A Review of Changeability in Complex Engineering Systems

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Dynamic pressures and calls by stakeholders for systems to maintain value in the presence of change requires the rethinking of how system value is provided. A successful approach to cope with these pressures is to design engineering systems that can be changed easily. However, to identify suitable aspects of change, one must be able to analyze the changeability of engineering systems. This paper introduces the roles and impacts of changeability in the design of complex engineering systems through a review of literature in the field. The literature conveys that changeability is suitable for assessing the effects of potential change and can support the effective exploration of design space as a means of maintaining stakeholder value throughout a systems lifecycle.

Keywords: systems engineering, system change, changeability, complex systems, engineering change, design management, "ilities"

1. INTRODUCTION

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, defence and software projects (Sanders and Klein, 2012).

Systems engineering is an effective method for improving efficiencies in complex systems through an interdisciplinary approach that "focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: operations, performance, testing, manufacturing, cost & schedules, training & support, as well as disposal" (INCOSE, 2004).

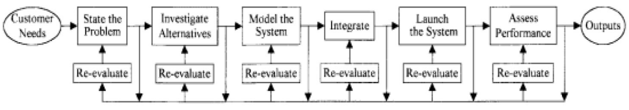

Fig. 1. System Engineering Process (Bahill & Gissing, 1998).

Change is inevitable, due to changes in stakeholder preferences, therefore the perception of a systems' value will change. Changeability focuses on the development of systems that are capable of managing dynamic pressures and maintain stakeholder value, to eliminate the difference between offerings and expectations (Ross, Rhodes and Hastings, 2008).

Changeability is grounded in systems thinking and systems engineering, and relevant to the development of complex systems (Fitzgerald and Ross, 2012; Koh, Caldwell and Clarkson, 2013). To maintain value and performance in the presence of uncertainties, changeability operates to reduce the poignant impact that changes imposed on complex systems have (Fricke *et al.*, 2000; Fitzgerald, Ross and Rhodes, 2012). Changeability, regarding complex systems is "a change made to a system as a transition from one state to an altered state over time," and has been suggested as a method to reduce change propagation and preserve stakeholder value throughout a system's lifecycle (Adam M Ross, Rhodes, et al., 2008).

When considering changeability, it is essential to identify the specific type of complex system being considered as well as its behaviors. Complexity is determined by the amount of information necessary to define a system, including its components, behaviors, contexts, circumstances, processes, patterns, relationships, and other relevant aspects (Magee and De Weck, 2004). When considering changeability, two types of complex systems can be differentiated as shown in Table 1; (i) complex systems that are engineering systems, and (ii) other complex systems such as behavioral evolution or biologically adaptive systems (Magee and De Weck, 2004). For purposes of this analysis, systems that are designated as complex engineering systems are considered. Complex engineering systems are human designed, task centric systems that maintain human and technical complexity (Magee and De Weck, 2004; Rhodes and Ross, 2010).

Table 1. Complex engineering systems distinguished from other complex systems (Magee and De Weck, 2004).

Complex Engineering Systems	Other Complex Systems
Maritime Vessel	Amazon Basin Ecosystem
Airbus A380-800 (aircraft system)	Epigenetics
Automotive Products and Plants	Genetic Networks

Based on the distinctions outlined in Table 1, an effective and relevant analysis of a systems architecture must consider complexity and the environment the system will be deployed. These distinctions enable a review of changeability, that provides contextual relevance based on system characteristics.

2. LITERATURE REVIEW METHODOLOGY

The literature review is based upon the findings of academic publications that were found to have relevance to system changeability. The review followed a "scientific" approach developed by (Cooper, 1989). This methodology relies on the scientific method as a guide, as opposed to an "intuitive" approach whereby researchers interject their own judgment when selecting sources. The evaluation and selection process was employed as a means of identifying the most relevant and impactful literature. This approach employed the following steps: (2.1) Problem Formulation, (2.2) Data Collection, (2.3) Data Evaluation, (2.4) Analysis and Interpretation, (2.5) Presentation of Results. Each stage of the synthesis serves a function similar to the one it serves in primary research.

2.1. PROBLEM FORMULATION

Changeability has become increasingly relevant in the development of complex systems (Schulz et al. 2000; Fricke et al. 2000; Fricke & Schulz 2005; Reinhart & Grunwald 2001; Ross et al. 2009; Hosseinlou & Mojtahedi 2016).

Ilities have been utilized to describe this felicitous relationship, referring to the theoretical and applied notion of change within systems (Colombo, Cascini and de Weck, 2016). The literature suggests differences in how the research community address changeability, and how different disciplines/industries view the concept (Schulz, Fricke and Igenbergs, 2000; Ross, Rhodes and Hastings, 2008; Colombo, Cascini and de Weck, 2016). The literature identified two primary fields of changeability, "Production/Manufacturing Systems" (Andersen et al. 2017; Francalanza et al. 2014; Deif 2015; Spena et al. 2016), and "System Value Design" (Ricci et al. 2013; Fitzgerald et al. 2012; Mekdeci et al. 2015).

Based on (de Weck, 2011; Colombo, Cascini and de Weck, 2016) there are roughly 10,000 journal articles that used the term "adaptability" as a central tenant of the work, and roughly 5,000 papers that reference "flexibility." With over 114,463 total papers identified that incorporate system "ilities," research in the field continues to grow as shown in Figure 2.

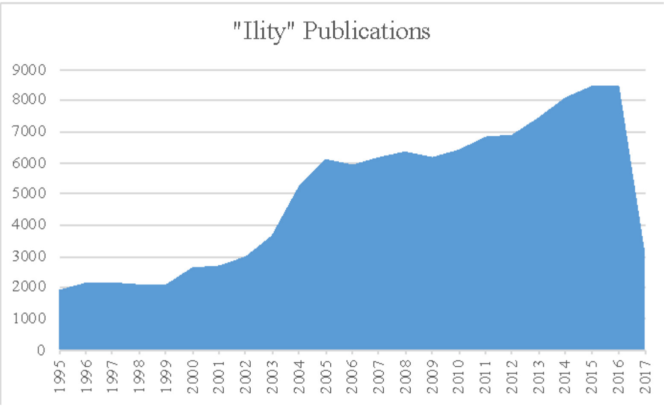

Fig. 2. System "ility" publications (SCOPUS, April, 2017)

The subsequent literature collected was evaluated to determine the ability of changeability when applied to complex systems to extend stakeholder value.

2.2. DATA COLLECTION

SCOPUS was used due to its broad search capabilities, and access to a large journal database (Aghaei Chadegani *et al.*, 2013). The literature was collected through a two-stage process (1) first level SCOPUS search, and (2) bottom-up search focusing specifically on "System Value Design."

Due to the specificity of the field, journals, conference proceedings, and book chapters, were considered. Only sources available on SCOPUS published from 1995 to April 2017 were selected. This choice was based on a decision to try and balance the findings discussed by (de Weck, 2011), and the current state of research. It was found that the term "ilities" was not commonly focused on until the mid-1990's. The search criteria was limited to the term "changeability."

The bottom-up search identified key authors and other potentially relevant papers by reviewing referenced literature identified during the SCOPUS search. This process was performed through a qualitative three step process: (1) article selection, (2) keyword evaluation, (3) abstract review.

2.3. DATA EVALUATION

Literature was evaluated based on relevancy to changeability and "ilities" in complex systems to extend stakeholder value. There is a wide variation of interpretation regarding changeability across all fields (Ross, Rhodes, et al. 2008; Colombo et al. 2016; de Weck 2011), and a precise interpretation has not been universally agreed upon. Thus, a need exists to verify the significance of system "ilities" within complex systems and their impacts on system value (Beesemyer, Ross and Rhodes, 2012; Ricci *et al.*, 2014).

Through SCOPUS the literature was limited to journals and conferences published from 1995-2017 and filtered based on subject area (Engineering), language (English) and an initial singular keyword (Changeability). This criterion reduced the source list from 1680 to 138. By refining the keywords, the list of sources was ultimately reduced to 18 sources.

Stated in Section 2.2 the data was compiled through two searches. The second search identified 110 additional articles, with each serving as a source of other papers to be identified. Expanding the relevant literature field from 18 sources in the SCOPUS first-level search, to a total of 128 sources (journals 41.2%, conference proceedings 55.2%, books and book chapters 2.2%, and two PhD Research Thesis 1.6%).

2.4. DATA ANALYSIS

The literature review focused exclusively on the identification of sources related to changeability in complex engineering systems. Each paper was read and evaluated case by case, to verify they answered at least one of the following criterion (C):
C1: *Does the source describe changeability, systems engineering, or a related concept such as flexibility, or agility?*
C2*: Does the source evaluate system lifecycle or trade space design?*
C3*: Does the source consider system complexity and/or value?*
C4*: Is the source an applied case study, or methodology that evaluated or implemented changeability?*

The sources were evaluated using the above-mentioned criterion, reducing the literature database to 98 sources. 39.8% of the articles were journal papers, with 18% being published in journals with a Q1 Scientific Journal Ranking (SJR), and 23% published in a SJR Q2 journal. Conferences papers represented 53.1% of the sources identified.

2.5. DATA PRESENTATION

In 42% of the papers identified research emphasis resided on the establishment and formalization of design trade-spaces to extended system value. While over half (58%), focused either exclusively, or in consideration of system complexity.

Table 2. Research Focus and Publication Area

Research Focus	Percentage of Literature	# of Papers
Design trade-space (to extended system value through changeability)	27%	32
Management of system complexity	49%	57
Methodological development or implementation	33%	39

Based on the research areas in Table 2 a majority of the literature focused on the decomposition and management of complexity in changeable systems, with far fewer publications addressing value and methodological development

The following key authors defined and established taxonomies for changeability that are central to this review. Armin Schulz and Ernst Fricke developed early taxonomies that develop and consider the appropriateness and implementation of system changeability (Fricke *et al.*, 2000; Schulz, Fricke and Igenbergs, 2000; Fricke and Schulz, 2005). Olivier De Weck worked to identify and establish a classification structure for change-related "ilities", his 2011 books serves as a standard in the field (Giffin *et al.*, 2009; de Weck, 2011; Colombo, Cascini and de Weck, 2016). (Ross, 2006) built upon the works of Schulz and Fricke to define and identify critical aspects of system changeability as well as introduce methods of assessing changeability within systems.

3. UNDERSTANDING THE CONCEPT

Literature provides an overview of changeability in complex systems while considering the definitions of change in Table 3. Complexity increases when a change scenario or sequence is enacted by single/multiple agents. Motivation for the inclusion and suitability of changeability in complex systems to extend value is presented in three parts: (1) Externalities, (2) Changeability, and (3) Ilities.

Table 3. Technical System Change Definitions (Wright, 1997; Fricke and Schulz, 2005; Siddiqi *et al.*, 2011)

Source	Defintion
Wright, 1997	An engineering change is a modification to a component of a product, after the product has entered production.
Fricke & Schulz, 2005	Changes, encompass all kinds of changes, whether changes of needs, requirements, specifications, already built components, processes, cost, schedule, and so on.
Sidiqi et al., 2011	Change is a process in which a design that had been previously considered as finished or completes is revised.

3.1. Externalities

Even the best project planners and systems engineers cannot account for every unforeseen possibility (Fricke *et al.*, 2000; Rebentisch, Rhodes and Murman, 2004; Ross *et al.*, 2004). 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 a regular impact factor in systems engineering since the 1970's (INCOSE, 2004). The advancement of technology, shifts in political policies, and uncertain market behaviours can all serve as catalysts for the introduction of change to systems (Danilovic & Browning, 2007; Fricke & Schulz, 2005).

The incorporation of changeability in systems is related to the variety of environment, policy driven, dynamic market, and technological externalities (Ross and Hastings, 2005; Ross, Rhodes and Hastings, 2008; Shah *et al.*, 2008; Montagna, 2014; Niese and Singer, 2014). The literature offered a slight revision to (Fricke and Schulz, 2005) by incorporating policies as one of the externalities that influence the application of changeability in systems. These externalities result in two significant aspects systems that the inclusion of changeability addresses: the ability to be changed easily and rapidly; and they must be insensitive or adaptable towards changing environments (Schulz, Fricke and Igenbergs, 2000; Ross, Rhodes and Hastings, 2008).

Variety of environments can be understood as the complexity, through the number of embedded systems, and number of systems that share operational ties (Fricke and Schulz, 2005).

Policy externalities are a regular occurrence, found in political jargon and public speeches, that call for "affordability", "reliability" and "maintainability" (Schulz, Fricke and Igenbergs, 2000; Niese and Singer, 2014; Ross and Rhodes, 2015). This analysis does not detail this phenomenon in the realm of social theory, rather is considered as critical aspect to understanding the intricacies placed on system design.

Market externalities, are pressures placed on all areas of industry and not necessarily unique to complex systems (Fricke and Schulz, 2005). However, as markets open and expectations shift, gaps in demand are created, requiring companies to be able to produce higher quality systems capable of offering extended value (Ross, McManus and Long, 2008, a; Ricci *et al.*, 2013). In today's economy, companies must stay ahead of the competition and offer value through the introduction of highly robust systems open to change (Schulz, Fricke and Igenbergs, 2000).

Technological externalities are technologies in a system that can be novel, rapidly changing or unpredictable (Schulz, Fricke and Igenbergs, 2000; Shah *et al.*, 2008; Mekdeci, 2013). In complex systems, technology is a direct design variable that influences all aspects of the system architecture and is as an enabler for new and advanced systems (Fricke *et al.*, 2000; Schulz, Fricke and Igenbergs, 2000).

Engineering "change" accounts for some of the largest resource intensive processes in engineering design (Schulz, Fricke and Igenbergs, 2000; Eckert, Clarkson and Zanker, 2004; Colombo, Cascini and de Weck, 2016).

(Ross, Rhodes and Hastings, 2008, b) applied the definition of changeability and system change, establishing three classes of change that can be applied to system components and system interfaces: modification (a change in parameters), substitution and addition/removal (Beesemyer, Ross and Rhodes, 2012; Ross and Rhodes, 2015; Colombo, Cascini and de Weck, 2016). In recognizing the types of changes that can take place within a system you are then able to classify changes according to the initiator of the change shown in Table 5 (Ross, Rhodes and Hastings, 2008; Colombo, Cascini and de Weck, 2016).

Table 5. Classification of changes according to the initiator (Colombo, Cascini and de Weck, 2016).

Change	Initiator	Example
Initiated Change	Reason external to the technical system	-Change in requirements -Market shift -Innovations
Emergent change	Reason internal to the technical system	-Vague communication -Errors in design -Defect or Wear
Propagated change	Another change inside the technical system	-Inadequate design process, methods or tools

3.2. Changeability

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 (Ross and Hastings, 2006; Mekdeci, 2013). For this changeability represents the suitability for the system to change, to extend value (Ross and Hastings, 2006; Ricci, Rhodes and Ross, 2014).

Changeability has been defined as "the ability of a system to change easily" based on consideration of four categories: robustness, agility, adaptability and flexibility (Fricke and Schulz, 2005). Robustness is understood as the ability of a system to deliver value throughout its lifecycle despite change (Schulz, Fricke and Igenbergs, 2000; Ross, Rhodes and Hastings, 2008). Agility is the ability to change rapidly (Schulz, Fricke and Igenbergs, 2000; Mekdeci *et al.*, 2012). Flexibility and adaptability deal with the ability of a system to change as differentiated by an external change agent (flexibility) or internal change agent (adaptability) (Schulz, Fricke and Igenbergs, 2000; Ross, Rhodes and Hastings, 2008; Ross and Rhodes, 2015).

A theoretical based definition based on a higher level assessment of changeability, was developed by (Ross, 2006) to facilitate universality and relevance. Derived from technological literature and research, this definition does not present a distinction for the suitability of changeability in systems. Stating rather that "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 system itself and of its environment. The inevitability of the effects of time on systems and environments is constant, thus dictates a perpetual series of change, both for the initial system as well as to the environment… a working definition, assumes that change corresponds directly to the ability of a system to be altered either through physical design parameter shifts or through changes to the operations of the system… throughout the entire system lifecycle. Offering an improved and enhanced system to meet and satisfy customer needs for the whole of the system lifecycle." (Ross, Rhodes and Hastings, 2008, b).

The aspects of changeability identified by (Schulz, Fricke and Igenbergs, 2000; Fricke and Schulz, 2005) and considered by (Ross, Rhodes and Hastings, 2008, b) enabled the identification of system characteristics, that are suitable and not suitable for changeability incorporation. Derived from (Steiner, 1998) these characteristics seek to explain the functions and abilities of changeability in a pragmatic manner.

The system architectures identified by (Schulz, Fricke and Igenbergs, 2000; Fricke and Schulz, 2005) as being capable of benefitting from the incorporation of changeability are:

- Architecture that are used for different products with a common basic set of attributes.
- Systems that have a stable core functionality but variability in secondary functions and/or external styling.
- Systems that have a long lifecycle with fast cycle times of implemented technologies driving major quality attributes.
- Architecture and systems that are subject to a marketplace with a varying customer base and strong competition.
- Architectures and systems that are highly interconnected with other systems sharing their operational context.
- Systems requiring high deployment and maintenance costs.
- Complex and highly unprecedented system.

Fricke and Schulz suggested that changeability was probably non-cost efficient for system architectures that are (Fricke and Schulz, 2005):

- Highly expedient, short life systems without needed product variety,
- High precedent systems in slowly changing markets and no customer need variety,
- Insensitive to change over time,
- Developed for ultrahigh performance markets with no performance loss allowable.

3.3. System "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, b). In avoiding the perplexity of numerous definitions, "ilities" are to be understood strictly as "requirements of systems, such as flexibility or adaptability, 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; Ross and Rhodes, 2015).

System "ilities" have been used in systems designs, systems processes, and software development to promote and extend value (McManus *et al.*, 2007). Systems "ilities" allow for stakeholder values and system behaviors to be extended throughout the entire lifecycle. Increasing robustness, and value to the whole system (Fricke & Schulz 2005; McManus et al. 2007; de Weck 2011). System processes behave and view the concept to increase flexibility and operational efficiency (Wright, 1997), and software development views "ilities" as a tool for facilitating change access throughout a lifecycle (Paskevicius, Damasevicius and Štuikys, 2012).

Table 4. Lifecycle "ilities" (Schulz, Fricke and Igenbergs, 2000; Ross, McManus and Long, 2008; Ross and Rhodes, 2015; Colombo, Cascini and de Weck, 2016)

Property	Description
Flexibility	Ability to change by agents external to the system
Adaptability	Ability to change by agents internal to the system
Agility	Ability to change quickly
Reconfigurability	Ability to change components arrangement and links reversibly

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, system environments and mission considerations, as well as the seminal responsibility for determining the final systems form.

4. CONCLUSIONS

Dynamic pressures and calls by stakeholders for systems to maintain value in the presence of change requires the rethinking of how system value is provided. Over the past decade, changeability has demonstrated the ability to increase stakeholder value and reduce development costs (Agrawal *et al.*, 2013). The aspects of changeability introduced in this review provides an overview into the considerations necessary for implementing changeability in complex systems. Through the consideration of "ilities" and externalities, changeability enables the identification of appropriate aspects of change that can increase value. A benefit of utilizing changeability in pursuit of value-centric design is that it focuses attention on what is important and what can be done to achieve it.

The literature suggests that changeability is suitable for assessing the effects of potential change and can support the effective exploration of design space as a means of maintaining/extending stakeholder value throughout a systems entire lifecycle. Extending system value through system changeability offers a structured and meaningful approach of conducting system level development in a dynamic environment. This review found that in systems featuring low complexity and few changes, the costs of implementing changeability might be prohibitive (Fricke and Schulz, 2005). Whereas complex systems that employ changeability have demonstrated the ability to accommodate change and the propagation of change within the entire system, extending stakeholder value at a feasible cost (Ross and Hastings, 2006).

While it is known that all systems should provide some value to the stakeholder, while maximizing value delivery at efficient levels of resource expenditure, understanding the characteristics of changeability in complex systems is critical. Such an understanding allows dynamic environments to be better managed to maintain value in the presence of change and preserve superior system capabilities.

Considering the benefits of changeability there remains a need to develop additional analytical methods that offer a practical and applicable means of analyzing the cost of implementing changeability within a system. To achieve this real-time and legacy system changes can be incorporated into the design process to satisfy requirements and extend system value. Allowing for predictive change outcomes and change considerations to be considered early in development to provide a cost-effective and actionable solution.

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