Characteristics for the implementation of changeability in complex systems

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Abstract: Changeability has become increasingly relevant in the development of complex systems. The definition of system changeability is determined by the ability of the system to change from one state to another in order to overcome encountered changes to deliver and provide for extended value. Considering the dynamic changes encountered in system development and increasing concern over the value of systems, a need to understand which system characteristics should be present to effectively implement changeability is needed. This paper introduces a set of characteristics and elements that are suggested for the implementation of changeability in complex engineering systems based on a systematic literature review. The review showed when properly considered during the concept stage, changeability is an effective approach to deliver active value to systems and architectures.

Keywords: Changeability, Systems, System Design, System Architecture, Value Robustness, Value, Ilities

1. Introduction

When designing systems, it is important to understand how systems can change as well as the implications that specific changes have on value before making/recommending a decision. In the design and development of engineering systems, designers are challenged to deliver systems that maintain value throughout their lifecycle. Since change is inevitable, due to shifts in stakeholder preferences and missions or environments, the perception of a systems' value will continually change throughout its lifecycle (Beesemyer, Ross and Rhodes, 2012).

Consideration for change has become an important part of engineering efforts, with failure to anticipate and design appropriately causing perturbations that can affect the value and reliability of systems. In pursuit of value robustness, changeability seeks to provide value irrespective of context, in order for the system to transition from different states irrespective of time (Mekdeci *et al.*, 2015).

To contribute and consolidate the understanding for incorporating changeability a review of literature in the field was performed to familiarize researchers and practioners of critical and system characteristics. For this paper, complex engineering systems (Table 1) are considered.

Table 1: Complex Systems (Magee and De Weck, 2004)

Complex Engineering Systems	Complex Systems (N, H, and T)
Maritime Vessel	Amazon Basin Ecosystem (N)
Airbus A380-800 aircraft system	Epigenetics (N)
Military Air Transport System	NASDAQ Trading System (T)
Global Satellite Launch System	NASA Deep Space Network (H)

Complex engineering systems are human designed, task centric systems with technical complexity (Ross and Rhodes, 2015). In this review complexity is based on Magee and De Weck, pertaining to the amount of information needed to define a system, including components, behaviors, contexts, circumstances, processes, patterns, and relationships (Gaspar, Ross, *et al.*, 2012).

The rationale for this work is due to an absence of a systematic review on this topic and the rapid expanse of the field that has created conflicting definitions, relationships and understandings relating to ilities. This review aims to identify specific characteristics of complex engineering systems that are desirable for implementation.

1.1 Motivation

Ilities such as flexibility, agility and robustness have become increasingly important for handling uncertainty in the presence of change. These system properties can be generalized to the term changeability, which has become not only an academic but practioner consideration for systems pursuing active value robustness (Altenhofen, Oyama and Jacques, 2015). Increasingly relevant in the development of complex engineering systems and architectures, changeability allows for dynamic pressures to be managed in pursuit of active system value delivery. This allows when for the valuation of a systems changeability level to go beyond describing the presence of a system ility, and rather to determine the value effect of the ilities presence within the respective system.

Such considerations when properly managed (quantification of a systems changeability levels, optimization of a systems level of changeability, and deliverance of value robustness) can have significant positive impacts on the unarticulated value of complex systems (Ross and Rhodes, 2008b). However adding and implementing changeability typically represents additional costs, including management, ideation/development costs, and physical build and inclusion costs. Therefore before ever considering adding/implementing changeability it is critical to understand the characteristics of systems that are most well suited to leverage the benefits of changeability (Beesemyer, Ross and Rhodes, 2012). These characteristics are directly related to the latent costs of implementation and can help determine if such an approach is appropriate for the system.

2. Literature Review Methodology

Owing to the novelty of the field, there is not a unified framework that can broadly encapsulate the different areas of research dealing with changeability literature. In an attempt to frame the multifaceted contributions of changeability a systemic review was identified as being essential, so as to prevent fragmentation. Following a scientific approach, opposed to an intuitive approach each step employed in this review served as a means of identifying the most relevant and impactful literature.

This approach allowed for the identification of the most evidence-based research, permitting a wide range of settings and methods to be gathered (Cooper, 2010). The review has been used to identify, evaluate and summarize the state-of-the-art relating to system changeability. This review aims to construct a general vision to a specific question and give it a fair summary based on literature to improve understanding the characteristics and considerations for implementing changeability in complex systems.

2.1 Problem Formulation

Formulation of the literature review problem focused on examining changeability in complex systems. Since before one can identify how changeable a system should be, one needs first to be able to understand what characteristics should be present in a system to improve the successfulness of implementation and what considerations pertinent to changeability must be understood.

Based on an initial unstructured review of papers was conducted on "Changeability" (comprised of 33 papers, 18 on SCOPUS), serving to identify articles that study changeability and in order to identify the key constructs, research domains and principal keywords. Since the establishment of the concept, changeability has evolved with different interpretations depending on the research track (manufacturing & production systems were excluded).

Research Questions

The following research questions were established to understand the determinants and characteristics necessary for implementing changeability and identify types of change and relationships that make it possible for implementing/adopting changeability.

- What system characteristics are beneficial for the implementation of changeability?
- What is the current state of literature for implementing changeability in complex systems?

2.2 Literature Collection

In accordance to systematic approach, each step was carefully considered and evaluated to try and guarantee the most relevant and impactful literature was identified. The total selection of published articles analyzed in this review is based on the output of a three-stage search process, culminating in the identification of 785 documents.

Due to the field and strong level of conference participation related to system engineering, it was decided to include both academic journals and conference proceedings. Articles in the primary search were limited to those published from 1990 up to April 2018, based on the findings discussed by Colombo (de Weck, 2011), and the current state of research. It was found that the term changeability in this research context was not introduced until 1999 (Schulz and Fricke, 1999) and that "ilities" were not commonly used until the 1990's.

Primary Search

The primary search used SCOPUS and Web of Science (WoS) using two distinct search strings. Primary Search 1 (PS1) identified literature focusing on the characteristics and determinants for adopting or implementing changeability in complex systems. Primary Search 2 (PS2) identified literature on value related to complex systems.

The outputs generated in in PS1 identified 43 publications in Scopus and 37 in WoS. Within PS2 a greater number of documents were identified, attributed to the broader search terms. This resulted in 517 documents being identified, with Scopus representing 397 articles, and WoS 120.

Bibliographic Search

The Bibliographic Search was performed to identify additional authors and relevant papers referenced but not found during the primary search. In accordance to the search protocol articles cited in references were used as secondary sources. This was performed by reviewing the titles included in the references of the primary search to identify relevant publications related to the current state of literature (identification of 188 additional articles).

2.3 Literature Evaluation

The first step was to remove duplicate papers found during the collection process (785 identified - 36 duplications). The literature database of 749 was evaluated to confirm relevancy towards changeability, ilities, complex systems and system value through a review of the paper title and keywords. The 396 papers identified to be in scope were then read and evaluated, to verify they answered at least one of the following criteria:

- **C1**: Does the source describe changeability, systems engineering, or a related change ility?
- **C2**: Does the source describe system characteristics or determinants for adopting or implementing changeability?
- **C3**: Does the source consider system complexity when evaluating/assessing changeability or system value?
- **C4**: Does the source calculate system value in the presence of change?
- **C5**: Does the source describe an applied case, or formulate a methodology that evaluates an aspect of changeability?

Papers that did not meet at least one of the established criteria were removed from the literature data base. However, articles could meet more than one evaluation criteria, as show in Table 2.

Table 2: Literature Evaluation – Based on Criteria

Phase	# of Papers	# of Papers per Criteria*					# Cut	Total
		C1	C2	C3	C4	C5		
PS1	140	72	31	56	39	13	34	100
PS2	256	56	6	27	87	39	125	115
Total	396	128	37	83	126	52	159	237

2.4 Literature Analysis

The articles analyzed based on the results of Table 2 and the 237 papers, were used to develop Sections 3-6. The use of the two databases allowed for rigorous search, detecting the same articles, which evidences the strength of the search.

In the same way, the selection of publications was performed, the evaluation occurred in an equally systematic and analytical approach. The first part of this evaluation required identification of the publication types as shown in Table 3: journals accounted for 36.74% of all papers, while conference proceedings represented 56.74%, books and book chapters were 2.33%, reports and whitepapers resulted in 0.93%, and miscellaneous documents including critical and significant thesis represented 3.26%. The results were expected due to the high-quality conferences.

Table 3: Distribution of Publication Types

Phase	Papers	Journal	Conference	Book	Report	Misc.
PS1	100	37%	59%	2%	0%	2%
PS2	115	36.52%	54.78%	2.61%	1.74%	4.35%
Total	237	36.74%	56.74%	2.33%	0.93%	3.26%

The literary database was analyzed to determine the distribution of journals with published articles based on Scientific Journal Ranking (SJR). Q1 journal publications accounted for 41.77% of all journal publications, Q2 journals account for 36.71%, and Q3 accounted for 17.72% of the publications. In evaluating the relevant literature, the most frequently referenced conferences included those organized by INCOSE, IISE, and IEEE, particularly the IEEE International Systems Conference, and Conference on Systems Engineering Research (CSEA).

Seminal Authors

It was found based on the evaluated literature that in 1992 a paper presented by Kaneko and Tanie was one of the first to discuss Changeability (Makoto Kaneko, 1992). Although the paper is not specifically aligned with complex systems, it defines changeability as the ability of the system to change itself to changing needs of the system. The first seminal papers to discuss changeable systems was published in 1999 by Armin Schulz and Ernst Fricke where they worked to develop early taxonomies relating to changeability, then expanded to include basic characteristics and conditions for implementation (Fricke *et al.*, 2000; Schulz, Fricke and Igenbergs, 2000; Fricke and Schulz, 2005).

Since then an attempt to quantify and examine aspects of changeability was presented and offered by Martin and Ishii (Martin and Ishii, 2002). In their 2002 paper, they describe the use of square matrices and how such an approach could be used to capture the dependencies between system components. Subsequently Suh, deWeck, and Chang developed a method for absorbing future system changes through a change propagation index (CPI) to identify suitable system components for embedding flexibility (Suh and De Weck, 2007). Since then deWeck worked to identify and establish a classification structure for change-related "ilities", his 2011 book serves as a standard in the field (de Weck, 2011). With a follow-up paper published in 2018 which addresses the classification of change related system ilities, according to the aims of changeability (Colombo, Cascini and de Weck, 2016). Other various approaches such as those considering network approaches and the integration of modularity are presented by Sosa and Rowles (Sosa, Eppinger and Rowles, 2007).

In a different approach to develop changeable engineering systems, Adam Ross and Donna Rhodes built upon the works of Schulz and Fricke to further define and develop the concept of changeability through application in real and simulated projects (Ross, Rhodes and Hastings, 2008). This led about to the creation of Epoch-Era-Analysis which is built upon the earlier work of the MATE (Ross *et al.*, 2009) framework presented by Ross for Tradespace exploration and evaluates systems through both counting and magnitude metrics developed out of exploring the cost-utility trade- space (Ross, Fitzgerald and Rhodes, 2011).

3. State of Art

Based on the analysis and evaluation of the collected literature the effective and relevant analysis of changeability requires an understanding of related system ilities. Through a brief introduction of ilities it is possible to better understand that changeability is a higher level ility comprised of different lower level ilities such as flexibility, adaptability, agility and versatility.

3.1 Systems Engineering

Grounded in systems thinking and systems engineering, changeability is a means of reducing the poignant impact that changes imposed/introduced to complex systems, through ilities such as flexibility, agility and adaptability (Fricke *et al.*, 2000; Fitzgerald, Ross and Rhodes, 2012). The aim of this paper is to synthesize the most impactful methods of assessment in the field to identify system architectures suitable for changeability and the characteristics/principles of changeability that allow for systems to respond to change.

It is difficult to identify the exact origin of systems engineering, but it is generally considered to have emerged in the post-World War II development of large military systems. By the 1940s, Bell Labs was the first organization to use the term "systems engineering" in its design and development processes (Brill, 1998). Over the past fifty years' systems engineering has been applied prominently in aerospace, defense and software projects (Sanders and Klein, 2012).

Systems engineering is a method for improving efficiencies in systems through an interdisciplinary approach that "focuses on defining needs and required functionality early in the development cycle, documenting requirements, proceeding with design synthesis and system validation while considering the complete problem: operations, performance, testing, manufacturing, cost & schedules, training & support, and disposal" (INCOSE, 2015).

3.2 Changeability

Changeability represents a collective term that represents the ability of a system to change form, function, or operation, according to system characteristics and ilities such as flexibility, agility, adaptability, evolvability, upgradeability, and versatility. A change is defined as the transition of a system from state i to a future state at time i+1 (Ross, Rhodes and Hastings, 2008). Representing the ability for a system to change from one state to another irrespective of the effects of time, in order to provide for active system value (Ross, Rhodes and Hastings, 2008). The definition provided by Ross is suited due to its higher level of assessment and ability to facilitate universality and relevance in the field (Ross, 2006). Derived from technological literature and research, this definition does not present a distinction for the suitability of change in systems rather focuses on the number of acceptable changes a system can make.

All systems aim to provide some level of value to stakeholders occupying or utilizing that system (Boehm *et al.*, 2012). Despite the possibility for change to a system propagated by a shift in the system mission or environment, it is within the interest of the stakeholder that the system continues to provide value (Mekdeci, 2013). Change related ilities allow for the realization of systems that maintain to provide value in the presence of change throughout a systems life. This traditionally has been accomplished through the development of robust systems (passive value) that are capable to absorb changes with minimal negative effect to the entire system. Changeability in contrast allows for dynamic value sustainment, where the incurrence of change in a system extends the value of a system in an active manner.

- Passive value delivers value through the development designs insulated by system shells, which are perceived to maintain value over time irrespective of change (Ross, Fitzgerald and Rhodes, 2011). Meaning that design alternatives are selected based on their ability to deliver value to stakeholders in spite of changes in needs or context (value robustness).
- Active value generally requires less contextual and operational system knowledge, though does increase the complexity of the decision process by requiring an agent to initiate changes that allow for the system to maintain a high value perception throughout its life (Ross and Rhodes, 2008c).

Ilities

"Ilities" are grounded in strategic thinking and decision theory, as both fields encourage the long-term valuation of actions to promote extend value (Ross, Rhodes and Hastings, 2008). Within systems thinking, "ilities" refer to the theoretical and applied notion of change within systems (Colombo, Cascini and de Weck, 2016). Determining not only what is changing, but also determining how changes are enacted throughout a systems lifecycle, which enables for class distinctions (McManus *et al.*, 2007). "Ilities" provide an applied and theoretical backdrop to manage system development in the consideration of; system roles/expectation, functions, environments and missions, as well as the seminal responsibility for determining the final systems form.

According to the specific research track, there is a large number of publications and varying definitions relating to "ilities," such as adaptability, and flexibility. In avoiding the perplexity of the different fields and their ambiguous definitions, "ilities" are to be understood strictly as "requirements of systems … often ending in the suffix "ility": properties of systems that are not necessarily part of the fundamental set of functions or constraints and sometimes not in the requirements" (de Weck, 2011).

4. Elements Impacting Changeability

Systems operate within a particular context, which includes considering the specific conditions, resources and stakeholder' expectations. Systems designed with long lifecycles, are expected to operate through dynamic and sometimes unfavorable environments during operation. In these cases the establishment of the context is advantageous considering the elements of changeability presented in Figure 1. Understanding the context for changeability (purpose for pursuing) allows for the addressment of externalities through the evaluation of the specific change (type and agent) placed on the system. Even if the context is static, systems themselves may change as well, either intentionally or unintentionally. Regardless of whether the context changes or the system changes, whether the perturbations were intentional or unintentional, stakeholders desire systems that will continue to effectively perform no matter what (Mekdeci *et al.*, 2012). This section discusses elements of changeability (Ross, Rhodes and Hastings, 2008) that can guide system architects in identifying and selecting design choices that will sustain a value throughout the systems life based on the model developed by Ross (Ross and Rhodes, 2017).

Table 4: Elements of Changeability

Element	Description
Externalities	External forces put on systems.
Change Agent	The initiator for the specific change that is being enacted
Change Type	The specific type of change that is initiated by the agent.
Change Mechanism	The specific path that the change takes from state i to state i+1. .
Change Effect	The difference between system states (state i vs. state i+1).

In the implementation of changeability (Figure 1) five elements are necessary: (1) externality causing or responsible for the change, (2) the type of change that is occurring, (3) the agent of change responsible for implementing the change, (4) the mechanism of change, and (5) the effect of the change.

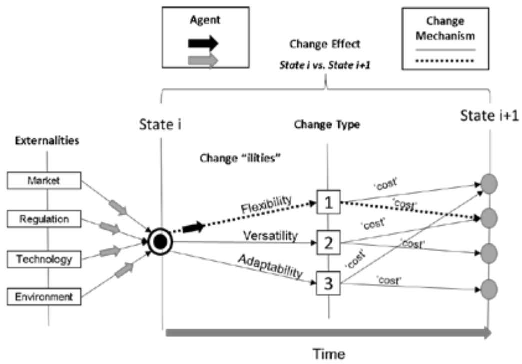

Figure 1: Elements of Changeability

4.1 Externalities

Even the best project planners and systems engineers cannot account for every unforeseen possibility (Ross, Rhodes and Hastings, 2008). By incorporating socio variables into the design and planning stages, not only are limitations able to be transferred into design variables but also aid in the design of a system that is able to operate beyond its initial environment (de Weck, 2011). Socio variables have been considered as critical impact factors in systems engineering since the 1970's (INCOSE, 2004). Based on the work of Fricke such dynamic pressures and changes being encountered in system development can be viewed in three distinct domains; the dynamics of the marketplace, technological evolution, and variety of environments (Fricke and Schulz, 2005). The literature supported adding dynamic regulations to the three dimensions presented by Fricke (Fricke and Schulz, 2005).

- **Dynamic Marketplace:** market pressures require the development of systems able to deliver active value while maintaining a high level of responsiveness in terms of supporting design changes to reduce the time gap between design freeze and system delivery (Fricke and Schulz, 2005). Systems must stay ahead of competition (changeable) during design, development and post deployment to satisfy market and customer needs. Can be effected by policy and regulations, while affecting technological evolution and variety of environment.

- **Dynamic Regulations**: represents regulations mandating some aspect of the system (Ross and Rhodes, 2015). Effected by the market though needs, this externality affects technology choice and environment.
- **Technological Evolution:** the ability to meet specific market and needs requires the ability to efficiently change the system to accommodate new, novel technologies (which can be unpredictable) (Schulz, Fricke and Igenbergs, 2000). Technology influences all aspects of the system and is an enabler for new and advanced systems (Fricke *et al.*, 2000).
- **Variety of Environments:** may be indicated by the number of embedded systems, integration of diverse technologies, or number of operational contexts (Mekdeci, 2013). Interrelated elements and embedded system (SoS) can be impacted by all changes placed upon the system and are affected by the evolution of technology (Ross and Rhodes, 2008a).

4.2 Change Agent

The forces representing what the system must respond to (change for) are presented and acted upon through a distinct agent. The respective change can be either intentional or implied, but always requires the ability to set the necessary change in motion. As shown in Table 5 the initiator can either be in or out of the technical system.

When classifying the respective change agent it is important to consider what is necessary for the decision maker to initiate this change. According to Ross this requires 3 major steps, consideration of the impact, observation and decision-making (Ross, Rhodes and Hastings, 2008). Impact is the actual ability of the agent (internal or external) to implement the change. Observation is the ability of the agent to gather relevant information in order to conduct effective decision-making. This can increase the likelihood of making good decisions and reduce the likelihood for propagated changes. Decision-making is the ability to process information in a structured manner in order to determine a course of action, regarding whether to exert influence and implement the change.

4.3 Change Type

All changes can be seen as both threats and opportunities. On one hand, changes enacted by the agent can increase the amount of rework and can lead to additional changes, thus increasing costs and effort; on the other, they offer the chance to improve the system, increasing the performance, providing useful functionalities or reducing undesired features (Jarratt *et al.*, 2011). The forces representing what the system must respond is categorized on how each change emerges depending on the agent and the decision taken (impact, observation, decision-making) (Table 5).

Table 5: Change Types and Change Agent (Colombo, Cascini and de Weck, 2016)

Change	Agent
Initiated Change	Reason external to the technical system
Emergent change	Reason internal to the technical system
Propagated change	Another change inside the technical system

- **Initiated Change**: Can be planned and unplanned changes that are generated by an outside source. The most typical initiated change is due to change in requirements. Several papers (Mcmahon, 1994; Fricke *et al.*, 2000; Altenhofen, Oyama and Jacques, 2015) distinguish the reasons for change into generic and specific to the project; the latter can be separated according to the stakeholders' degree of control.
- **Emergent Change**: Are "caused by the state of the design, where problems occurring across the whole design and throughout the product life cycle can lead to changes" (Ross and Rhodes, 2008b).
- **Propagated Change:** Undesired changes that come due to other changes having been made (Giffin *et al.*, 2009).

4.4 Change Mechanism

The mechanism of change describes the path taken in order transition the system from state i to state i+1. There could be more than one change mechanism for a change process. Each change mechanism in turn comes with different types of costs. The number of potential paths that can be enacted upon determines the level of changeability (how changeable) the system is and is determined by the cost of making the change, both time and money, incurred. The mechanism can have an implementation or design cost, a carrying cost to maintain the ability, and an execution cost when the change mechanism is used in operations.

The change mechanisms is intended to assist the broader goal of providing prescriptive design principle guidance on how to actively create more 'value' for the stakeholder (Ross and Rhodes, 2011). Each change mechanism will an enabling "ility" that allows the change to occur as shown in Figure 1. The mechanism will have an effective start time and expiration time, as well duration for how long it takes to implement, or how long that specific change type effects the system (Ross and Rhodes, 2011).

4.5 Change Effect

The effect of change is the difference between system states before and after a change has taken place (quantifying the difference in the system state before and after the change). Often it is the effect that is first noticed to indicate a change has occurred. The final desired systems changeability can then be classified according to its inherent robustness, modifiability, or scalability (Ross, Rhodes and Hastings, 2008). This is the change effect that that was expected out of the change process. The externalities can are as mentioned external forces have a governing role in the results of the change process. The change effect of a process is carried out to resolve externalities placed on the system as well as quantify the improvement offered through change of the agent (Ross and Rhodes, 2007). There may be different extents for the change effect, depending on the type of agent or mechanism involved in the change process.

5. Characteristics for Implementation

In recognizing the active value approach of changeability when it comes to systems and stakeholders, systems must not only meet current needs but also anticipate and design for changes to accommodate the needs of tomorrow. A working list of system characteristics has been developed from the literature that was reviewed bridging practical and research gaps, for generating characteristics that are suitable for changeability. Influenced by Steiner (Steiner, 1998) these characteristics seek to the systems in a pragmatic manner. The characteristics presented in Table 6 are comprised of those initially developed by Fricke and Schulz (Fricke and

Schulz, 2005), with additional characteristics presented based on extractions from other papers in the field.

Table 6: System Characteristics for Implementation

Cost	Architecture and systems that are subject to a dynamic (that is, rapidly growing and strongly changing) marketplace with varying customer base and strong competition (Steiner, 1998; Fricke and Schulz, 2005).
	Systems requiring sustained/extended or active value in the face of changing contexts (Ross and Rhodes, 2008c; Ross, Rhodes and Hastings, 2008; Beesemyer, Ross and Rhodes, 2012).
	Systems requiring high deployment and maintenance costs (Fricke and Schulz, 2005).
	Systems requiring large infrastructure support (Ross and Rhodes, 2008a; Altenhofen, Oyama and Jacques, 2015; Rehn *et al.*, 2019).
	Systems that shall be effectively/affordably sustainable over their lifecycle (Ross and Rhodes, 2015)
Function	Systems or system architectures that are used for different products with a common basic set of attributes (Fricke and Schulz, 2005)
	Systems that have a stable core functionality but variability in secondary functions and/or external styling (Fricke and Schulz, 2005).
	Transferability, the capacity to be used with minimal modification in different locations (Ross and Hastings, 2006; Sun *et al.*, 2014).
	Systems with fast cycle times for implemented technologies and require the ability to change be easily modified to leverage/implement new technologies (Fricke and Schulz, 2005; Ross, Rhodes and Hastings, 2008)
	System requires the ability to remain 'constant' in parameters in spite of change (Fricke *et al.*, 2000; Mekdeci *et al.*, 2015; Ross and Rhodes, 2015).
	Systems requiring the ability to change in mission, requirements or operational variables [3(Fitzgerald and Ross, 2012)].
	Expandable/scalable, and systems designed to accommodate growth in capability (Ross, Rhodes and Hastings, 2008).
	Systems able to function in unknown or unclear conditions. Shifts and uncertainties in the context of the system (i.e. the operational profile, market, technology, or environment (Gaspar, Rhodes, *et al.*, 2012).
Lifecycle	Systems with a long lifecycle, or expect to be required to change in different manners during distinct lifecycle phases (Steiner, 1998; Fricke and Schulz, 2005).
	Distributed ownership of the systems, with the potential for multiple stakeholders with different needs (Ross and Rhodes, 2008a; Mekdeci *et al.*, 2015)
Uncertainty	Systems where change can have negative impact on safety (risk) or project technical performance, cost or schedule (Fitzgerald and Ross, 2012).
	Expected changes to technical requirements or specifications during design (Ross, Rhodes and Hastings, 2008; Mekdeci, 2013; Hu and Cardin, 2015)
Complexity	Architectures and systems that are highly interconnected with other systems sharing their operational context (Fricke *et al.*, 2000; Fricke and Schulz, 2005; Ross and Rhodes, 2015)
	Complex and highly unprecedented systems (Magee and De Weck, 2004; Fricke and Schulz, 2005; Ross, Rhodes and Hastings, 2008; Colombo, Cascini and de Weck, 2016)
	Systems with external operating circumstances, such as external entities, interfaces and factors that affect system behavior (Gaspar, Rhodes, *et al.*, 2012).

The characteristics identified represent consideration in the following categories: cost, function, lifecycle, uncertainty, and complexity. While the list is anticipated to grow, it aims to help engineers determine if a system is suitable for implementing changeability (this is not a checklist).

5.2 Considerations for Adoption

In order for the identified characteristics to be relevant a process for adoption should consider the systems context as well as the following steps:

- Determine if the system is suitable for implementing changeability. Establish with the stakeholders if a changeable active value design approach is desired, and how changeable the system should be.
- Calculate the implementation costs for changeability in the system. Determine cost estimates for vying changeability, based on parameters and requirements.
- Determine the stakeholder's willingness to pay for specific design considerations and changes. Establish changeability level objective that is implementable and in line with stakeholders needs. For each specific change identify the externality or shift in needs that is forcing the change, and the change agent.
- Identify and determine the desired change effect: robustness, modifiability, scalability. Establish a viable change path (mechanism) that abides by the desired changeability level and costs.

6. Concluding Remarks and Future Work

The desire for changeable robust systems, is related to the recognition that that change is inevitable, both in reality and perception for all systems. Inevitably the effect of time on systems, mission and environments represents persistent series of change, both for the system and its provided value. Implicitly, value therefore is a key consideration when any engineering design decisions is made to a system to accommodate for change.

Changeability seeks to actively deliver value to systems throughout their lifecycle by either increasing technical performance or by reducing the cost of recursive changes. A key challenge for designers is to create systems that will continue throughout its lifecycle to deliver value. The characteristics and elements of changeability discussed in this paper provide an initial basis for understanding the steps to implement changeability and overarching idea of active value regarding complex systems. However, there remains a need to further develop analytical methods that allow the estimation of changeability implementation costs. To achieve this investment considerations, budget planning, trade-offs, risk and training must be considered. Work is currently being undertaken to model such costs to help people reason about implementing changeability.

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