quotation marks, searching the same terms from the U.S. and from Europe and so forth did not change the basic rankings.

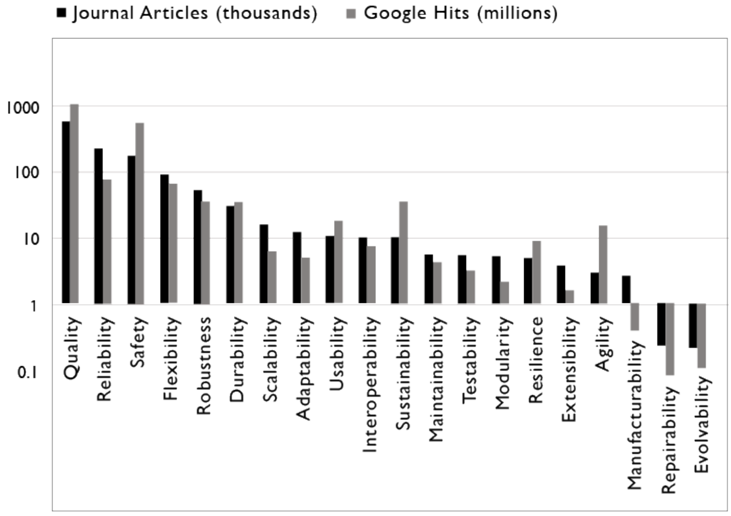

Fig. 1. Frequency of ilities mentioned in journal articles and Google hits on the internet.

We think of the top three aspects of artifacts and systems – safety, quality and reliability – as the classical ilities of engineering. More recently, the list of ilities has grown much longer. Some of the growth can be attributed to the fact that more attention to ilities led to more complex systems, and *vice versa*. More ilities emerged because growing complexity and scale of deployment led to more and more important side effects, particularly in the 2nd half of the 20th century. The rapidly increasing rate of change in systems and concomitant social changes also spurred this expansion of the ilities. No one wanted to pay for things that did not contribute directly to the primary functionality of the artifact, but over time it became untenable to run systems without paying attention to them – even if in some cases it took decades of use to come to that realization. Today there is an increasing realization that much of the value that Engineering Systems generate depends on the degree to which they possess certain lifecycle properties, a.k.a 'ilities'.[4]

The cumulative number of scientific articles published in the engineering literature on our set of twenty ilities from 1884 (the earliest date for which such data was available) to 2010 illustrates this point. Fig. 2 shows only the top fifteen, to allow readers to see the time dependence more clearly.

Indeed, quality and safety were given consideration early on, first in the building of national infrastructure such as railroads and bridges as well as in mining, and later in the 20th century when various electromechanical products became available to a wider population. Over time, new ilities became the subject of intense interest and scientific research.

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[4] For example, see Ross (2006).

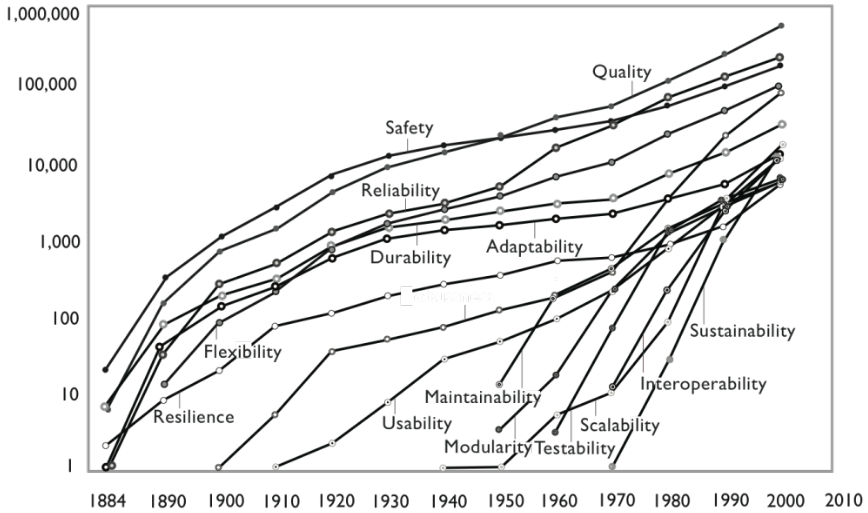

Fig. 2. Frequency of ilities mentioned in literature from late 19th century to early 21st century.

3 Potential Relationships amongst Ilities

3.1 Relationships amongst Ilities based on Co-Occurrence (2-tupel-correlation)

Based on our search results for all the ilities shown in Fig. 1, we see that some ilities are much more prominent than others. We see different ilities become more important over time (Fig. 2) and that some, such as sustainability and interoperability are still in a nascent state. But what are the relationships of the ilities with respect to each other? We conducted a more detailed search on the Internet, looking for instances where two ilities (e.g. safety and reliability) are mentioned together in the same article or page. We call this a 2-tupel-correlation matrix analysis. From the search results, we first constructed a 20 by 20 matrix to tell us which ilities are most strongly connected to each other and whether these connections are symmetric.[5] For example, we found that of the 69.9 million pages containing the word "reliability" as the first keyword, 15.3 million also contain the word "safety." In other words, 22 percent of hits about reliability mention its relevance to safety. On a scale of 0 to 10, this represents a strength of relationship of about 2 out of 10 (0.2). Fig. 3 shows a hierarchical network of ilities; their strength of relationship to each other is depicted by the weight of edges between the ilities based upon the weighting just described.

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[5] In Google and most other search engines, the sequence in which keywords are entered matters. Thus, a search for "safety" AND "reliability" may yield 3.2 million results, while a search for "reliability" AND "safety" may find 15.3 million. This is due to the particular way in which pages are matched to word groups (n-grams) in the search algorithm.

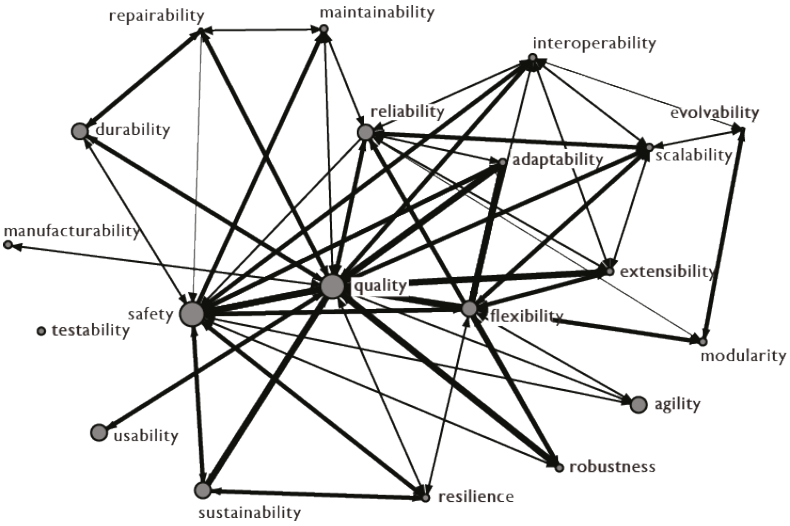

Fig. 3. Ility co-occurrence in the literature, with implied dependence. A cutoff value of 0.1 is used to draw the network of ilities shown here.

Fig. 3 suggests the existence of hierarchical levels: the most prevalent and more independent ilities are shown near the center, whereas the periphery contains some ilities that, while important, are essentially supporting other ilities (e.g., reliability, durability and robustness strongly support quality). Also, some of the newer ilities such as sustainability, resilience, interoperability and evolvability appear at the perimeter because they are relatively new and may not yet have developed their own set of supporting ilities.

Reliability, durability and robustness have the expected strong relationship to quality and are shown in direct support of quality with strong ties. Safety is also shown as a strong ility with inward pointing supporting properties such as durability, maintainability, reliability and resilience among others. Flexibility emerges as a strong cluster on the right side of Fig. 3, including robustness, modularity, extensibility, scalability and adaptability as correlated ilities. An interesting point to note is that modularity appears to be an important enabler of both flexibility and evolvability. We note that sustainability in the lower left (our fastest growing ility) has as yet no clear second level supporting ilities which may reflect its relative immaturity. The figure reveals a number of ilities that are all closely related to the concept of flexibility – the ability to change or adapt to new circumstances. Other ilities *influence* each other but may not subsume each other (e.g., higher reliability will have a beneficial impact on safety, but does not guarantee safe operation); and some ilities are essentially orthogonal to each other and *have little interaction*[6].

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[6] Our analysis in Fig. 3 used a cutoff value of 10%, meaning that that if two Ilities had less than 10% overlap in the web pages we found the interaction was deemed to be weak.

3.2 Preliminary Investigation of a Means-Ends Ilities Hierarchy

In an effort to gain deeper insight into the existence of an ilities hierarchy as suggested by Fig. 3, we conducted a preliminary exercise to investigate whether a “means-ends” hierarchy exists amongst the ilities. A “means-ends” hierarchy is one that represents the relationships between ilities in terms of using one ility as a “means” for accomplishing another ility (“ends”). For example, modularity can be a means to achieving flexibility and evolvability (e.g. by reducing the switching cost (Silver and de Weck, 2007) and providing options for swapping system components).

Table 1. Ilities with definitions provided to groups for the “means-ends” hierarchy exercise.

Ility Name	Definition (“ability of a system…”)
adaptability	to be changed by a system-internal change agent with intent
agility	to change in a timely fashion
changeability	to alter its operations or form, and consequently possibly its function, at an acceptable level of resources
evolvability	design to be inherited and changed across generations (over time)
extensibility	to accommodate new features after design
flexibility	to be changed by a system-external change agent with intent
interoperability	to effectively interact with other systems
modifiability	to change the current set of specified system parameters
modularity	degree to which a system is composed of modules (not an ability-type ility)
reconfigurability	to change its component arrangement and links reversibly
robustness	to maintain its level and/or set of specified parameters in the context of changing system external and internal forces
scalability	to change the current level of a specified system parameter
survivability	to minimize the impact of a finite duration disturbance on value delivery
value robustness	to maintain value delivery in spite of changes in needs or context
versatility	to satisfy diverse needs for the system without having to change form (measure of latent value)

The means-ends hierarchy was investigated through a multi-round exercise with twelve individuals with between one to ten years of experience researching and applying “ilities.” In the first round, the twelve participants were randomly split into four groups of 2-4 people. Each group was given a master list of ilities, similar but not identical to the one shown in Fig. 1, with definitions, and asked to construct a means-ends hierarchy. The list of ilities included is described in **Error! Reference source not found.**, with definitions derived from Ross et al. (2008) and Ross (2006).

The groups were then asked to “construct an ‘ility’ hierarchy showing multiple child-parent links describing ‘means’ - ‘ends’ relationships among the ilities (using each ility at least once)”. Each group constructed their own hierarchies without external consultation and then shared their results with the rest of the groups, justifying their construct. Over the next week, each group was interviewed individually to revise or update their hierarchy based on further introspection and given the “arguments” presented by the other groups. Each group made minor modifications during this period. The four resulting hierarchies from these two rounds are shown in Fig. 4.

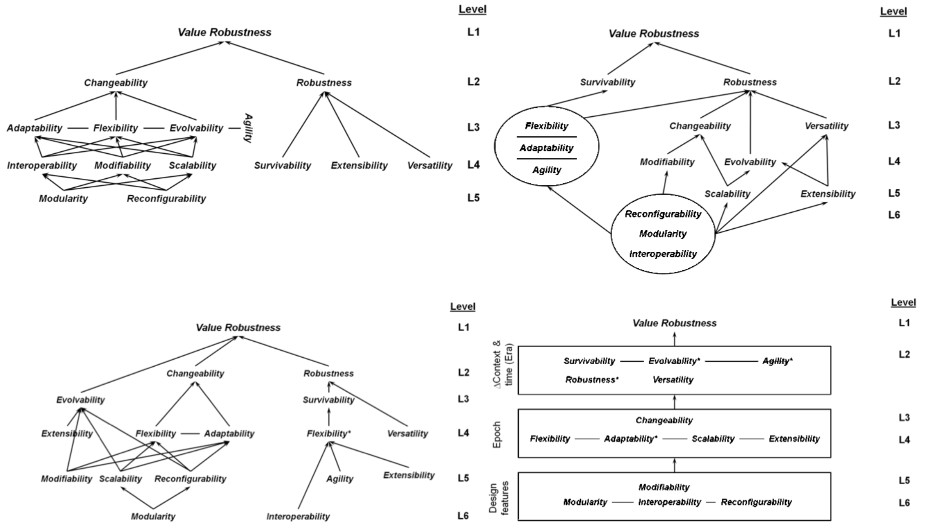


Fig. 4. Four means-ends hierarchies from group exercises, with emergent layered structure.

Upon inspection, one can see at least two patterns in the responses. Firstly, all “hierarchies” were not strict hierarchies in that two have mixed layered structures, for example the flexibility-adaptability-agility cluster in the top right response, and the cluster of changeability, flexibility-adaptability-scalability-extensibility in the bottom right response. These layered structures within the hierarchy were meant to express sibling-like relationships, which are tight within a layer, but weak between layers. Secondly, each of the hierarchies specified “levels” in addition to the links between ilities, suggesting a “distance” criterion beyond simple means-ends linkages. As seen in the robustness to survivability, extensibility, and versatility relationship in the top left response, not all children are only one level distant from a parent. Even though not requested in the exercise, this “leveling” was independently proposed by each group and explicitly discussed by the groups when presenting their hierarchies. The four hierarchies were then analyzed using matrices, and aggregated based upon response. The aggregate median level, as well as linkage strength, for each ility was calculated based on cite response rate of reported means-ends relationships between each pair of ilities. The resulting aggregate “hierarchy” is shown below in Fig. 5.

Results in Fig. 5 suggest that Value Robustness is to be considered as the root node, that is, the ultimate goal of Engineering System Design (level 0). The ilities that directly enable value robustness at level 1 are (from left to right): survivability, evolvability, robustness and changeability, with robustness deemed to be the closest ility to value robustness. Each of these ilities is in turn enabled by other ilities, for example robustness is enabled by versatility, and evolvability is enabled by extensibility, scalability, and modifiability. The “bottom” ilities enable many other ilities, for example interoperability enables extensibility, scalability, adaptability, and flexibility, while modularity and reconfigurability each enable the same four ilities plus modifiability. Agility appears as an outlier, with no links to other ilities.

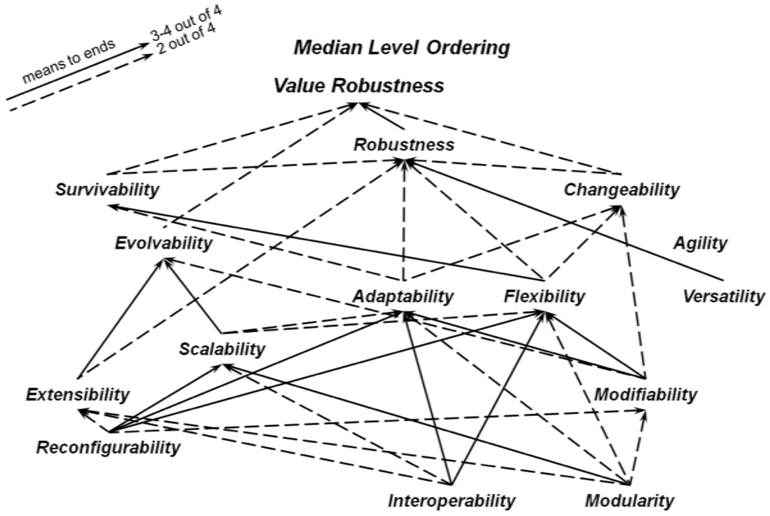


Fig. 5. Aggregate median level ordering means-ends ilities hierarchy.

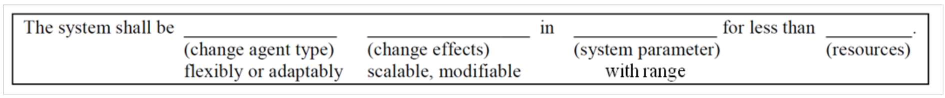
Even though this exercise was preliminary and conducted with subjects familiar with the given set of ilities, it is interesting to note that even given identical ilities definitions, and experience with the ilities, the groups still came up with very different hierarchies. Of the 80 total reported links between ilities (across the 4 groups), only 13 of the links were reported in common among 3 to 4 groups (strong links), and when including agreements among 2 groups (weak links), this number rises to 36. This means 44 out of 80 reported links were only described by one of the 4 groups, a surprisingly divergent result.

What did emerge from the exercise, however, was an emergent intergroup insight that some of these ilities tend toward the "bottom," meaning they tend to be means to achieving other ilities. Such means-tending ilities were modularity and interoperability. This is consistent with their peripheral position in Fig. 3 which is remarkable given that those results were obtained with a very different methodology. Reconfigurability (Siddiqi and de Weck, 2008) was also a means ility, but was considered to be at a slightly higher "level" than modularity and interoperability. At the top of the hierarchy was value robustness (full agreement across the four teams), with robustness, changeability, and survivability just below. Interestingly, none of the groups agreed upon how agility was related to the hierarchy, resulting in agility as a disconnected ility. Similarly agility was also only weakly connected in Fig. 3.

A difficulty that arose during the exercises was the need for precision in specifying ilities statements in order to assign an ility a place in a hierarchy. That is, each group recognized the inherent ambiguity in using each ility term abstractly. In order to place each ility in a hierarchy, each group tried to apply each ility to an example system. In this way, each ility had to take on a precise meaning in order to help justify and place the other ilities in a means-ends hierarchy. Recognizing that many of the ilities actually relate to changes in function or form of the system over time, the groups decided to build upon a method for specifying changeability as a starting point for considering a more general approach to specifying ilities. From Ross et al. (2008):

1. Specify location of change agent (internal or external to the system)
2. Specify desired change effect (change or no change; level or set)
3. Perform system evaluation (calculate changeability metrics)
4. Specify subjective acceptability thresholds (conditions for "valuable")

After following these four steps, one can formulate an ility statement as in Fig. 6.



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

Fig. 6. Example formulation of an operational ility statement (from Ross et al. 2008).

Using the changeability specification approach was an imperfect exercise at best. The groups were unable to clearly differentiate between survivability and robustness, for example, as their meaning was determined to be related, but distinct; imperfect synonyms. Likewise, multiple groups interpreted flexibility in slightly different ways, reflecting the inherent polysemy[7] of many of the ilities. A clear need exists for determining the dimensions by which the ilities can be made distinct, as well as reflecting the semantic similarity amongst related terms (e.g. flexibility, adaptability, and changeability). In linguistics, a semantic field is "a group of words with related meanings, for example kinship terms or color terms" (Akmajian et al., 2001). The existing ilities suffer from ambiguity by displaying both synonymy (multiple terms having similar meaning) and polysemy (the same term having multiple meanings). It is no wonder that technical usage of these terms, and verification of systems displaying desired ilities, remains a challenge to practicing engineers.

While not a universal solution, research is seeking to develop a prescriptive semantic basis for clarifying and positioning a subset of ilities in a ten dimensional space (Ross et al., 2011). The goal is not only a less ambiguous representation of "ilities" desires, but also ability to generate ilities specification statements. Using this approach can uncover potential hierarchical relationships among the ilities, beyond a means-ends relationship.[8] It is expected that a superset-subset hierarchy can be constructed using the semantic basis, representing "higher order" encompassing relationships between ilities. For example, flexibility and adaptability are two related "sub-types" of

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[7] Polysemy is "the property of having multiple meanings that are semantically related" (Akmajian et al., 2001, p. 585).

[8] The existence of the second "distance" criterion of "level" implied that a means-ends relationship was not sufficient for describing relationships amongst ilities. A higher dimensional basis would provide additional degrees of freedom for describing relationships.

changeability (differing by specification of the change agent). With such a semantic basis, system requirements for survivability, resilience, and robustness can be made explicit and verifiable, thereby increasing the likelihood that systems can be developed with such ilities explicitly considered. This would also allow trading off ilities against each other in a more deliberate way where such tradeoffs exist.

4 Discussion and Future Work

We have begun investigating the relationships amongst ilities to better understand which ilities may support (means) other ilities (ends) that lead to ultimate value delivery over the lifecycle of complex engineering systems. We used two different methods, quantitative mining of prevalence and co-occurrence from the scientific literature and the internet, as well interactive multi-round elicitation of an ility hierarchy with system designers and researchers. Since the two methods were administered in parallel with only loose coordination, the sets of ilities have only partial overlap (9 ilities highlighted in **bold**) as shown in Table 2.

Table 2. Ilities investigated in Sections 3.1 (Literature Survey) and 3.2 (Hierarchy Exercise)

Literature Survey	Hierarchy Exercise	Literature Survey	Hierarchy Exercise
adaptability	**adaptability**		reconfigurability
agility	**agility**	reliability	
	changeability	repairability	
durability		resilience	
evolvability	**evolvability**	**robustness**	**robustness**
extensibility	**extensibility**	safety	
flexibility	**flexibility**	**scalability**	**scalability**
interoperability	**interoperability**		survivability
maintainability		sustainability	
manufacturability		testability	
	modifiability	usability	
modularity	**modularity**		value robustness
quality			versatility

Despite these differences, the two methods led to similar high-level conclusions:

- Some ilities are closely related to each other and form semantic sets that are tied together by both synonymy and polysemy relationships.
- The results in Fig. 3 and Fig. 5 suggest that system value is heavily driven by the ability of a system to be robust (despite internal and exogenous disturbances), flexible or changeable and resilient or survivable over time.
- A hierarchy of ilities with two or three levels appears to exist whereby some ilities, such as modularity and interoperability appear at lower levels and serve as enablers of higher level ilities.

Future work will apply both methods to larger sets of ilities and use consistent sets of ilities with complete overlap in Table 2. The ability to specify ility requirements with greater precision might also be accelerated by creating formal Object-Process-Methodology (OPM) templates for each of them, similar to the semantic formalism presented in Fig.6. We expect that this future work will lead to a more fine-grained elicitation of ilities and their interrelationships and will ultimately confirm the preliminary conclusions presented here. The ultimate goal is to operationalize not only crisp definitions and requirements for ilities, but also to be able to derive lower level requirements and trade off ilities against each other, where such tradeoffs exist.

Despite their somewhat awkward collective name, the ilities nevertheless capture and express the subtle and important behavior of systems beyond their primary intended function and use. At the dawn of the industrial age (about 1880-1920), the classical properties of systems were born: safety, quality, and reliability. During the middle of the 20th century, as highways were built, telephone networks expanded, and the electrical grid reached into nearly every household of an increasingly industrialized world, new properties such as usability, extensibility and robustness became increasingly important. Today, the complexity and density of connections between previously separate systems keeps surprising us. So, we grasp at yet another set of ilities such as resilience, flexibility and sustainability. They result from the collective structure and behavior of the various technological, human, and natural components and subsystems that are woven together in complex ways.

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