Journal of Engineering Design

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/cjen20

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To cite this article: Brendan P. Sullivan, Elias Arias Nava, Monica Rossi & Sergio Terzi (2023) A systematic literature review of changeability in engineering systems along the life cycle, Journal of Engineering Design, 34:12, 1046-1098, DOI: 10.1080/09544828.2023.2273248

To link to this article: https://doi.org/10.1080/09544828.2023.2273248

Published online: 09 Nov 2023.

JOURNAL OF ENGINEERING DESIGN
2023, VOL. 34, NO. 12, 1046–1098
https://doi.org/10.1080/09544828.2023.2273248

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A systematic literature review of changeability in engineering systems along the life cycle

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ABSTRACT

The escalating dynamism of external pressures and the persistent demand from stakeholders for systems to maintain value amidst continuous change necessitates a re-evaluation of how system value is delivered. This literature review addresses the ambiguously defined concept of changeability, which spans domains, incorporates various 'ilities' and has in part impeded the formulation of effective comprehensive industry strategies. As a successful approach to cope with change, changeability involves the design of engineering systems that can continue to change, quickly (agile) and easily (flexible). This paper elucidates how changeability is defined, and the elements used to evaluate change in engineering systems. Subsequently, it reviews the methods and strategies employed to quantify, measure, and analyse changeability and change-related 'ilities'. An examination of various cases and applied research sets allowed the researchers to illustrate the roles, features and effects of changeability in the design of complex engineering systems throughout the entire lifecycle, thereby confirming and consolidating how changeability is both perceived and executed. Based on these findings, future research related to the quantification of changeability levels, and the cost implications associated are proposed, with an emphasis on utilising and integrating systems models (model-based systems engineering) to standardise and simplify implementation across various engineering systems.

ARTICLE HISTORY
Received 21 February 2022
Accepted 17 October 2023

KEYWORDS
Systems engineering; changeability; change management; design management; model-based systems engineering

1. Introduction

In the process of designing and developing engineering systems, many important decisions are made with varying levels of uncertainty. Due to the inability to predict and anticipate every situation that a system may encounter the probability for unexpected and unpredictable behaviours increases. In an effort to better plan for future changes (known/unknown effects), changeability offers a unique solution that not only helps manage the associated obstacles faced when introducing/modifying/replacing system elements but can also extend the value of complex systems throughout their life cycle

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(Colombo, Cascini, and De Weck 2016; Fitzgerald and Ross 2012b; Niese and Singer 2014; Ricci et al. 2013; Ross and Hastings 2006). Within this paper changeability is considered as the inherent and intended ability of a system to 'transition from one state to an altered state over time' (Ross, Rhodes, and Hastings 2008). While complexity refers to the amount of information necessary to define an engineering system, including its components, behaviours, contexts, circumstances, processes, patterns, relationships and other relevant aspects (Gaspar et al. 2012; Schulz, Fricke, and Igenbergs 2000). Changeability has become increasingly relevant in the development of complex system architectures through an ability to manage dynamic pressures and maintaining stakeholder value, to eliminate the difference between offerings and expectations (Fricke et al. 2000; Fricke and Schulz 2005; Hosseini and Welo 2016; Reinhart and Grunwald 2001; Ross, Rhodes, and Hastings 2008; Schulz, Fricke, and Igenbergs 2000).

On the premise of intent, it is important to understand not only how a system can change, but also the implications the respective change can have. Since change is hard to avoid in complex systems due to shifts in requirements, missions or environments, the ability for such actions to be value positive (enhancing or maintaining the value of the total system) is both an approach for future proofing and life cycle extending.

The rationale for this work is due to an absence of a systematic literature review (SLR) on this topic and the rapid expanse of the field that has fostered diverging definitions, inconsistent ility relationships and varied implementation objectives. While numerous papers have been published addressing individual system ilities, and unique assessment methods for changeability they each look at the implementation goal and relationships between ilities differently. The generalisation of change, coupled with the unsystematic conceptualisation of changeability has precluded the intricacies and relationships of changeability in complex engineering systems to be consolidated.

Through the evaluation of over 36 definitions and conceptualisations of changeable engineering systems extracted from 367 papers a consolidated description of the current state of the art is presented. This allows for the review to include a broader range of sources and literature than past publications, providing for a more comprehensive and reliable review of the existing literature. In Section 2, the SLR method is introduced to support repeatability and ensure that the most relevant publications have been considered. In the following sections, three areas of changeability are presented based on the synthesis of the SLR: Section 3 provides a comprehensive analysis of the definitions pertaining to engineering systems and the prevalent characteristics of changeable systems, Section 4 examines the measures and factors used in various methods of analysis to identify common and diverging metrics, and Section 5 consolidates the prevalent factors extrapolated from theoretical and practical cases to support and facilitate implementation.

1.1. Setting the scene for the review

Changeability is an inherent and intended capability that transforms changes introduced to a system into a value positive, life cycle extending situation (Curry and Ross 2016). The ability for this to occur as planned requires a thoughtful and comprehensive rationalisation of the system, interfaces, environments, missions, and stakeholders due to the traditional opinion that changes increase complexity and when enacted post development reduce overall system function. It is an approach to engineering that leads to solutions that are most often reasonably close to the best possible answers. The notion of creating a system that fits-all is highly desirable when there can be many uncertainties that would otherwise diminish the system's value if/when they materialise. Therefore, if the system can be designed to leverage change in a positive manner (value extending), while increasingly complex the number of operational scenarios can be increased as well as the lifespan of the system. This requires that the system change in some manner (agility, flexibility, adaptability, etc.) to meet new expectations/realities (Fricke and Schulz 2005; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000).

Roughly one hundred years since the first identified publications that referenced changeability for wire wheels (quickness to change) and changeable pitch propellers (ability to change), it has become apparent that the concept has proceeded along a number of paths, ranging from engineering system, computer/software systems, production systems, to biological sciences (Colombo, Cascini, and De Weck 2016; Dickey and Cook 1932; Sullivan, Rossi, and Terzi 2018). Across the various disciplines it is apparent that internal/external factors, relationships and aspects of change are critical tenets that increase value and allow the systems to have an improved life cycle. The diverse diffusion of the concept and extant literature related to the principal tenets resulted in the identification of over 957,260 published articles, with terms such as 'adaptability' accounting for roughly 145,604 papers; approximately 782,743 papers that reference 'flexibility'; 49,677 papers that reference 'agility'; and 38,959 describing behaviours associated to system changes. While it is not uncommon to find disparity in how a concept in applied or defined, a lack of clarity in relationships can potentially undermine the development of theories and lead to contradictory metrics for analysis. As stated in introduction this study utilises an extensive and systematic review of the existing body of knowledge related to system changeability to decompose and isolate unique characteristics, features, and elements critical for implementation.

2. Systematic literature review

A systematic literature review was used as a means of identifying, evaluating and interpreting the diverse literature related to the concept of changeability in complex systems to ensure repeatability and increase the resiliency of the outcomes. This allowed for the identification of the most robust evidence-based research, permitting a wide range of publications to be gathered from among the various research efforts in the field (Kitchenham 2004). The approach in Figure 1 provides structure to the review and verifies the fulfilment of the established objectives according to the systematic review searching approach developed by Cooper (Cooper and Harris 1998).

2.1. Problem formulation

Formulation of the literature review problem focused on examining changeability in engineering systems through a pre-established and well-defined protocol. To define the research questions a preliminary literature review using the singular term 'changeability' was performed to understand how different research communities construe system changeability (Table 1). The ability to distinguish between research communities and domains allowed for specific keywords, conjunctions and search parameters to be identified and used in the formal SLR.

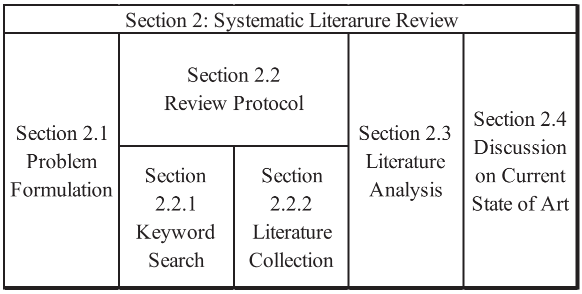

Figure 1. Methodological framework for SLR.

Table 1. Changeability research areas and basic definitions.

Domain and description	Referenced ilities
Manufacturing and production: Changeability refers to systems capable of changing across multiple levels of operation in response to varying factors (internal or external), to accommodate product variety, process variety, or production volumes to prevent significant disruptions and costs (Elmaraghy 2009; ElMaraghy et al. 2014; Wiendahl et al. 2007).	Flexibility, reconfigurability, transformability, agility.
Software engineering: Changeability refers to the ability of a software system to be easily and efficiently modified in response to changes in its requirements, design, or implementation without introducing errors or significant additional costs (Goyal and Srivastava 2017; Parashar and Chhabra 2016; Paskevicius, Damasevicius, and Štuikys 2012; Roško 2014).	Maintainability
Engineering systems: Changeability refers to the ability of a system to be altered easily and efficiently to accommodate the modification, addition or substitution of its environment, requirements, or design constraints without significant disruption or cost (Beesemyer 2012; Colombo, Cascini, and De Weck 2016; Enos 2019a; Enos, Farr, and Nilchiani 2017; Fitzgerald, Ross, and Rhodes 2012; Fricke et al. 2000; Fricke and Schulz 2005; Ross and Rhodes 2015; Ross, Rhodes, and Hastings 2008; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Sullivan, Rossi, and Terzi 2018; Turner, Monahan, and Cotter 2018)	Flexibility, adaptability, agility, robustness, scalability, interoperability, extensibility

Previous reviews on changeability have been limited in scope, either focusing on individual ilities or the classification of change features and types. With the rapid expansion of the field, there is a wide range of publications that present diverging definitions, inconsistent relationships between ilities, and varied implementation objectives. However, there has been no comprehensive review to date that synthesises the definitions, analysis methods and characteristics of systems suitable for changeability in engineering systems. This review aims to fill that gap by consolidating and synthesising the dispersed knowledge to provide a comprehensive understanding of the current state of the literature. By doing so, it enables researchers to identify gaps, inconsistencies and areas requiring further investigation. Furthermore, this review enhances the reliability and repeatability of research findings by ensuring that the most relevant and rigorous publications are considered.

To achieve these goals, the following research questions were established: What are the determinants and characteristics necessary for implementing changeability? What types of change and relationships facilitate the adoption of changeability? By addressing these

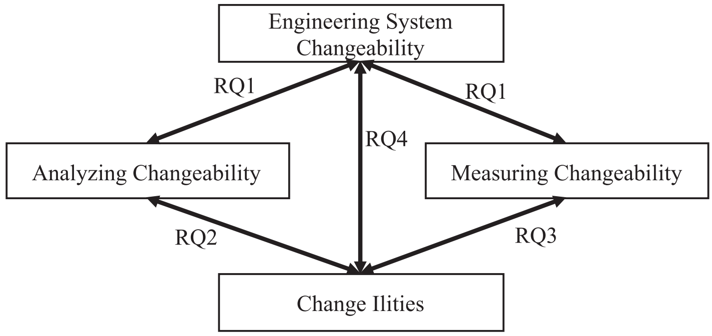

Figure 2. Research framework.

questions, this review seeks to contribute to a better understanding of changeability and provide valuable insights for future research in the field.

(1) What is the current state of changeability literature?
(2) How is changeability analysed in the domain of engineering systems?
(3) How can changeability be measured?
(4) What relationships do lower level ilities have and how do they provide value throughout the system life cycle?

The framework in Figure 2 outlines how the research outcomes relate to one another. To address the first research questions, a systematic review was performed to identify the key areas, considerations and literature related to changeability. Within the second research question, the scope of the literature (research solely on 'changeable' engineering systems) was established to provide a boundary where unto the search could function within. This allowed for the most relevant definitions to be analysed and for the relevant system ility relationships to be decomposed. With respect to the second research question several issues were considered: (1) Were the methods analysed intended for application, or assessment; (2) Had the method been applied to a physical (real system) or theoretical (conceptualised system); and (3) Is the fidelity of the method at a level whereby it can be implemented, measured and used to assess the real long-term value of changeability, if not, is it improving? With respect to the third research question, the publications were analysed to determine if the publications are contributing to practice by defining guidelines/standards to support adoption and implementation.

The resolution of the research questions aims to support researchers, by providing a body of related knowledge that when applied can help:

- Determine if a system is suitable for implementing changeability. Establish with the stakeholders if a changeable system is desired, and how changeable the system should be.
- Measure and identify factors that influence changeability.
- Establish changeability level objectives that are implementable and in line with stakeholders needs.

Table 2. Keyword search inclusion/exclusion criteria.

Criteria	Unit of analysis
Database	Scopus and Web of Science. according to Mongeon and Paul-Hus (Mongeon and Paul-Hus 2016) these databases are the main sources for citation data and are amongst the most extensive databases available.
Keyword	Changeability
Subject area	Engineering
Language	English
Source type	All Publications (journals, conference proceedings, books, book chapters, reviews)
Time frame	January 1999–1 December 2021
Exclusion criteria	Software (cryptography, data, digital, software, signal, speaker, noise, wireless); Healthcare/biology (ecology, climate, evolution, health, pharma); Manufacturing (factory, manufacturing, production, I4.0)

Table 3. Changeability keyword identification.

	Scopus and Web of Science search	
Identification	Keyword Search	
	SCOPUS	**WoS**
	Keyword: 'changeability'; Inclusion 'Engineering' and 'English'	
	Scopus ($n = 567$)	WoS ($n = 397$)
	Total # of publications identified and included in DB ($n = 964$)	

- Identify and determine specific scenarios when changeability should be applied and the associated enabling lower-level change ilities.

2.2. Review protocol

The review is based on the findings of academic publications that were found to have relevance to changeability in engineering systems. Following a scientific approach, as opposed to an intuitive approach each step employed in this review served as a means of identifying the most relevant and impactful literature. Scopus and Web of Science (WoS) were used due to these two databases being are the main sources for citation data with most access to a broad set of journals (Aghaei Chadegani et al. 2013; Mongeon and Paul-Hus 2016). The following steps undertaken in this review were utilised to ensure the most relevant literature was identified, and to ensure the repeatability of the process (Cooper 2017; Cronin, Ryan, and Coughlan 2008; Denyer et al. 2003; Mareth et al. 2016).

2.2.1. Identification of keywords

To construct the combined WoS and Scopus (Table 2) database for changeability keyword bibliometric analysis, the search method introduced by Cooper was used (Cooper et al. 2018). To identify keywords from the database, the following steps were followed: identification, screening, eligibility and inclusion.

During the identification stage (December 2021) a list of keywords relevant to changeable engineering systems were analysed by scanning literature based on the inclusion/exclusion criteria found in Table 2. The 964 publications identified were exported in a BibTeX file format that included all publication data (Table 3).

During the screening step (Table 4), Microsoft Visual Basic was used to filter the publications remove duplications, resulting in 683 publications from the combined databases

Table 4. Changeability keyword screening procedure.

	Total # of publications screened from DB *(n = 964)*	
Screening	Duplicate publications removed from DB *(n = 281)*	
	Publications removed (title)	**Publications DB #**
	n = 544	*n* = 139
	Total # of publications screened and remaining in DB *(n = 139)*	

Table 5. Changeability keyword eligibility procedure.

	Total # of publications evaluated for eligibility from DB *(n = 139)*	
Eligibility	**Publications removed (abstract)**	**Publications DB #**
	n = 53	*n* = 86
	Filtered total # of publications remaining in DB for keyword analysis (*n* = 86)	

being identified. Additionally, the papers were screened by title where terminology pertaining to software (cryptography, data, digital, software, signal, speaker, noise, wireless), healthcare/biology (ecology, climate, evolution, health, pharma) and manufacturing (factory, manufacturing, production, I4.0) were removed, resulting in the identification of 139 publications.

During the eligibility step (Table 5), publication abstracts were reviewed to confirm research relevance, literature that was out of the scope of the research domain, non-descriptive or foundationally limited were excluded. The final database of 86 publications were then analysed using Bibliometrix RStudio to investigate author keywords through a semantic network structure and word frequency diagram. This enabled the identification of the most relevant keywords and terminology coupling for critical analysis in the following section of this paper.

Based on a Bibliometrix analysis of the 86 publications identified during the eligibility phase (Table 6), keyword frequency, title word frequency and abstract word frequency of the publications were calculated as shown in Table 3. Non-technical words were removed from the analysis (e.g. figure, one, research, may, new, used, also, based, data, set, number, example, level, different, information, use, table, two). This analysis ensured that the publications selected were well within the scope of research, and to potentially help identify additional terms to add to the literature search performed in the next stage of the review protocol.

2.2.2. Literature collection

As shown in Table 7, keywords and terms identified in the keyword search process were applied. The use of the two databases (Scopus and WoS) allowed for a rigorous search, with the ability to detect the same articles, which evidences the strength of the search. The identification phase consisted of the consolidation of three search strings based on the keywords identified, application of inclusion and exclusion criteria, then the extraction of cited references from each publication which were then screened to remove duplications. Inclusion criteria related to 'engineering' and written in 'English', while 'manufacturing' and 'software' were used as exclusion variables.

The first search string utilised author-listed keywords and was important to identify a broad range of relevant literature. This search helped to identify the scope of the research area and provides a starting point for the subsequent searches. The second search string

Table 6. Keyword frequency identification.

	Term	Keyword Frequency	Title Word Frequency	Abstract Word Frequency
Filtered Total # of Publications Remaining in DB for Keyword Analysis *(n = 86)*				
Bibliometrix (RStudio) Keyword Analysis, NVivo Total Publication Word Frequency Analysis Characteristics of changeability not considered (foundational terms and context missing)				
Inclusion	1. Changeability	14	9	48
	2. Flexibility	10	15	76
	3. Adaptability	5	5	22
	4. Change Propagation	5	6	26
	5. Ilities	5	2	19
	6. Modularity	5	2	17
	7. Robustness	5	10	37
	8. Value Robustness	5	–	1
	9. Systems Design	4	19	155
	10. Systems Engineering	4	12	188

used additional filters, searching for terms in the title and abstract. This refined the focus of the literature search and ensured the publications identified were relevant to the research questions. The third search string which is highly specific, incorporates lower-level system ilities (flexibility, agility, robustness, scalability, evolvability, survivability), because in literature changeability may not be explicitly defined but rather described as an attribute of the system. This enabled the identification of publications that may not use the exact same terminology, but are highly relevant.

The literature search as illustrated in Table 8 resulted in a total of 14,856 papers being identified (calculated based on search string outcomes plus extracted references). Literature analysis was restricted to conference proceedings and peer-reviewed journal publications that were published between 1 January 1991 and 1 April 2021. According to the review process duplicates were removed from the search list, and each paper using Bibliometrix was analysed according to keywords, title, and then the abstract and full text was read. Author keywords were screened first, so the most relevant documents were identified, rather than implementing inclusion terms, exclusion terms were applied (which were determined in the keyword search process, with the most frequently used unrelated words being placed as strict measures). By excluding keywords determined to be unrelated to the subject matter the publication list was refined to include 2862 papers that were suitable for title screening. To screen publication titles, word frequency to determine if common phrases, conjunctions, or terms outside of the research scope were applied, the documents were then filtered to remove foundational terms beyond the scope of the review and finally, the research context was evaluated (manufacturing, software, etc.). The abstract screening of 454 publications was performed through direct literature review, to ensure conformity in the documents selected, relevance to research topic and appropriateness of the context. The 319 publications identified for full text review were read and filtered as shown in Table 8. This ensured that any relevant information pertaining to changeability was not omitted from the final list of 83 documents.

The analysis of keywords was a critical aspect of the systematic literature review, as shown in Table 9 provides insights into the most important concepts and themes related to the research question. By identifying the 10 most frequent keywords used in the 83 selected publications, it was possible to gain a better understanding of the literature and ensured that the most important findings were highlighted.

Table 7. Literature search inclusion/exclusion criteria.

	Search String	Criteria	Unit of analysis
1	*Author keyword 'changeability' AND NOT keyword 'manufacturing AND NOT keyword 'software' (LIMIT-TO (Subject area, 'Engineering')) AND (LIMIT-TO (LANGUAGE, 'English'))*	Database	Scopus and Web of Science
		Search Type	Author Keyword
		Keyword	Changeability
		Subject area	Engineering
		Language	English
		Source type	All Publications (journals, conference proceedings, books, book chapters, reviews)
		Time frame	Until 1 April 2021
		Exclusion criteria	Software, Manufacturing
2	*Title-Abstract-Keyword 'changeability', AND NOT Title-Abstract-Keyword 'manufacturing AND NOT Title-Abstract-Keyword 'software' (LIMIT-TO (Subject area, 'engineering')) AND (LIMIT-TO (LANGUAGE, 'English'))*	Database	Scopus and Web of Science
		Search Type	Title, Abstract, Author Keywords
		Keyword	Changeability
		Subject area	Engineering
		Language	English
		Source type	All Publications (journals, conference proceedings, books, book chapters, reviews)
		Time frame	Until 1 April 2021
		Exclusion criteria	Software, Manufacturing
3	*Title-Abstract-Keyword 'changeability' AND keyword (ilities OR flexibility OR agility OR robustness OR scalability OR evolvability OR survivability) AND (LIMIT-TO (SUBJAREA, 'ENGI')) AND (LIMIT-TO (LANGUAGE, 'English'))*	Database	Scopus and Web of Science
		Search Type	Title, Abstract, Author Keywords
		Keyword	Changeability, Flexibility, Agility, Robustness, Scalability, Evolvability, Survivability
		Subject area	Engineering
		Language	English
		Source type	All Publications (journals, conference proceedings, books, book chapters, reviews)
		Time frame	Until 1 April 2021

Table 8. Changeability literature collection process.

	Scopus and Web of Science Search		
	Literature DB search	Publications from bibliography identified	Publications DB #
Identification	**Search String 1** *Scopus (n = 32)* *WoS (n = 85)*	**String 1** *Scopus (n = 692)* *WoS (n = 651)*	*n* = 1460
	Search String 1 *Scopus (n = 250)* *WoS (n = 469)*	**Search String 2** *Scopus (n = 4139)* *WoS (n = 3773)*	*n* = 8631
	Search String 1 *Scopus (n = 63)* *WoS (n = 314)*	**Search String 3** *Scopus (n = 1527)* *WoS (n = 2861)*	*n* = 4765
	Total # of publications identified and placed in DB *(n = 14,856)*		
Screening	**Duplicate Publications Removed** *n = 7258*		*n* = 7598
	Publications Removed (Keywords) *n = 4736*		*n* = 2862
	Publications Removed (Title) *n = 2166*		*n* = 454
	Publications Removed (Abstract) *n = 135*		*n* = 319
	Filtered total # of publications remaining in DB *(n = 319)*		
Eligibility	**Publications Removed (Full Paper Review)***n* = 268 • Papers without full-text access (open access) • Non-descriptive publications (not associated to changeability) • Characteristics of changeability not considered (foundational terms and context missing)		*n* = 83

Table 9. Most frequent terms present in (83) identified publications.

Term	Keyword	Abstract	Title
Changeability	23	63	14
Flexibility	16	46	6
Ilities	10	47	9
robustness	9	26	8
adaptability	7	28	5
change propagation	7	30	8
systems engineering	7	97	4
value robustness	7	1	6
system of systems	5	29	7
Uncertainty	5	23	5

2.3. Literature analysis

During the review of the 83 publications included in this review (Table 10) a database was constructed that included the individual FWCI for each publication, enabling a comparison of each publication's total citations based on the average of the subject field. The findings of the publications according to the research questions were categorised allowing for a taxonomic scheme to be presented in Section 3.

2.3.1. Distribution of articles published over time and by country

On review of the annual number of publications (Figure 3) the highest rates of publication occurred between 2006–2009 and 2012–2015 with a third rise in 2019. Overall, the number of publications addressing changeability, in the form of systems design, conceptual design, system of systems, ilities illustrates a balanced trend over time, however utilisation of the term changeability has steadily increased since 2015 (annual publication growth rate of 3.93%). This indicates that there is an awareness attracting both practitioners and academics; however, investigating how the perception of the term 'changeability' has changed over time is challenging.

Figure 4 below displays the distribution of authorship related to the research publications 1998–2021. The review showed that the 83 publications included in this paper were authored by researchers located in the United States, United Kingdom, Germany, Norway, Italy and Singapore.

Additionally, Figure 5 displays the allocation of keywords derived from research articles published between 1999 and 2021 according to nation and institution. It is acknowledged that research related to changeability utilises a diverse set of related keywords, which is expected due to changeability being a higher-level system ility.

2.3.2. Distribution of publication by source

Regarding the distribution of publications, Systems Engineering, Research in Engineering Design and the Journal of Mechanical Design Transactions of ASME were identified as being the most frequently published peer-reviewed sources. The following largest source is the IEEE Systems Journal and the Journal of Engineering Design, Procedia Computer Science while being the third highest source is discussed last due to the articles published being

Table 10. Total publication database.

Title	Ref.	FWCI	SCOPUS Citation (%)
Ring 1998	Ring 1998	1.78	83
Schulz and Fricke 1999	Schulz and Fricke 1999	0.77	65
Fricke et al. 2000	Fricke et al. 2000	1.08	73
Schulz, Fricke, and Igenbergs 2000	Schulz, Fricke, and Igenbergs 2000	N/A	N/A
C. M. Eckert, Clarkson, and Zanker 2004	Eckert, Clarkson, and Zanker 2004	41.115	99
Fricke and Schulz 2005	Fricke and Schulz 2005	7.47	98
Nilchiani and Hastings 2005	Nilchiani and Hastings 2005	2.68	91
Ross and Hastings 2006	Ross and Hastings 2006	N/A	38
C. M. Eckert et al. 2006	Eckert et al. 2006	1.59	82
T. Wang and De Neufville 2006	Wang and De Neufville 2006	5.84	97
McManus et al. 2007	McManus et al. 2007	7.32	98
Ross and Rhodes 2008	Ross and Rhodes 2008	3.37	93
Ross, Rhodes, and Hastings 2008	Ross, Rhodes, and Hastings 2008	3.88	95
Engel and Browning 2008	Engel and Browning 2008	1.77	96
Bahill and Botta 2008	Bahill and Botta 2008	2.04	86
Siddiqi and De Weck 2008	Siddiqi and De Weck 2008	1.73	83
Ewart et al. 2009	Ewart et al. 2009	2.54	90
Rhodes and Ross 2009	Rhodes and Ross 2009	0.54	58
Roberts et al. 2009	Roberts et al. 2009	5.42	97
Rhodes, Ross, and Nightingale 2009	Rhodes, Ross, and Nightingale 2009	4.43	96
C. Eckert et al. 2009	Eckert et al. 2009	3.44	94
Giffin et al. 2009	Giffin et al. 2009	7.61	98
Silver and Weck 2010	Silver and Weck 2010	1	72
Rhodes and Ross 2010	Rhodes and Ross 2010	3.84	95
Jarratt et al. 2011	Jarratt et al. 2011	23.47	99
Beesemyer, Ross, and Rhodes 2012	Beesemyer, Ross, and Rhodes 2012	0.76	65
M. E. Fitzgerald and Ross 2012b	Fitzgerald and Ross 2012b	4.66	96
M. E. Fitzgerald and Ross 2012a	Fitzgerald and Ross 2012a	6.79	98
M. E. M. Fitzgerald, Ross, and Rhodes 2012	Fitzgerald, Ross, and Rhodes 2012	2.31	89
Gaspar et al. 2012	Gaspar et al. 2012	1.81	84
Hamraz, Caldwell, and John Clarkson 2012	Hamraz, Caldwell, and John Clarkson 2012	2.89	92
Koh, Caldwell, and Clarkson 2012	Koh, Caldwell, and Clarkson 2012	12.23	99
Morkos, Shankar, and Summers 2012	Morkos, Shankar, and Summers 2012	4.57	96
Pate, Patterson, and German 2012	Pate, Patterson, and German 2012	2.68	91
Allaverdi, Herberg, and Lindemann 2013	Allaverdi, Herberg, and Lindemann 2013	1.85	85
M. E. Fitzgerald and Ross 2013	Fitzgerald and Ross 2013	1.04	72
Ricci et al. 2013	Ricci et al. 2013	0.46	54
Cardin et al. 2013	Cardin et al. 2013	8.69	98
Kissel and Lindemann 2013	Kissel and Lindemann 2013	1.36	79
Koh, Caldwell, and Clarkson 2013	Koh, Caldwell, and Clarkson 2013	4.85	96
Chalupnik, Wynn, and Clarkson 2013	Chalupnik, Wynn, and Clarkson 2013	2.04	87
Ryan, Jacques, and Colombi 2013	Ryan, Jacques, and Colombi 2013	1.72	84
Niese and Singer 2014	Niese and Singer 2014	1.93	86
Rader, Ross, and Fitzgerald 2014	Rader, Ross, and Fitzgerald 2014	N/A	32
Ricci, Rhodes, and Ross 2014	Ricci, Rhodes, and Ross 2014	1.01	71
Cardin 2014	Cardin 2014	5.58	97
Ricci et al. 2014	Ricci, Fitzgerald, et al. 2014	3.03	93
Tackett, Mattson, and Ferguson 2014	Tackett, Mattson, and Ferguson 2014	2.03	87
Altenhofen, Oyama, and Jacques 2015	Altenhofen, Oyama, and Jacques 2015	N/A	29
Keane, Gaspar, and Brett 2015	Keane, Gaspar, and Brett 2015	2.72	91
Mekdeci et al. 2015	Mekdeci et al. 2015	0.12	33
ElMaraghy and AlGeddawy 2015	ElMaraghy and AlGeddawy 2015	0.57	57
Koh et al. 2015	Koh et al. 2015	3.53	94
Miner et al. 2015	Miner et al. 2015	N/A	29
Ross and Rhodes 2015	Ross and Rhodes 2015	3	93
Davendralingam and DeLaurentis 2015	Davendralingam and DeLaurentis 2015	1.75	84
Broniatowski 2016	Broniatowski 2016	N/A	0
Colombo, Cascini, and De Weck 2016	Colombo, Cascini, and De Weck 2016	0.22	38
Gralla and Szajnfarber 2016	Gralla and Szajnfarber 2016	0.11	31
Corpino and Nichele 2017	Corpino and Nichele 2017	0.09	29

(*continued*).

Table 10. Continued.

Title	Ref.	FWCI	SCOPUS Citation (%)
Koh 2017	Koh 2017	1.11	73
Schuh, Riesener, and Breunig 2017	Schuh, Riesener, and Breunig 2017	2.32	89
J. R. Enos, Farr, and Nilchiani 2017	Enos, Farr, and Nilchiani 2017	1.3	78
B. P. Sullivan, Rossi, and Terzi 2018	Sullivan, Rossi, and Terzi 2018	0.84	67
Turner, Monahan, and Cotter 2018	Turner, Monahan, and Cotter 2018	2.08	88
Avalos, Grenn, and Roberts 2019	Avalos, Grenn, and Roberts 2019	0.07	26
Ross and Rhodes 2019	Ross and Rhodes 2019	0.82	65
B. Sullivan et al. 2019	Sullivan et al. 2019	0.55	55
Rehn et al. 2019	Rehn et al. 2019	1.05	72
H. Wang, Thomson, and Zhang 2019	Wang, Thomson, and Zhang 2019	0.09	27
Chavy-Macdonald et al. 2019	Chavy-Macdonald et al. 2019	0.23	37
J. R. Enos 2019a	Enos 2019a	0.15	31
J. R. Enos 2019b	Enos 2019b	N/A	24
J. Enos, Farr, and Nilchiani 2019	Enos, Farr, and Nilchiani 2019	N/A	N/A
Rousseau 2019	Rousseau 2019	0.75	63
Douglas, Mazzuchi, and Sarkani 2020	Douglas, Mazzuchi, and Sarkani 2020	0.24	38
Moallemi, Elsawah, and Ryan 2020	Moallemi, Elsawah, and Ryan 2020	1.06	74
Allaverdi and Browning 2020	Allaverdi and Browning 2020	0.41	49
Bashir and Ojiako 2020	Bashir and Ojiako 2020	1.24	78
Arjomandi Rad, Stolt, and Elgh 2020	Arjomandi Rad, Stolt, and Elgh 2020	N/A	24
Obieke, Milisavljevic-Syed, and Han 2020	Obieke, Milisavljevic-Syed, and Han 2020	2.02	88
J. R. Enos 2021	Enos 2021	0.14	35
Hein et al. 2021	Hein et al. 2021	1.11	74

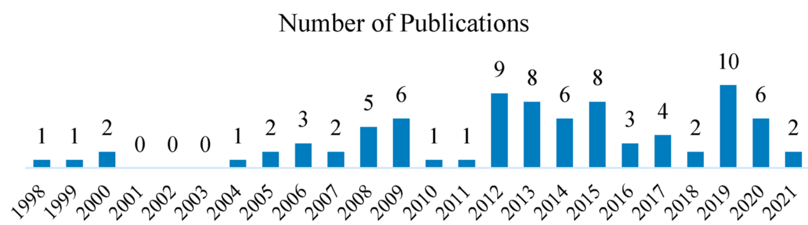

Figure 3. Research publications per tear.

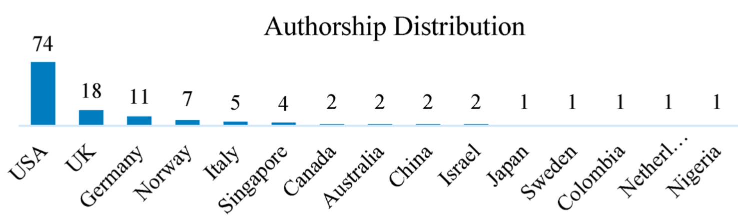

Figure 4. Research authorship geographical distribution.

conference proceedings. Figure 6, further illustrates conferences that have published proceedings relating to changeability, which is one of the primary methods for publishing changeability-related research.

Journals were classified according to their title and scope (Table 11. Distribution of Journal Publications) and analysed according to the number of papers per journal field (systems engineering, engineering design and Technical Management) and impact (Impact Factor and h-Index). The impact factor for each journal was considered since it combines both the quality and quantity of publications, by considering the number of citations in a given

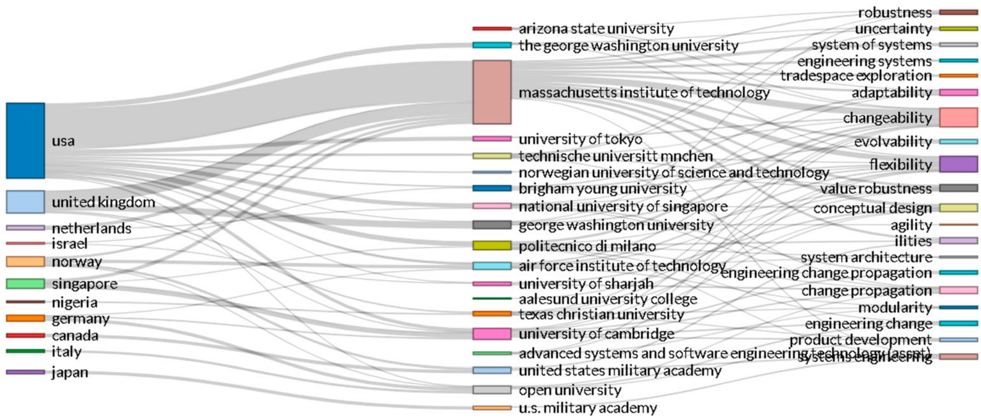

Figure 5. Three-fields plot (country of publication; institution; publication keyword).

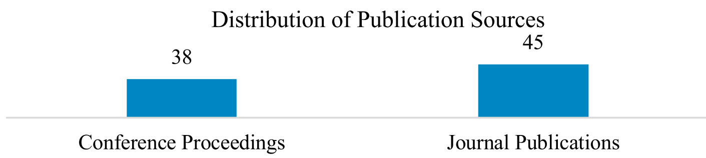

Figure 6. Distribution of the research articles by source (journals and conference proceedings).

year to articles published in the previous 2 years, divided by the number of source articles. Additionally, the h-index was included since it emphasises volume and quality of the publications, however since the score includes self-citations attention to publication relevance and value had to be carefully considered.

Conferences were classified according to scope (Table 12) and analysed according to two indicators, the number of conferences per field and the number of papers per field. Procedia Computer Science was included in the list of conferences due to the origin of the document.

2.3.3. Distribution of publication by authorship

As initially illustrated in Figure 5, American researchers at the Massachusetts Institute of Technology (MIT), University of Cambridge and National University of Singapore have the most active publication record. A database of publications comprised of 83 documents allowed for the identification of the most relevant authors and publications (Figures 7 and 8). The basis for many of the detailed changeability studies authored are the 2005 publication by Fricke 'Design for Changeability' (Fricke and Schulz 2005) and/or the 2008 publication by Ross 'Defining Changeability' (Ross, Rhodes, and Hastings 2008). Collectively these two publications have allowed researchers to assess several specific systems and change effects. The success of MIT in applying changeability and performing high-quality research is supported by the 2011 Epoch-Era analysis method (Ross, Fitzgerald, and Rhodes 2011) developed by Ross to evaluate the changing contexts over time on the perceived value of a system.

Table 11. Distribution of journal publications.

Journal and description	Impact	h-Index	Field	Occ.
IEEE Systems Journal: R*esearch related to systems engineering and systems science, with the aim of advancing the state-of-the-art in these fields and fostering interdisciplinary research and collaboration among various engineering and science disciplines.*	4.802	98	Systems engineering	5
Journal of Mechanical Design Transactions of the ASME: R*esearch related to mechanical design, including design theory and methodology, design automation and optimisation, product design and development, manufacturing and assembly, and human factors and design for sustainability, with the aim of advancing the state-of-the-art in mechanical design and its application in various domains.*	3.441	134	Engineering design	6
Research in Engineering Design: *research related to engineering design, such as design theory, methodology, cognition, creativity, automation, optimisation, product development, manufacturing, assembly and education, to advance the state-of-the-art in engineering design and its application in various domains.*	2.964	75	Engineering design	7
Journal of Engineering Design: *research related to engineering design, such as design theory, methodology, cognition, automation, optimisation, product development, manufacturing, assembly and education, to advance its application in various domains.*	2.400	60	Engineering design	4
Systems Engineering: *research related to systems modelling, optimisation, automation, machine learning, energy systems, and social systems engineering, to advance systems engineering theory, practice, and education, and promote interdisciplinary research and collaboration.*	2.034	55	Systems engineering	14
Defense Acquisition Journal: research *related to defence acquisition, including programme management, contracting, logistics, and technology.*	N/A	N/A	Technical mgmt.	1
Engineering Management Journal: *research related to engineering management, including project management, leadership, innovation, and entrepreneurship.*	2.548	41	Systems engineering	1
International Journal of Product Lifecycle Management: *research related to product lifecycle management, including product design, development, manufacturing, and end-of-life management.*	1.5	23	Engineering design	1
Journal of Integrated Design and Process Science: *research related to the integration of design and process science, including design methodology, process modelling, and optimisation.*	0.43	19	Engineering design	1
Journal of Ship Production: *research related to ship production, including ship design, construction and maintenance.*	0.304	26	Engineering design	1
Military Operations Research: *research related to military operations, including modelling and simulation, decision analysis, and logistics*	0.5	14	Technical mgmt.	1
Reliability Engineering and Systems Safety: *research related to reliability, safety, and risk management, including reliability analysis, safety engineering, and risk assessment.*	7.247	171	Systems engineering	1
Technological Forecasting and Social Change: *research related to the intersection of technology and society, including technology forecasting, innovation, and social change.*	10.884	134	Technical mgmt.	1
Journal of Aircraft: *research related to the design, development, and operation of aircraft, including aerodynamics, propulsion, and materials science*	1.919	102	Engineering design	1

Table 12. Classification of conference proceedings by field.

Conference	Field	Occ.
IEEE International Systems Conference: *Addresses the discipline of systems engineering, including theory, technology, methodology, and applications of complex systems, system-of-systems, and integrated systems of national and global significance.*	Systems engineering	8
Procedia Computer Science: *Conference on Systems Engineering Research, Conference on Life Cycle Engineering*	Systems engineering	6
AIAA Space: *Addresses information-sharing on space systems and technology topics, including commercial space, intelligent systems, national security space, robotic technology and space architecture, space and earth science, colonisation and tethers, exploration, history, policy, logistics and supportability, operations and resources, systems and sensors, and transportation and launch systems.*	Systems engineering	2
International Symposium of the International Council on Systems Engineering: *International forum for systems engineering and systems approaches.*	Systems engineering	3
AIAA/IEEE Digital Avionics Systems Conference: *Addresses machine learning in practice, Integration, and digital controls.*	Technical mgmt.	2
International Conference on Engineering Design: *Addresses design solutions (system engineering, team of teams and system of systems concepts), simulation (virtual and augmented reality, multi-agent systems, human models in the loop), and operation (digital twins, connected service), how to make it intelligent (machine learning).*	Technical mgmt.	2
Other: *IIE Annual Conference, Industrial and Systems Engineering Conference, International Conference on Model-Based Systems Engineering, System of Systems Engineering Conference, International Annual Conference of the American Society for Engineering Management*	Systems engineering/technical mgmt./engineering design	15

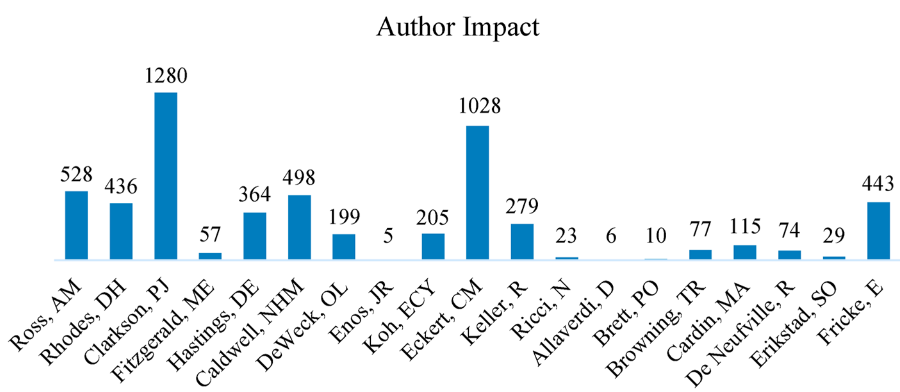

Figure 7. Author impact (number of citations for analysed documents).

2.3.4. Cluster analysis

Using VosViewer a citation network was developed to illustrate the links between authors, using citation/references (Figure 9). The lines in the graph originate from the source paper to associated citing papers, which represents the flow of knowledge. The 83 papers included in the review demonstrated some connection in all contexts, however not all

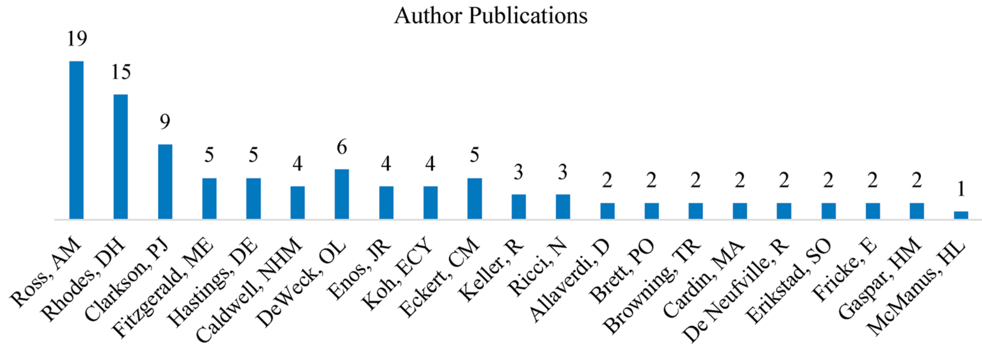

Figure 8. Number of publications authored.

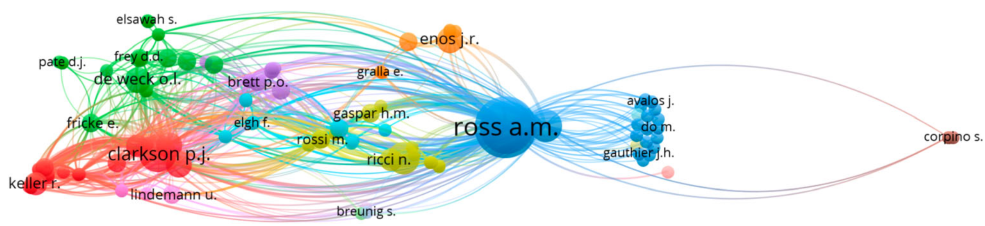

Figure 9. Authorship network cluster.

papers are expected to originate from the same source given the diversity of lifecycle focus and methods for analysis employed. Focusing on the connected components which were defined as 'nodes' the papers were grouped in clusters. The results of this evaluation found that there were 15 resulting clusters: cluster 1 includes publications from 26 authors, followed by the second (22), the third (19 papers); the remaining communities were smaller with 16, 14, 13, 7, 5, 5, 1, 1 and 1. Given the large number of authors in the first six clusters, the key route (the research backbone) was generated. The nodes highlighted in blue are related to foundational publications (cluster 1), while articles highlighted red, green and yellow act as hubs in reference to later publications. The quantification of the relationship between papers was calculated according to the ratio between the number of paths present (including citation count and total number of paths between sources). All paths with a low (below 0.5 value) were removed to highlight only the most significant relationships.

Both the first cluster presented here, and the second cluster analysed the relationship between change options and systems ilities from a conceptual point of view with different analysis methods present. Cluster 1 papers largely share the same approach to system changeability or one of its evolutions (Epoch Era Analysis). The purpose of this stream of literature is the exploration of the interdependencies between system ilities and change options within an engineering system as well as the derived quantification methods for both change and externalities.

Based on authorship co-citation as shown in Figure 10, three clusters were identified. In cluster 1, the works of Clarkson, Eckert and Fricke present the basis for conceptualising how change can extend value throughout a systems lifecycle (Clarkson, Simons, and Eckert 2001). As a higher-level system ility changeability is composed of semantic set of system

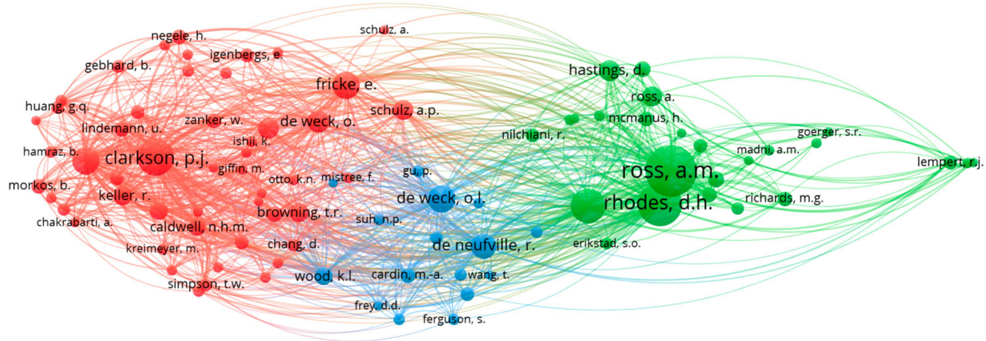

Figure 10. Co-citation network cluster.

characteristics and '-ilities' commonly including, but not limited to flexibility, adaptability, robustness, scalability, modifiability, margins, interoperability, reconfigurability and modularity form the basis of changeability (Curry and Ross 2016; Fitzgerald and Ross 2012b). Cluster 2 is specifically concerned about the analysis and quantification of system changeability. On review three main paths represented by Ross, Rhodes and Hastings where found, where system ilities conceptualisation and quantification is described, whereby agents, change and events are measured within the design of new engineering systems. This is an important point in the stream of the literature because from this point as mentioned previously the Epoch Era Analysis became the most frequently used method and serves as the primary reference source most of the research utilised. Cluster 3, represented by DeWeck, and deNeufville focuses on the evaluation of change through different system ilities, system complexity implications and real change options.

2.3.5. Co-occurrence analysis

The assumption of a co-occurrence (or co-word) analysis is that authors' keywords help to determine the proximity of publications and the repositioning of terms used over time. The co-occurrences around the same word or a pair of words may correspond to a research theme as shown in Figure 13 below, suggesting the existence of patterns and trends. The co-occurrence analysis was performed by extracting the authors' keywords, and then creating a co-word network. The network determines the locations of items in a map by minimising a function depending on the similarity measures between items. Figure 11 below shows that since 2000 three cluster areas (change management, changeability and evolvability) have shifted. The first critical shift can be seen where change management has repositioned from being a core focal point of research to primarily focusing on change propagation, conceptual design and ilities. The second shift occurred in the area of changeability where most of the publications remain dedicated to the cluster, however, a portion of literature began emphasising robustness. This shift can primarily be attributed to the works by Ross where the author introduced the concept of passive and active system robustness (as shown in Table 16). The third shift occurred in relation to the evolvability cluster, where the emphasis transitioned towards systems of systems and ilities.

Figure 12 below shows the results obtained analysing the author keywords through VosViewer of the 83 papers included in the review. Starting from a total of 221 author

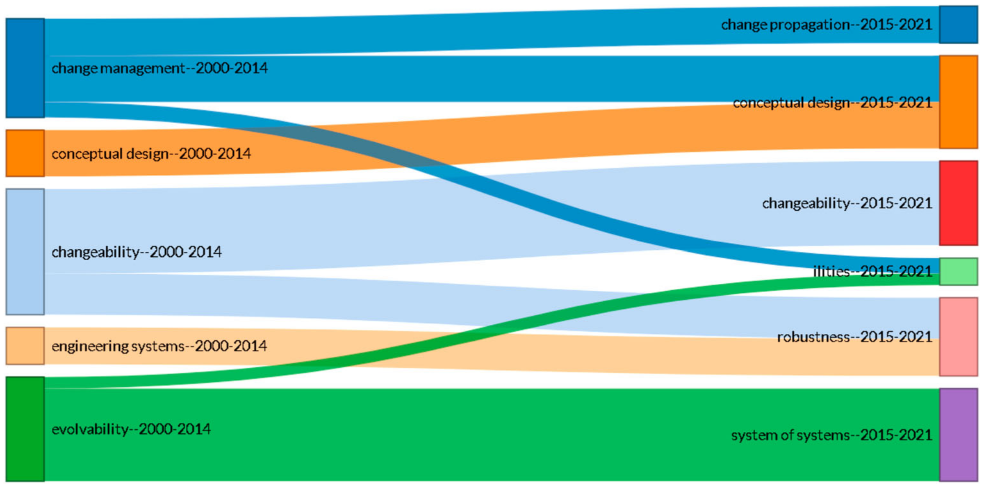

Figure 11. Co-occurrence keyword timeline.

keywords, 4 main clusters were identified, which reflect the clusters previously analysed through the Network Cluster Analysis. The minimum number of occurrences for a specific keyword was set to 4. This value was critical to integrity of the analysis since if a value is too small it will not give enough significance to the analysis, leading to the inclusion of keywords not highly relevant; while a value too high is not optimal as well because it will determine the exclusion of the most recent/trending keywords, which do not yet have enough co-occurrences. A minimum number of 4 was determined to be adequate, considering prior knowledge about the topic. The size of each circle is determined by the number of like keywords (or set of keywords) among all the papers: the larger the circle is, the more common the keyword is (or set of keywords). Furthermore, the weight of each link shows the total strength of a keyword in comparison with others: the thicker the line is, the stronger is the link.

'Changeability' is the central keyword of cluster 1, and based on the circle's size, it is the most important term/keyword of the network (and its evolutions) is one of the widest terms used in this field of study. Cluster 2 is certainly the most ility centric term/keyword set. Flexibility, agility, adaptability, robustness were several of the possible terms used to describe types of specific change, to test the interdependencies between changeability and different system ilities the quantification of both direct and indirect references are considered. Based on thematic knowledge it is possible to identify a connection between cluster 2 and cluster 3 where ilities (robustness, flexibility, adaptability) transition from concept to application (tradespace exploration). Cluster 4 (change propagation, engineering change) appears based on the analysis to be less related to the core keywords and more a related yet different area of research.

3. Findings and discussion

Every system looks to deliver value to the customer, ensuring their satisfaction. Systems designed and manufactured today are operating with longer lifecycles in changing environments. To accommodate, systems for change, they must be able to be changed easily

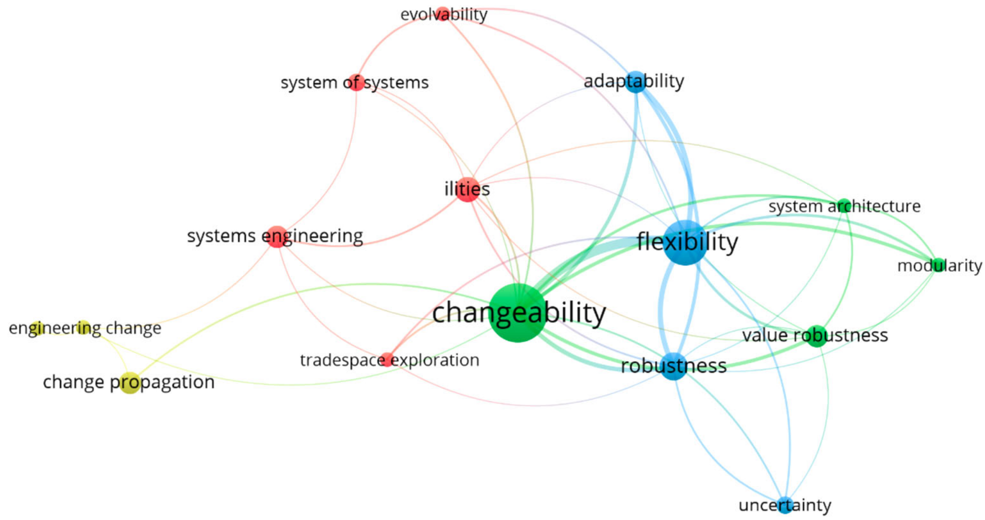

Figure 12. Co-occurrence keyword clusters.

and rapidly, and they must be insensitive or adaptable towards changing environments (Curry and Ross 2016; Ricci et al. 2013).

3.1. *Schematic of changeability research*

The cluster illustrated in Figure 13 helps to structure the present review. The schematic areas were defined based on the results of the 83 articles included in the review according to their research focus. The articles are not divided among the identified research streams due to each of them potentially belong to more than one stream irrespective of the life cycle area they focus on. Four research clusters were identified, which allows focusing on the current research on changeability. Stream #1, Analysing Changeability; Stream #2, Quantifying Changeability; Stream #3, Analysis of Change Related System Ilities, i.e. flexibility, agility, robustness, scalability; Stream #4, Applied Research.

Table 13 details the match between papers and streams, a check mark indicates that the paper in the row addresses the specific stream in the column. Multiple matches are possible indicating a multi-perspective focus and partial overlap amongst the research streams. Furthermore, in Table 13 articles are listed per year, from last to date, allowing tracking the rising and evolution of each topic by the literature.

3.1.1. *Analysing changeability – stream #1*

This section addresses Research Question #2: How is changeability analysed in the domain of engineering systems. Resulting in an overview of the elements of changeability described in publication Stream #1. The deconstruction of changeability allows for distinct aspect and elements to be described, measured and assessed. As described in this section, irrespective of the change context and whether the perturbations were intentional or unintentional, the system should at all times continue to effectively perform no matter what/how changes while providing some form of value (Ross and Rhodes 2008). In the analysis of changeability five central elements were identified: (1) the Change Affect (CA) which

Table 13. Literature review stream classification.

Year	Stream #1	Stream #2	Stream #3	Stream #4
1998			Ring 1998	
1999		Schulz and Fricke 1999	Schulz and Fricke 1999	
2000		Fricke et al. 2000; Schulz, Fricke, and Igenbergs 2000	Fricke et al. 2000; Schulz, Fricke, and Igenbergs 2000	
2004		Clarkson, Simons, and Eckert 2001	Eckert, Clarkson, and Zanker 2004	Eckert, Clarkson, and Zanker 2004
2005	Fricke and Schulz 2005	Nilchiani and Hastings 2005	Fricke and Schulz 2005; Nilchiani and Hastings 2005	Nilchiani and Hastings 2005
2006	Ross and Hastings 2006	Eckert et al. 2006	Eckert et al. 2006; Ross and Hastings 2006	Eckert et al. 2006; Ross and Hastings 2006
2007	McManus et al. 2007		McManus et al. 2007	
2008	Ross and Rhodes 2008; Ross, Rhodes, and Hastings 2008	Engel and Browning 2008	Bahill and Botta 2008; Engel and Browning 2008; Ross and Rhodes 2008; Ross, Rhodes, and Hastings 2008; Siddiqi and De Weck 2008	Engel and Browning 2008; Ross and Rhodes 2008; Ross, Rhodes, and Hastings 2008; Siddiqi and De Weck 2008
2009	Ewart et al. 2009; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Roberts et al. 2009	Eckert et al. 2009; Giffin et al. 2009; Roberts et al. 2009	Ewart et al. 2009; Giffin et al. 2009; Rhodes and Ross 2009; Roberts et al. 2009	Ewart et al. 2009; Giffin et al. 2009; Rhodes and Ross 2009; Roberts et al. 2009
2010	Silver and Weck 2010	Silver and Weck 2010	Rhodes and Ross 2010; Silver and Weck 2010	Silver and Weck 2010
2011		Jarratt et al. 2011	Jarratt et al. 2011	
2012	Beesemyer, Ross, and Rhodes 2012; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2012b; Fitzgerald, Ross, and Rhodes 2012; Gaspar et al. 2012	Beesemyer, Ross, and Rhodes 2012; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2012b; Fitzgerald, Ross, and Rhodes 2012; Hamraz, Caldwell, and John Clarkson 2012; Koh, Caldwell, and Clarkson 2012; Morkos, Shankar, and Summers 2012	Beesemyer, Ross, and Rhodes 2012; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2012b; Fitzgerald, Ross, and Rhodes 2012; Hamraz, Caldwell, and John Clarkson 2012; Koh, Caldwell, and Clarkson 2012; Morkos, Shankar, and Summers 2012; Pate, Patterson, and German 2012	Beesemyer, Ross, and Rhodes 2012; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2012b; Fitzgerald, Ross, and Rhodes 2012; Gaspar et al. 2012; Morkos, Shankar, and Summers 2012; Pate, Patterson, and German 2012
2013	Allaverdi, Herberg, and Lindemann 2013; Fitzgerald and Ross 2013; Ricci et al. 2013	Cardin et al. 2013; Fitzgerald and Ross 2013; Kissel and Lindemann 2013; Koh, Caldwell, and Clarkson 2013; Ricci et al. 2013	Allaverdi, Herberg, and Lindemann 2013; Cardin et al. 2013; Chalupnik, Wynn, and Clarkson 2013; Fitzgerald and Ross 2013; Kissel and Lindemann 2013; Koh, Caldwell, and Clarkson 2013; Ricci et al. 2013; Ryan, Jacques, and Colombi 2013	Allaverdi, Herberg, and Lindemann 2013; Cardin et al. 2013; Kissel and Lindemann 2013; Ricci et al. 2013

(*continued*).

Table 13. Continued.

Year	Stream #1	Stream #2	Stream #3	Stream #4
2014	Niese and Singer 2014; Rader, Ross, and Fitzgerald 2014; Ricci, Rhodes, and Ross 2014	Cardin 2014; Rader, Ross, and Fitzgerald 2014; Ricci, Fitzgerald, et al. 2014; Tackett, Mattson, and Ferguson 2014	Cardin 2014; Niese and Singer 2014; Rader, Ross, and Fitzgerald 2014; Ricci, Fitzgerald, et al. 2014; Ricci, Rhodes, et al. 2014; Tackett, Mattson, and Ferguson 2014	Cardin 2014; Niese and Singer 2014; Rader, Ross, and Fitzgerald 2014; Ricci, Fitzgerald et al. 2014; Ricci, Rhodes, et al. 2014
2015	Altenhofen, Oyama, and Jacques 2015; Keane, Gaspar, and Brett 2015; Mekdeci et al. 2015	Altenhofen, Oyama, and Jacques 2015; ElMaraghy and AlGeddawy 2015; Koh et al. 2015	Keane, Gaspar, and Brett 2015; Koh et al. 2015; Mekdeci et al. 2015; Miner et al. 2015; Ross and Rhodes 2015	Davendralingam and DeLaurentis 2015; ElMaraghy and AlGeddawy 2015; Keane, Gaspar, and Brett 2015; Koh et al. 2015; Mekdeci et al. 2015; Miner et al. 2015
2016			Broniatowski 2016; Colombo, Cascini, and De Weck 2016	Broniatowski 2016
2017		Corpino and Nichele 2017; Koh 2017; Schuh, Riesener, and Breunig 2017	Corpino and Nichele 2017; Enos, Farr, and Nilchiani 2017; Koh 2017; Schuh, Riesener, and Breunig 2017	Corpino and Nichele 2017; Gralla and Szajnfarber 2016; Koh 2017; Schuh, Riesener, and Breunig 2017
2018	Sullivan, Rossi, and Terzi 2018	Turner, Monahan, and Cotter 2018	Sullivan, Rossi, and Terzi 2018; Turner, Monahan, and Cotter 2018	
2019	Avalos, Grenn, and Roberts 2019; Ross and Rhodes 2019; Sullivan et al. 2019	Rehn et al. 2019; Wang, Thomson, and Zhang 2019	Avalos, Grenn, and Roberts 2019; Chavy-Macdonald et al. 2019; Enos 2019a, 2019b; Enos, Farr, and Nilchiani 2019; Rehn et al. 2019; Ross and Rhodes 2019; Rousseau 2019; Sullivan et al. 2019	Chavy-Macdonald et al. 2019; Enos 2019a; Enos, Farr, and Nilchiani 2019; Rehn et al. 2019; Wang, Thomson, and Zhang 2019
2020	Douglas, Mazzuchi, and Sarkani 2020; Moallemi, Elsawah, and Ryan 2020	Allaverdi and Browning 2020; Bashir and Ojiako 2020	Allaverdi and Browning 2020; Arjomandi Rad, Stolt, and Elgh 2020; Bashir and Ojiako 2020; Douglas, Mazzuchi, and Sarkani 2020; Moallemi, Elsawah, and Ryan 2020; Obieke, Milisavljevic-Syed, and Han 2020	Allaverdi and Browning 2020; Moallemi, Elsawah, and Ryan 2020
2021		Enos 2021; Hein et al. 2021	Enos 2021; Hein et al. 2021	Enos 2021; Hein et al. 2021

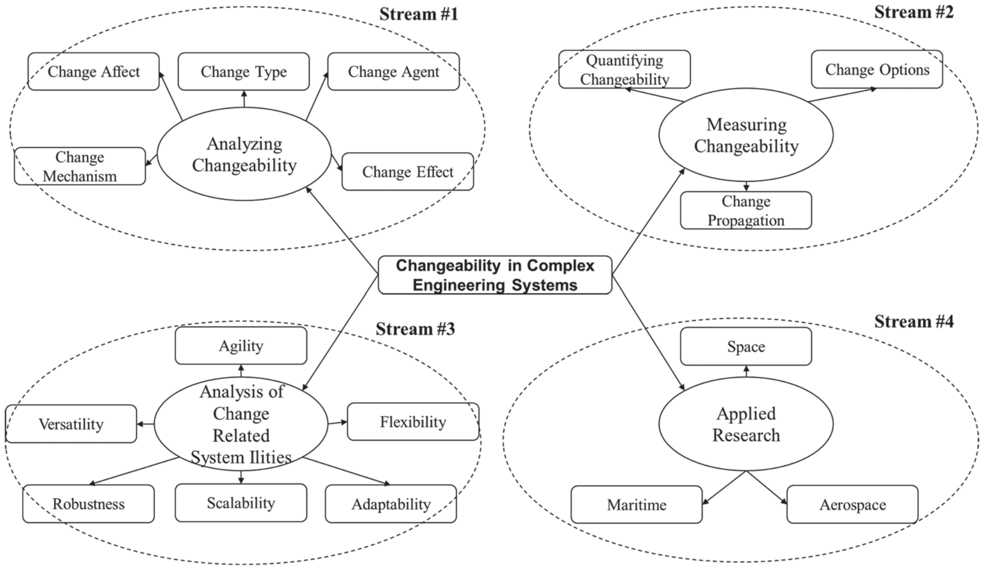

Figure 13. Co-occurrence keyword clusters.

is the externality causing or responsible for the change, (2) the Change Agent (C_Agt.) who is responsible for initiating the change, (3) the Change Type (CT) that is initiated by the agent, (4) the Change Mechanism (CM) that describes the change path and (5) the Change Effect (CE) which describes the difference between the system states (Table 14).

3.1.1.1. Change affect. 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 value sustaining/extending system. Based on Fricke such dynamic pressures and changes being encountered in system development can be viewed in three distinct domains; however recent literature has included dynamic regulations to the three original dimensions (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 affected by policy and regulations, while affecting technological evolution and variety of environment.
- **Dynamic Regulations**: represents regulations mandating some aspect of the system. This externality affects technology choice and environment. Regulatory based externalities refer to norms set by the standardising organisation, governments, governing bodies and the organisation itself. The laws and regulations are models that require companies to analyse the potential impacts of the system (health, safety, compliance). Regulations can include the Stakeholder security interests like Intellectual Property

Table 14. Elements of changeability based on stream #1 (33 publications).

Area of analysis		Ref.	Occ.
CA	Market	Allaverdi, Herberg, and Lindemann 2013; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fricke et al. 2000; Fricke and Schulz 2005; Gaspar et al. 2012; Keane, Gaspar, and Brett 2015; Moallemi, Elsawah, and Ryan 2020; Niese and Singer 2014; Rader, Ross, and Fitzgerald 2014; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Ross and Rhodes 2008; Ross, Rhodes, and Hastings 2008; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Silver and Weck 2010; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	19
	Regulation	Allaverdi, Herberg, and Lindemann 2013; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald, Ross, and Rhodes 2012; Gaspar et al. 2012; Keane, Gaspar, and Brett 2015; Mekdeci et al. 2015; Moallemi, Elsawah, and Ryan 2020; Niese and Singer 2014; Rader, Ross, and Fitzgerald 2014; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Ricci, Rhodes, and Ross 2014; Roberts et al. 2009; Ross and Hastings 2006; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	17
	Technology	Allaverdi, Herberg, and Lindemann 2013; Avalos, Grenn, and Roberts 2019; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald, Ross, and Rhodes 2012; Fricke et al. 2000; Fricke and Schulz 2005; Gaspar et al. 2012; Keane, Gaspar, and Brett 2015; Moallemi, Elsawah, and Ryan 2020; Niese and Singer 2014; Rader, Ross, and Fitzgerald 2014; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Ricci, Rhodes, and Ross 2014; Roberts et al. 2009; Ross and Rhodes 2008; Ross, Rhodes, and Hastings 2008; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Silver and Weck 2010; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	23
	Environment	Allaverdi, Herberg, and Lindemann 2013; Beesemyer, Ross, and Rhodes 2012; Douglas, Mazzuchi, and Sarkani 2020; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald, Ross, and Rhodes 2012; Fricke et al. 2000; Fricke and Schulz 2005; Gaspar et al. 2012; Keane, Gaspar, and Brett 2015; Mekdeci et al. 2015; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Ricci et al. 2013; Ricci, Rhodes, and Ross 2014; Roberts et al. 2009; Ross and Hastings 2006; Ross and Rhodes 2008; Ross, Rhodes, and Hastings 2008; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Silver and Weck 2010; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	24
C_Agt.	Internal	Allaverdi, Herberg, and Lindemann 2013; Altenhofen, Oyama, and Jacques 2015; Avalos, Grenn, and Roberts 2019; Beesemyer, Ross, and Rhodes 2012; Douglas, Mazzuchi, and Sarkani 2020; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2013; Fitzgerald, Ross, and Rhodes 2012; McManus et al. 2007; Mekdeci et al. 2015; Moallemi, Elsawah, and Ryan 2020; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Ricci et al. 2013; Ricci, Rhodes, and Ross 2014; Ross and Hastings 2006; Ross and Rhodes 2008; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Silver and Weck 2010; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	23
	External	Allaverdi, Herberg, and Lindemann 2013; Altenhofen, Oyama, and Jacques 2015; Avalos, Grenn, and Roberts 2019; Beesemyer, Ross, and Rhodes 2012; Douglas, Mazzuchi, and Sarkani 2020; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald, Ross, and Rhodes 2012; McManus et al. 2007; Mekdeci et al. 2015; Moallemi, Elsawah, and Ryan 2020; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Ricci, Rhodes, and Ross 2014; Roberts et al. 2009; Ross and Hastings 2006; Ross and Rhodes 2008; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Silver and Weck 2010; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	22

(*continued*).

Table 14. Continued.

Area of analysis		Ref.	Occ.
CT	Emergent	Allaverdi, Herberg, and Lindemann 2013; Avalos, Grenn, and Roberts 2019; Beesemyer, Ross, and Rhodes 2012; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2013; Fricke et al. 2000; Mekdeci et al. 2015; Rhodes and Ross 2009; Rhodes, Ross, and Nightingale 2009; Ricci, Rhodes, and Ross 2014; Ross and Hastings 2006; Ross and Rhodes 2008; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Schulz and Fricke 1999; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	18
	Propagated	Altenhofen, Oyama, and Jacques 2015; Fricke et al. 2000; Mekdeci et al. 2015; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	5
CM	Mechanism	Allaverdi, Herberg, and Lindemann 2013; Avalos, Grenn, and Roberts 2019; Beesemyer, Ross, and Rhodes 2012; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2012b; Fitzgerald, Ross, and Rhodes 2012; McManus et al. 2007; Moallemi, Elsawah, and Ryan 2020; Ricci et al. 2013; Ricci, Rhodes, and Ross 2014; Roberts et al. 2009; Ross and Hastings 2006; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	17
CE	Effect	Allaverdi, Herberg, and Lindemann 2013; Avalos, Grenn, and Roberts 2019; Beesemyer, Ross, and Rhodes 2012; Ewart et al. 2009; Fitzgerald and Ross 2012a; Fitzgerald and Ross 2012b; Fitzgerald and Ross 2013; Fitzgerald, Ross, and Rhodes 2012; Fricke et al. 2000; Keane, Gaspar, and Brett 2015; McManus et al. 2007; Mekdeci et al. 2015; Moallemi, Elsawah, and Ryan 2020; Ricci et al. 2013; Roberts et al. 2009; Ross and Hastings 2006; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Silver and Weck 2010; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018	21

Rights, Information Assurance, Security Laws, Supply Chain Compliance and Security Standards (Gaspar et al. 2012; Niese and Singer 2014; Rhodes and Ross 2009).

- **Dynamic Technology:** is a response to the development of new technologies that are required to produce the specific product, or at behest of the change agent. Technology changes are necessary to keep a system competitive, meet changing market demands, or requirements for customisation (Fitzgerald and Ross 2012a; Fricke et al. 2000). Technology influences all aspects of the system and is an enabler for new and advanced systems.
- **Variety of Environments:** may be indicated by the number of embedded systems, integration of diverse technologies, or number of operational contexts (Ross and Hastings 2006; Ross, Rhodes, and Hastings 2008). Interrelated elements and embedded systems (SoS) can be impacted by all changes placed upon the system and are affected by the evolution of technology.

3.1.1.2. 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. In all cases 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 three major steps, consideration of the impact, observation and decision-making (Ross, Rhodes, and Hastings 2008). The 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 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 to determine a course of action, regarding whether to exert influence and implement the change.

3.1.1.3. 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 performance, providing functionalities or reducing undesired features (Jarratt et al. 2011). The forces representing what the system must respond is categorised based on how the change emerges and the decision taken (impact, observation, decision-making).

- **Initiated Change**: Can be planned and unplanned changes that are generated by an external of the technical system. The most typical initiated change is due to change in requirements (Fitzgerald and Ross 2012a; 2012b; Fricke et al. 2000; Schulz, Fricke, and Igenbergs 2000).
- **Emergent Change**: Can arise across/throughout the system when changes are required to rectify a situation within the internal technical system (Allaverdi, Herberg, and Lindemann 2013; Fricke et al. 2000).
- **Propagated Change:** Undesired changes that come due to other changes having been made within the technical system (Altenhofen, Oyama, and Jacques 2015; Fricke et al. 2000; Sullivan, Rossi, and Terzi 2018).

3.1.1.4. 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 are intended to assist the broader goal of providing prescriptive design principle guidance on how to actively create more 'value' for the stakeholder (Beesemyer, Ross, and Rhodes 2012; Fitzgerald, Ross, and Rhodes 2012; Ross, Rhodes, and Hastings 2008). Each change mechanism allows the change to occur according to an effective start time and expiration time, as well as duration for how long it takes to implement, or how long that specific change type affects the system (Fitzgerald and Ross 2012b; Ross and Rhodes 2008).

3.1.1.5. 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 system 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 be 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, Rhodes, and Hastings 2008). There may be different extents for the change effect, depending on the type of agent or mechanism involved in the change process.

3.1.2. Measuring changeability – stream #2

Measuring changeability has evolved alongside methods and approaches for analysis methods to model changes in complex engineered systems. The output of the review of Stream #2 allowed for the evaluation of factors and approaches used to measure system changeability, and Research Question #3: How can changeability be measured. In this section, four method areas for measuring changeability were identified: (1) Change Prediction which measures the relationship between changes within systems, (2) Change Value Analysis which measures the utility value of the change/ility on the system through either monetary or non-monetary means, (3) Changeability Quantification measures the level of changeability within a system and (4) Real Options which present viable changes a system can benefit from, as shown in Table 15.

- **Change Prediction:** Change prediction within the literature has been utilised to identify high-volume (a large number of change events) and high-value change mechanisms within engineering systems (Giffin et al. 2009; Hamraz, Caldwell, and John Clarkson 2012; Koh, Caldwell, and Clarkson 2012). The method identifies and proposes changes within changeable systems (flexibility, agility, adaptability, etc.) that allow for the mechanism to be implemented in a robust manner. To predict valuable changes within the system the use of Change Favorable Representation (C-FAR) (Morkos, Shankar, and Summers

2012), Design Structure Matrix (DSM) (Allaverdi and Browning 2020; Cardin et al. 2013; ElMaraghy and AlGeddawy 2015; Koh et al. 2015) developed by Eppinger and Browning, and the Change Propagation Index (CPI) (Giffin et al. 2009) have been utilised. C-Far utilises system attributes, elements and relationships to describe the coupling between entities and is effective at evaluating the effect of one attribute to another (Morkos, Shankar, and Summers 2012). DSM focuses on direct propagation and captures the dependencies between components (tight vs. loose coupling) to support the development of decoupled system architecture that requires less design effort for subsequent variants (platforms) (Koh, Caldwell, and Clarkson 2013). While CPI emphasises the comparison of change effects (positive vs. negative) so that changes imposed on the system are capable of being absorbed (robustness, the more changes allowed for without negative effects are preferred) (Giffin et al. 2009). A comprehensive review on engineering change prediction and change propagation can be found in Jarratt et al. (2011).

- **Change Value Analysis:** The benefit and value of change to a system are the second most discussed area of literature in this section and have been examined through both monetary and non-monetary means. While cost is a significant consideration in changeability the ability of the system to increase value through the change is the primary consideration, as each change allows for an aspect of the system to improve. To measure valuable changes within the system the use of Epoch-Era Analysis (EEA) (Fitzgerald and Ross 2012b; Keane, Gaspar, and Brett 2015; Rader, Ross, and Fitzgerald 2014), and SoS Architecting with Ilities (SAI) (Ricci, Fitzgerald, et al. 2014) have been utilised. Ross considers change value as a critical factor that leads to and facilitates the creation of new value aspects during development, distinguishing between (1) passive value robustness and (2) active value robustness (Fitzgerald and Ross 2012b; Ricci et al. 2013).
  - Epoch-Era Analysis: Was developed out of the work on MATE with the intent to model uncertain system future contexts that impact system value which provides visualisation and a structured way of representing plausible alternate future contexts (Keane, Gaspar, and Brett 2015). This approach infers systems can be described both in terms of traditional design variables that are selected to directly create value, and through inclusion of path enablers that facilitate and enhance the changeability of the system over time to deliver active value robustness. Within the approach an epoch (period of time characterised by fixed exogenous variables) is designed to clarify and provide designers with information related to design alternatives based on their ability to change contexts, while an era represents (series of epochs representing potential lifecycle contexts) the value potential of the system. EEA provides a means for analysing lifecycle uncertainty and design alternative evaluation when designing systems for sustained value delivery, though consideration of the optimal level of changeability for a systems changeability nor the costs associated are considered.
  - The SAI method: Is an extension of the Responsive Systems Comparison method developed by Ricci, providing additional steps and improved analytical tools to support the identification, inclusion, and quantification of specific system ilities. The method centres on the concept of change types and differentiates based on if the design can change to satisfy new requirements/needs/specifications/functions (change option), or if the system is resilient to change (traditional system robustness). The method utilises like principles of change to the EEA, though rather than focusing

exclusively on the value dimension of potential changes, focuses on the selection of the most beneficial ilities that directly/indirectly allow for value to be realised.

- **Real Options Analysis**: Within the literature, the economic value of design choices and inclusion of specific system ilities has been widely considered. Real Options Analysis (ROA) analyses the financial options cost of including various ilities and the broader concept of changeability into the design of systems by supporting decision makers in evaluating different financial arrangements during the design process. Within the literature options can be defined as taking the 'right, but not the obligated' action at a specific time in relation to a specific cost. As discussed in multiple instances ROA improves the ability to evaluate how different internal changes affect the cost/benefits of a specific system and can be used to model specific uncertainties. While a powerful decision-making tool there are distinct limitations in its ability to identify where in a system specific option should be located. To overcome this limitation, knowledge about the system and its respective boundaries, as well as being able to understand change types and related externality are vital to examine value in dynamic scenarios. In an effort to meet these points multiple variations of ROA exist in the literature including the specific evaluation of Flexibility (Six-Element Framework [Nilchiani and Hastings 2005]), calculation of Architecture Options according to a SysML decomposition (Engel and Browning 2008), and measurement of Net Present Value and Expected Net Present Value Analysis (Cardin et al. 2013).
  - o Six-element framework: The framework focusses on the inclusion and value of flexibility in the development of systems and system of systems based on the calculation of benefits and associated costs. By addressing specific uncertainties through the inclusion of flexibility the framework allows for multiple value areas to be measured. This framework while focusing exclusively on one system ility can be adapted to measure the value of other individual ilities, however is not optimal for evaluating scenarios when multiple ilities are introduced to a system.
  - o Architecture Options: Considers the value diminishment of systems throughout their life cycle by evaluating the adaptability of systems through the allocation of modules to better manage complexity, enable parallel work and accommodate future uncertainty. This distribution of modules allows for the inherent change within the module, the options available and the cost factors between modules (interface).
  - o NPV and ENPV: Within the work by Cardin the expected economic value of the system are examined quantitatively based on the cost/benefit associated with the ability for individuals to conceptualise and rationalise areas of change. This ideation process leverages the basic tenets of ROA, however, focuses primarily on the implications of decisions for decision makers.
- **Change Quantification Methods:** Quantification allows for the system and development process to be evaluated for a more complete and well-planned design to be created. This attempts to go beyond comparing system states alone, to support engineers in determining which level of changeability (more changeability allows for greater change options but comes at a real cost) can provide the greatest value. Based on the literature collected the quantification of changeability (Rehn et al. 2019) and specific ilities (Tackett, Mattson, and Ferguson 2014; Turner, Monahan, and Cotter 2018) have been explored resulting in the proposition of both top-down and bottom-up approaches.

- o The bottom-up approach provides a means of establishing more specific measures of changeability, measuring the changes from one physical design variable, or between two modes of operation to another. Reduction in change cost or time: measured for each relevant change separately (Rehn et al. 2019).
- o The top-down approach is more comprehensive and investigates the space of change opportunities available at a given change cost and time, related to a network model of possibilities provided by a specific system element. Number or fraction of states in the defined state space which can be changed into at given a cost and time (Rehn et al. 2019).

Despite the comprehensive solutions in place multiple topic areas require further research, particularly regarding calculating the associated cost of specific changeability/ility levels between system states. As well as the identification of components, systems and system of systems that are most suitable for changeability (various levels within the system whole) regarding value.

3.1.3. Analysis of change-related system ilities – stream #3

As introduced in Section 2.3.1 and 2.3.4 changeability as described and discussed within the literature is a high-level ility (Figure 14) that is composed of a semantic set of system characteristics and lower-level 'ilities' commonly including, but not limited to flexibility, adaptability, robustness, scalability, modifiability, margins, interoperability, reconfigurability and modularity form the basis of changeability (Curry and Ross 2016; Fitzgerald and Ross 2012b). This section addresses Research Question 4: What relationships do lower level ilities have and how do they provide value throughout the system life cycle. Based on the literature lower-level ilities represent the theoretical and applied notion of change, describing not only what can change, but also how changes can be enacted throughout the systems lifecycle (McManus et al. 2007). As descriptive elements, lower-level ilities (centre of Figure 14) are considered as a derivative of changeability the principal system level ility that enables change (left side of Figure 14). Despite the noted behavioural characteristics, ilities remain difficult to define since there is not a single agreed upon formal definition, list or taxonomy (Andersen et al. 2017; Colombo, Cascini, and De Weck 2016; Fricke et al. 2000; Fricke and Schulz 2005; Rajan et al. 2005; Siddiqi et al. 2011). However, through the literature analysed and illustrated in Figure 14, a list of ilities were investigated to determine how and when they are utilised within the system design. While not comprehensive, the figure and Table 11 below make it possible to classify ilities according to whether they enable systems life extension, or if they increase the chance that a systems life will be extended.

Based on the classification of the ility being either an enabler for systems life extension, or if it increases the chance that a systems life will be extended the relevant system life cycle phase was identified (right side of Figure 15). As observed below the greatest value for ilities is within the utilisation and support phase, which represent the periods where the most value change can occur. While ilities undoubtedly have an impact on the earlier life cycle phases (concept, development, production) by facilitating the realisation of changeability they have a lesser benefit in direct terms. This can be attributed to the size, scale and complexity of the engineering systems, as the value derived from the middle of life (utilisation and support) in most cases (according to the published cases Section 3.1.4) exceeds the beginning and end of life.

Table 15. Methods for measuring system changeability based on stream #2 (38 publications).

Method	Ref.	Occ.
Change prediction	Allaverdi and Browning 2020; Altenhofen, Oyama, and Jacques 2015; Bashir and Ojiako 2020; Cardin 2014; Eckert et al. 2006; Eckert et al. 2009; ElMaraghy and AlGeddawy 2015; Giffin et al. 2009; Hamraz, Caldwell, and John Clarkson 2012; Hein et al. 2021; Jarratt et al. 2011; Kissel and Lindemann 2013; Koh 2017; Koh et al. 2015; Koh, Caldwell, and Clarkson 2012; Koh, Caldwell, and Clarkson 2013; Morkos, Shankar, and Summers 2012; Ricci, Fitzgerald, et al. 2014; Schuh, Riesener, and Breunig 2017; Wang, Thomson, and Zhang 2019	20
Change value analysis	Allaverdi and Browning 2020; Corpino and Nichele 2017; Enos 2021; Nilchiani and Hastings 2005; Ricci, Fitzgerald, et al. 2014; Silver and Weck 2010; Wang and De Neufville 2006	7
Real options	Allaverdi and Browning 2020; Cardin et al. 2013; Engel and Browning 2008; Nilchiani and Hastings 2005; Silver and Weck 2010	5
Change quantification	Rehn et al. 2019; Tackett, Mattson, and Ferguson 2014; Turner, Monahan, and Cotter 2018	3

The documents and ilities previously referenced, presented in Table 16, present a base definition supported by the reference literature. It is acknowledged that the publication distribution is not balanced, and therefore ilities with fewer references (Occ.) could be incomplete.

A list of scenarios from the literature were extracted, describing when changeability has/can be applied and the associated ilities involved (Table 17). Influenced by Steiner (1998) these scenarios describe the general system conditions and the associated change related system ilities (introduced in Table 16).

3.1.4. Applied research and case studies – stream #4

Through the analysis applied research (case study) it was possible to identify characteristics present within the demonstrated cases. These cases not only show where the most research is being performed but also help to better explain the types of systems most suitable for changeability. The classification was made according to four sectors which were, Space (satellite, space tug), Aerospace (UAV, Aircraft), Maritime (ship/vessel) and Other (missile system, automotive). Other was identified as the sector in which more studies have been carried out (Table 18), results in line with the study of Colombo (Colombo, Cascini, and De Weck 2016), who found that most of the studies were general or conceptual in nature.

On the other hand, despite having fewer papers, it is important to note that Space and Aerospace have strong similarities from an operations and industrial perspective. Our findings clearly show that research in these two sections covers nearly half of all publications where applied cases were considered, while maritime sectors has a lower overall representation, the detail and relevancy in terms of complexity suggests an opportunity for future research.

By synthesising the findings and contributions from the publications in Table 18, a comprehensive understanding of changeability and maturity across various sectors was possible.

Table 16. Ilities linked to system changeability based on stream #3 (74 publications).

Ility	Lifecycle stage ISO/IEC 24748	Reference	#
1. Flexibility - the ease and ability with which a system to undergo classes of changes (initiated external/outside the system).	Production; Development; Utilisation; Support; Retirement	Fitzgerald and Ross 2012a; Ricci et al. 2013; Colombo, Cascini, and De Weck 2016; Ross and Hastings 2006; Ross, Rhodes, and Hastings 2008; Schulz, Fricke, and Igenbergs 2000; Fricke et al. 2000; Fricke and Schulz 2005; Schulz and Fricke 1999; Sullivan, Rossi, and Terzi 2018; Enos, Farr, and Nilchiani 2017; Enos 2019a; Ross and Rhodes 2015; Turner, Monahan, and Cotter 2018; Ring 1998; Eckert, Clarkson, and Zanker 2004; Nilchiani and Hastings 2005; McManus et al. 2007; Ross and Rhodes 2008; Engel and Browning 2008; Bahill and Botta 2008; Siddiqi and De Weck 2008; Ewart et al. 2009; Giffin et al. 2009; Silver and Weck 2010; Rhodes and Ross 2010; Jarratt et al. 2011; Beesemyer, Ross, and Rhodes 2012; Fitzgerald and Ross 2012a; Hamraz, Caldwell, and John Clarkson 2012; Morkos, Shankar, and Summers 2012; Pate, Patterson, and German 2012; Allaverdi, Herberg, and Lindemann 2013; Fitzgerald and Ross 2013; Tackett, Mattson, and Ferguson 2014; Mekdeci et al. 2015; Miner et al. 2015; Broniatowski 2016; Corpino and Nichele 2017; Koh 2017; Schuh, Riesener, and Breunig 2017; Avalos, Grenn, and Roberts 2019; Ross and Rhodes 2019; Sullivan et al. 2019; Rehn et al. 2019; Enos 2019a; Enos, Farr, and Nilchiani 2019; Douglas, Mazzuchi, and Sarkani 2020; Allaverdi and Browning 2020; Arjomandi Rad, Stolt, and Elgh 2020; Enos 2021	60
2. Robustness - a system is said to be robust if no changes from internal/external events must be implemented/introduced to accommodate changing preferences, environments, or system offerings. The literature suggests a distinction between 'passive robustness' and 'active robustness' in respect to value. a. Passive system robustness delivers value through the development designs insulated by system shells, which are perceived to maintain value over time irrespective of change (Ross, Rhodes, and Hastings 2008). Meaning that design alternatives are selected based on their ability to deliver value to stakeholders despite changes in needs or context (value robustness). b. Active system robustness 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, Rhodes, and Hastings 2008).	Utilisation; Development; Concept; Support; Retirement	Fitzgerald and Ross 2012a; Ricci et al. 2013; Colombo, Cascini, and De Weck 2016; Ross and Hastings 2006; Ross, Rhodes, and Hastings 2008; Schulz, Fricke, and Igenbergs 2000; Fricke et al. 2000; Fricke and Schulz 2005; Schulz and Fricke 1999; Sullivan, Rossi, and Terzi 2018; Enos, Farr, and Nilchiani 2017; Enos 2019a; Fitzgerald, Ross, and Rhodes 2012; Ross and Rhodes 2015; Turner, Monahan, and Cotter 2018; Nilchiani and Hastings 2005; McManus et al. 2007; Ross and Rhodes 2008; Ewart et al. 2009; Rhodes and Ross 2009; Roberts et al. 2009; Rhodes and Ross 2010; Beesemyer, Ross, and Rhodes 2012; Fitzgerald and Ross 2012a; Allaverdi, Herberg, and Lindemann 2013; Fitzgerald and Ross 2013; Chalupnik, Wynn, and Clarkson 2013; Ryan, Jacques, and Colombi 2013; Rader, Ross, and Fitzgerald 2014; Ricci, Rhodes, and Ross 2014; Ricci, Fitzgerald, et al. 2014; Tackett, Mattson, and Ferguson 2014; Keane, Gaspar, and Brett 2015; ElMaraghy and AlGeddawy 2015; Miner et al. 2015; Broniatowski 2016; Corpino and Nichele 2017; Koh 2017; Schuh, Riesener, and Breunig 2017; Avalos, Grenn, and Roberts 2019; Ross and Rhodes 2019; Sullivan et al. 2019; Rehn et al. 2019; Enos 2019a; Enos, Farr, and Nilchiani 2019; Rousseau 2019; Moallemi, Elsawah, and Ryan 2020; Allaverdi and Browning 2020; Arjomandi Rad, Stolt, and Elgh 2020; Enos 2021; Hein et al. 2021	51

(*continued*).

Table 16. Continued.

Ility	Lifecycle stage ISO/IEC 24748	Reference	#
3. Adaptability – characterises a system's ability to adapt itself towards changing environments. An adaptable system delivers functionality in varying operating conditions by changing themselves (initiated within the system).	Development; Utilisation; Support; Retirement	Allaverdi and Browning 2020; Allaverdi, Herberg, and Lindemann 2013; Arjomandi Rad, Stolt, and Elgh 2020; Avalos, Grenn, and Roberts 2019; Bahill and Botta 2008; Beesemyer, Ross, and Rhodes 2012; Cardin 2014; Chalupnik, Wynn, and Clarkson 2013; Colombo, Cascini, and De Weck 2016; Corpino and Nichele 2017; Douglas, Mazzuchi, and Sarkani 2020; Eckert et al. 2006; Eckert, Clarkson, and Zanker 2004; Engel and Browning 2008; Enos 2019a, 2019b; Enos 2021; Ewart et al. 2009; Fricke et al. 2000; Fricke and Schulz 2005; Hamraz, Caldwell, and John Clarkson 2012; Keane, Gaspar, and Brett 2015; Kissel and Lindemann 2013; McManus et al. 2007; Mekdeci et al. 2015; Miner et al. 2015; Moallemi, Elsawah, and Ryan 2020; Nilchiani and Hastings 2005; Pate, Patterson, and German 2012; Rader, Ross, and Fitzgerald 2014; Rehn et al. 2019; Rhodes and Ross 2010; Ring 1998; Roberts et al. 2009; Ross and Rhodes 2015; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Rousseau 2019; Ryan, Jacques, and Colombi 2013; Schuh, Riesener, and Breunig 2017; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Siddiqi and De Weck 2008; Silver and Weck 2010; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018; Tackett, Mattson, and Ferguson 2014; Turner, Monahan, and Cotter 2018	49
4. Modularity - is considered a sub-ility of flexibility and is a strong enabler of evolvability and agility (Enos 2019a). It can represent the encapsulation of functions or sub-functions (that can be changed with relative ease) of the larger system.	Production; Development; Utilisation; Support; Concept	Allaverdi and Browning 2020; Arjomandi Rad, Stolt, and Elgh 2020; Broniatowski 2016; Chavy-Macdonald et al. 2019; Eckert, Clarkson, and Zanker 2004; Engel and Browning 2008; Enos 2019a; Ewart et al. 2009; Fricke et al. 2000; Fricke and Schulz 2005; Jarratt et al. 2011; Koh et al. 2015; Nilchiani and Hastings 2005; Rader, Ross, and Fitzgerald 2014; Rehn et al. 2019 Ricci, Fitzgerald, et al. 2014; Ricci, Rhodes, and Ross 2014; Ring 1998; Ross and Hastings 2006; Ross and Rhodes 2015, Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Schuh, Riesener, and Breunig 2017; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Tackett, Mattson, and Ferguson 2014	26
5. Agility – Pertains to a system that can be changed quickly.	Development; Utilisation; Support; Retirement	Arjomandi Rad, Stolt, and Elgh 2020; Avalos, Grenn, and Roberts 2019; Beesemyer, Ross, and Rhodes 2012; Colombo, Cascini, and De Weck 2016; Enos 2019a, 2019b; Fricke et al. 2000; Fricke and Schulz 2005 Hamraz, Caldwell, and John Clarkson 2012; Keane, Gaspar, and Brett 2015; Mekdeci et al. 2015 Miner et al. 2015; Rader, Ross, and Fitzgerald 2014; Rehn et al. 2019; Ring 1998; Ross and Hastings 2006; Ross and Rhodes 2015; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Schuh, Riesener, and Breunig 2017; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Sullivan et al. 2019; Sullivan, Rossi, and Terzi 2018; Turner, Monahan, and Cotter 2018	25

(*continued*).

Table 16. Continued.

Ility	Lifecycle stage ISO/IEC 24748	Reference	#
6. Scalability - is the ability of a system to be independent of self-similar units through the process of adding or removing elements/functions/features.	Development; Utilisation; Support; Concept	Arjomandi Rad, Stolt, and Elgh 2020; Beesemyer, Ross, and Rhodes 2012; Chalupnik, Wynn, and Clarkson 2013; Corpino and Nichele 2017; Douglas, Mazzuchi, and Sarkani 2020; Ewart et al. 2009; Fricke and Schulz 2005; Koh, Caldwell, and Clarkson 2012; McManus et al. 2007; Mekdeci et al. 2015; Rader, Ross, and Fitzgerald 2014; Rehn et al. 2019 Rhodes and Ross 2010 Ricci, Rhodes, and Ross 2014; Ross and Hastings 2006; Ross and Rhodes 2008; Ross and Rhodes 2015; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008; Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000; Sullivan et al. 2019	22
7. Versatility - the ability of the system to perform variant tasks functions not initially defined by the systems requirements.	Utilisation; Support; Concept	Arjomandi Rad, Stolt, and Elgh 2020; Chalupnik, Wynn, and Clarkson 2013; Colombo, Cascini, and De Weck 2016; Enos 2019a, 2019b, 2021; Enos, Farr, and Nilchiani 2017; Enos, Farr, and Nilchiani 2019; McManus et al. 2007; Mekdeci et al. 2015; Rehn et al. 2019; Ricci, Fitzgerald, et al. 2014; Ross and Rhodes 2008; Ross and Rhodes 2015; Ross and Rhodes 2019; Ryan, Jacques, and Colombi 2013; Sullivan et al. 2019	17
8. Survivability - the ability of a system to minimise the impact of dynamic disturbances.	Utilization	Allaverdi, Herberg, and Lindemann 2013; Douglas, Mazzuchi, and Sarkani 2020; Enos 2019a; Fitzgerald and Ross 2013; McManus et al. 2007 Mekdeci et al. 2015; Ricci et al. 2013; Ricci, Fitzgerald, et al. 2014; Ricci, Rhodes, and Ross 2014; Ross and Rhodes 2019; Siddiqi and De Weck 2008	11
9. Evolvability - the property of a system that can be changed according to dynamic features easily through allowable means.	Production; Utilisation	Ewart et al. 2009; Mekdeci et al. 2015; Rehn et al. 2019; Ricci et al. 2013; Ricci, Fitzgerald, et al. 2014 Ricci, Rhodes, and Ross 2014; Ross and Hastings 2006; Ross and Rhodes 2019; Siddiqi and De Weck 2008; Tackett, Mattson, and Ferguson 2014	10
10. Modifiability – is the ability to add/remove a feature/function to the system with ease.	Utilisation	Allaverdi, Herberg, and Lindemann 2013; Arjomandi Rad, Stolt, and Elgh 2020; Douglas, Mazzuchi, and Sarkani 2020; Fricke and Schulz 2005; McManus et al. 2007 Mekdeci et al. 2015 Rader, Ross, and Fitzgerald 2014; Ross and Rhodes 2015; Ross and Rhodes 2019; Ross, Rhodes, and Hastings 2008	10

(*continued*).

Table 16. Continued.

Ility	Lifecycle stage ISO/IEC 24748	Reference	#
11. Reconfigurability – is the ability of the system to change the arrangement/structure of components to satisfy different multiple functions.	Development; Utilisation; Support; Concept	Arjomandi Rad, Stolt, and Elgh 2020; Ricci, Rhodes, and Ross 2014; Ross and Rhodes 2015; Ross and Rhodes 2019; Siddiqi and De Weck 2008; Sullivan, Rossi, and Terzi 2018; Tackett, Mattson, and Ferguson 2014;	7
12. Interoperability - the definition is challenging to standardise in the research context, however in general can be said to represent the ability of the system to effectively interact with other systems.	Utilisation; Support; Concept	Douglas, Mazzuchi, and Sarkani 2020; Enos 2021; Mekdeci et al. 2015; Ross and Rhodes 2015; Ross and Rhodes 2019; Schulz and Fricke 1999	6
13. Maintainability – refers to the degree with which a system can safely, quickly, and easily change through the replacement/service of its component parts.	Utilisation; Support	Allaverdi, Herberg, and Lindemann 2013; Douglas, Mazzuchi, and Sarkani 2020; Eckert, Clarkson, and Zanker 2004; Enos 2019a; Ewart et al. 2009; Ross and Rhodes 2015	6
14. High-Level Changeability – refers to the 'general' utilisation of the term changeability to represent a higher-level system ility (representing any number of change-related ilities).	Development; Utilisation; Support; Production; Concept	Bashir and Ojiako 2020; Chavy-Macdonald et al. 2019; Hein et al. 2021; Koh 2017; Koh et al. 2015; Niese and Singer 2014	6
15. Extensibility – is the ability of a system to change to facilitate new functions or sets of functions.	Utilisation; Support; Retirement	Enos 2019a, 2021; Mekdeci et al. 2015; Ross and Hastings 2006; Ross and Rhodes 2019	5
16. Reliability – is a central element of changeability and refers to the probability that the system will perform its intended function under defined conditions without failure, over a specific period.	Utilization	Arjomandi Rad, Stolt, and Elgh 2020; Enos 2021; Mekdeci et al. 2015 Sullivan et al. 2019	4
17. Upgradeability – reflects the relative technical ease or feasibility of supporting continuous system change/renewal and improvement throughout the system life cycle.	Utilisation; Support	Ewart et al. 2009 Rehn et al. 2019; Ross, Rhodes, and Hastings 2008; Sullivan et al. 2019	4
18. Integratability – refers to the compatibility and interoperability between (generic, open, or common/consistent) interfaces.	Concept; Utilisation; Support; Development	Ricci, Rhodes, and Ross 2014 Schulz and Fricke 1999; Schulz, Fricke, and Igenbergs 2000	3
19. Viability – refers to the likelihood that a change to and engineering system will provide acceptable value to its stakeholders, throughout its life cycle.	Utilisation; Support; Retirement	Mekdeci et al. 2015; Tackett, Mattson, and Ferguson 2014	2
20. Affordability – reflects the degree to which the systems performance, cost, and scheduling constraints can be balanced throughout the systems life cycle.	Concept; Development; Utilisation; Support; Retirement	Ross and Rhodes 2015; Ross and Rhodes 2019	2

(*continued*).

Table 16. Continued.

Ility	Lifecycle stage ISO/IEC 24748	Reference	#
21. Extendibility – represents the ability to increase systems functions and can be achieved through other ilities such as upgradeability and the customizability of components or sub-systems.	Utilisation; Retirement	Enos, Farr, and Nilchiani 2017	1
22. Pliability – refers to the ability of the system to remain viable by switching between different viable states according to the architecture.	Utilisation	Mekdeci et al. 2015	1
23. Manufacturability – refers to the ease with which a system or component can be produced according to specifications required by the system and directly impacts affordability of the system.	Production; Concept; Development	Enos 2021	1

Table 17. Relationship between change related systems ilities and system scenarios.

	Change Related System Ilities																				
Scenario	Flexibility	Robustness	Adaptability	Modularity	Agility	Scalability	Versatility	Survivability	Evolvability	Modifiability	Reconfigurability	Interoperability	Maintainability	Extensibility	Reliability	Upgradeability	Integratability	Viability	Affordability	Extendibility	Pliability
Systems and architectures that are subject to high dynamism (market, technology, regulatory, environment) (Fricke and Schulz 2005 Koh, Caldwell, and Clarkson 2012; Ross, Rhodes, and Hastings 2008)	x		x		x	x	x		x	x		x	x	x	x	x	x				
Distributed ownership, with the potential for multiple stakeholders with different needs (Mekdeci et al. 2015; Ross and Rhodes 2008)	x		x	x	x	x			x		x	x	x	x			x				
Systems requiring the ability to change in mission, requirements or operational variables (Fitzgerald and Ross 2012a; Ross, Rhodes, and Hastings 2008)	x		x		x	x			x		x	x	x	x			x				
Systems requiring high deployment and maintenance costs (Fricke and Schulz 2005)						x						x	x		x			x	x		
Systems requiring large infrastructure support (Altenhofen, Oyama, and Jacques 2015; Rehn et al. 2019; Ross and Rhodes 2008)	x		x			x						x	x	x	x			x	x		
Systems that shall be effectively/affordably sustainable over their lifecycle (Ross and Rhodes 2015)		x				x						x	x			x	x	x	x		
Systems with a long lifecycle, or expect to be required to change in different manners during distinct lifecycle phases (Enos, Farr, and Nilchiani 2017; Fricke and Schulz 2005)	x		x			x	x		x	x	x	x	x			x					
Systems requiring sustained/extended or active value in the face of changing contexts (Beesemyer, Ross, and Rhodes 2012; Ross, Rhodes, and Hastings 2008)	x	x	x		x	x			x	x		x	x			x	x		x		

(*continued*).

Table 17. Continued.

Scenario	Change Related System Ilities																				
	Flexibility	Robustness	Adaptability	Modularity	Agility	Scalability	Versatility	Survivability	Evolvability	Modifiability	Reconfigurability	Interoperability	Maintainability	Extensibility	Reliability	Upgradeability	Integratability	Viability	Affordability	Extendibility	Pliability
Systems or system architectures that are used for different products with a common basic set of attributes (Fricke and Schulz 2005)							x			x	x	x	x				x			x	
Systems that have a stable core functionality but variability in secondary functions and/or external styling (Fricke and Schulz 2005)	x				x	x	x		x	x		x	x		x	x	x			x	
Transferability, the capacity to be used with minimal modification in different scenarios (Ross and Hastings 2006)	x					x	x				x	x	x	x			x				
Expandable/scalable, and systems designed to accommodate growth in capability (Ross, Rhodes, and Hastings 2008)	x		x		x	x			x			x	x			x	x			x	
Expected changes to technical requirements or specifications during design (McManus et al. 2007; Ross, Rhodes, and Hastings 2008)	x		x	x		x			x	x		x	x			x				x	
Systems where change can have negative impact on safety (risk) or project technical performance, cost or schedule (Chavy-Macdonald et al. 2019; Fitzgerald and Ross 2012a)		x				x		x		x			x		x						

(*continued*).

Table 17. Continued.

Scenario	Change Related System Ilities																				
	Flexibility	Robustness	Adaptability	Modularity	Agility	Scalability	Versatility	Survivability	Evolvability	Modifiability	Reconfigurability	Interoperability	Maintainability	Extensibility	Reliability	Upgradeability	Integratability	Viability	Affordability	Extendibility	Pliability
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 et al. 2012)	x	x	x		x	x		x	x	x		x			x		x				
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)						x		x			x	x			x	x	x				
Complex and highly unprecedented systems (Colombo, Cascini, and De Weck 2016; Fricke and Schulz 2005; Ross, Rhodes, and Hastings 2008)	x	x	x		x	x		x	x	x			x		x						
Systems with external operating circumstances, such as external entities, interfaces and factors that affect system behaviour (Gaspar et al. 2012)		x				x						x	x		x		x				x
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)	x		x			x				x			x		x						x

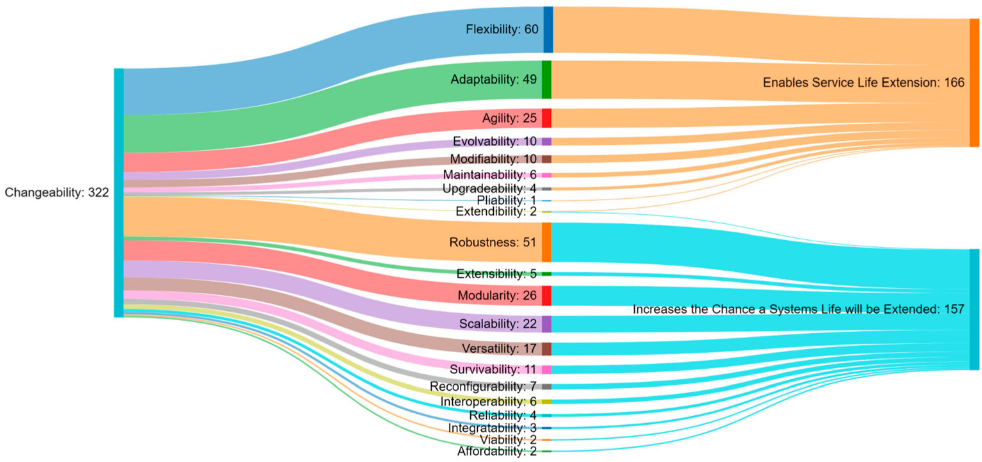

Figure 14. System Ilities (the node number relates to the number of ility references across the 83 analysed publications).

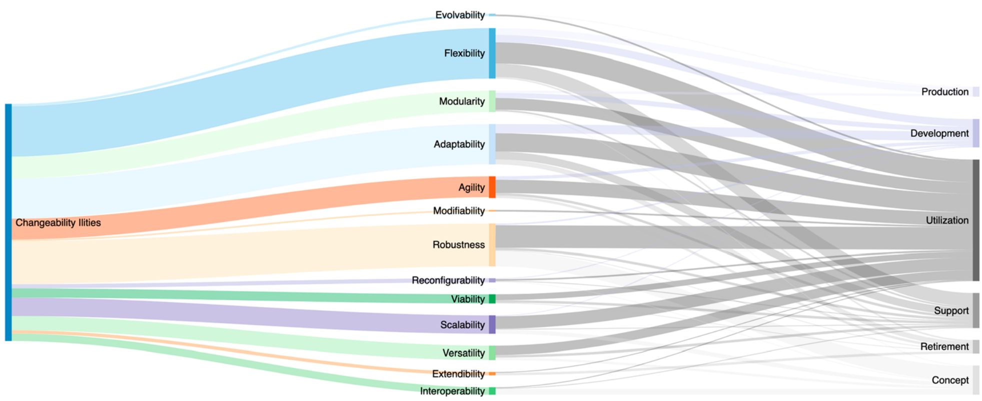

Figure 15. System ility life cycle relationship (the node number relates to the number of articles where the ility was referenced).

The utilisation of case studies and use cases provided and demonstrated real-world applications and lessons for stakeholders, including the implementation and analysis of the methods (Section 3.1.3). By covering multiple sectors (space, aerospace, maritime and other), the literature provides a comprehensive understanding of changeability which allows for a holistic understanding of the concept.

3.2. Results and discussion

The literature review revealed a predominant focus on value extension in the documents analysed. In most instances, the initial costs of implementing changeability in systems were found to be higher when compared to systems that did not incorporate changeability or change-related ilities. However, the long-term benefits of changeability outweighed these initial costs, making it a valuable investment for systems with long lifecycles. This aligns with

Table 18. Applied research and case studies based on stream #4 (49 publications).

Year	Space	Aerospace	Maritime	Other	Occ.
2000				Fricke et al. 2000	1
2004		Eckert, Clarkson, and Zanker 2004			1
2005	Nilchiani and Hastings 2005				1
2006		Ross and Hastings 2006			1
2008	Ross and Rhodes 2008	Ross, Rhodes, and Hastings 2008; Ross and Rhodes 2008; Siddiqi and De Weck 2008		Engel and Browning 2008	4
2009	Roberts et al. 2009	Ewart et al. 2009		Giffin et al. 2009; Rhodes and Ross 2009	4
2010	Silver and Weck 2010				1
2012	Fitzgerald and Ross 2012a; Fitzgerald and Ross 2012b; Fitzgerald, Ross, and Rhodes 2012	Pate, Patterson, and German 2012	Gaspar et al. 2012	Morkos, Shankar, and Summers 2012	6
2013		Kissel and Lindemann 2013; Ricci et al. 2013		Allaverdi, Herberg, and Lindemann 2013; Cardin et al. 2013; Kissel and Lindemann 2013	4
2014	Rader, Ross, and Fitzgerald 2014	Cardin 2014	Niese and Singer 2014; Ricci, Fitzgerald, et al. 2014	Cardin 2014; Ricci, Rhodes, and Ross 2014	5
2015			Davendralingam and DeLaurentis 2015; Keane, Gaspar, and Brett 2015	ElMaraghy and AlGeddawy 2015; Koh et al. 2015; Mekdeci et al. 2015; Miner et al. 2015	6
2016	Broniatowski 2016				1
2017	Corpino and Nichele 2017; Gralla and Szajnfarber 2016			Koh 2017; Schuh, Riesener, and Breunig 2017	4
2019		Enos 2019a; Enos, Farr, and Nilchiani 2019	Rehn et al. 2019	Chavy-Macdonald et al. 2019; Enos 2019a; Wang, Thomson, and Zhang 2019	5
2020		Moallemi, Elsawah, and Ryan 2020			1
2021		Enos 2021		Enos 2021; Hein et al. 2021	2

the system characteristics discussed in Section 3.1.4 and is corroborated by publications that conducted empirical analysis.

A notable finding from the review is that the most frequently referenced 'ilities' are typically associated with higher engineering effort demands. This extends beyond technical

Table 19. Ilities and Key Insights from Applied Literature.

Sector	Most Referenced Ilities	Key Insights
Space	- Flexibility, Adaptability, Modularity, Scalability, Survivability	- Changeability research in space sector is limited and conceptual. - Need for proactive change management in satellite development.
Aerospace	- Robustness, Agility, Versatility, Maintainability, Scalability, Extensibility	- Effective change management crucial for successful aircraft design. - Strategies for managing change in unmanned aerial vehicle (UAV) design. - Identification of factors influencing changeability in aircraft design. -
Maritime	- Adaptability, Modularity, Survivability, Reliability, Interoperability, Maintainability	- Change management challenges in shipbuilding industry identified. - Complexity of change management in maritime sector highlighted. - Importance of modular design for facilitating change in vessel construction.
Other	- Evolvability, Modifiability, Interoperability, Agility, Versatility	- Studies in the 'Other' sector focus on general or conceptual research. - Importance of aligning change management with organisational goals.

requirements to encompass project management, human resource management and process management. This finding underscores the multidimensional nature of system changeability, requiring a breadth of skills and resources beyond engineering (Table 19).

The analysis of the literature facilitated the identification and differentiation of the benefits and limitations of these 'ilities'. Through the combination of multiple ilities the greatest extended value is expected to be possible, however at a high cost upfront due to the number of interfaces, requirements and size of the overall system. While many publications acknowledged the need and potential extended value of various changes throughout a system's lifecycle, few provided a comprehensive view, instead focusing on specific types of changes or effects at distinct lifecycle phases, as shown in Table 20. The table synthesises and illustrates the impact of each 'ility' on the systems lifecycle, and is categorised according to the following:

- **Positive** (+ net increase): This means that the specific 'ility' contributes positively to the system, enhancing its overall performance. For example, 'flexibility' might lead to a net increase in the system's ability to adapt to changes, thereby improving its long-term viability.
- **Neutral** (0 no critical shift): This implies that the addition of the 'ility' doesn't significantly alter the system's performance. For instance, the 'ility' of 'modularity' might not cause a critical shift in the system's development time, meaning it neither speeds up nor slows down the process noticeably.
- **Negative** (- net reduction): This indicates that the 'ility' might detract from the system's performance. For example, 'scalability' could lead to a net reduction in the system's operational costs, but it might also increase the complexity of the system, thereby raising the overall system engineering effort.

The documents identified throughout the review focused mainly on value extending, and while in most cases the upfront costs of changeability were higher than comparative systems (without) the long-term benefits were greater. This is in line with the system

Table 20. Changeability life cycle distribution.

	Total Life Cycle Cost	Total System Engineering Effort	Development Time	Development Costs	# of Recursive levels in the design	# of System Requirements	Requirements Change Management	# of Major Interfaces	Passive Robustness	Active Robustness	Operational Costs	Uncertainty	Maintenance/Support Cost	Life Cycle Extension	# of Operational Scenarios	# and Diversity of platforms
Robustness	–	+	+	+	0	0	+	+	+	+	–	–	–	+	+	+
Flexibility	–	+	+	+	+	+	+	+	0	+	0	–	–	+	+	+
Adaptability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Modularity	–	+	–	+	–	0	0	–	0	0	+	–	–	0	+	+
Agility	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Scalability	–	+	+	0	0	+	+	0	0	+	–	–	–	+	+	+
Versatility	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Survivability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Evolvability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Modifiability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Reconfigurability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Interoperability	–	+	+	+	+	+	+	+	+	+	–	–	–	+	+	+
Maintainability	–	0	0	0	+	+	0	+	+	+	–	–	–	+	+	+
High-Level Changeability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Extensibility	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Reliability	0	0	0	0	0	0	0	0	+	+	–	–	–	+	+	+
Upgradeability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Integrability	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Viability	0	+	+	+	+	+	+	0	0	+	–	–	–	+	+	+
Extendibility	–	+	+	+	+	+	+	+	0	+	–	–	–	+	+	+
Sustainability	0	0	0	+	0	0	0	0	+	+	0	0	0	+	0	0
Pliability	0	+	+	+	+	+	+	0	0	+	–	–	–	+	+	+
Manufacturability	–	0	0	0	0	0	0	0	0	0	0	0	–	0	0	0
Affordability	–	0	0	0	0	0	0	0	+	+	–	–	–	+	+	+

characteristics described in Section 3.1.4 and the publications where true measures were taken. An important finding was that the most referenced ilities, typically have higher engineering effort demands, extending to include project management, human resource management and process management. The high relevance of these management aspects can be attributed among other factors to the fact that many of the researchers focused on conceptual models with limited real application. Leading to human effort being one of the most disruptive and preventive factors for changeability, therefore for future research it is recommended to use indicators beside change options to measure system changeability. Whereby this generalisation can be better analysed to support the real (initial and extended) costs for changeability, and the diagnosability of systems to determine suitable changeability levels according to specific system needs.

3.3. Areas for future research

In this review, it is evident that the concept of changeability has grown and evolved over the past decade. Noteworthy developments of various methods such as the DSM, EEA and ROA have supported industry-driven changeability, and demonstrated promising results.

However, it is clear that further research is necessary to transition the concept from a highly theoretical analysis to one of practical and quantifiable value. Emerging areas of research cover the entire lifecycle, with emphasis on (i) increasing the robustness and transparency of change decisions, (ii) integration of various system models into the design scenario and (iii) balancing the costs and level of changeability for systems. We anticipate based on the literature and evolving landscape of the domain that future research will focus on the following key areas:

(1) **Modelling and Simulation of Change Effects**: Developing advanced modelling and simulation techniques which leverage Model-Based Systems Engineering (MBSE) to predict and analyse the effects of alterations within complex systems represents a crucial field of research. This is particularly vital in changeability research as it provides a structured platform for the simulation and analysis of diverse change scenarios, enabling researchers to predict and comprehend potential impacts of change on system performance, reliability and safety. The ability to evaluate various components and their interactions throughout a system makes MBSE vital to superior planning and decision-making processes, minimising the risks associated with change and leading to the creation of more robust and changeable systems.
(2) **Integration of Change Management Practices:** There is a need for further research on integrating changeability into the design and development processes. This includes studying effective strategies, tools and techniques that can be applied across different industries and sectors. Research into this domain will support in the development of tools, and techniques providing a structured approach to managing change in complex systems with long lifecycles. This can enable industries to navigate change more effectively, leading to improved efficiency, reduced costs and increased competitiveness.
(3) **Integration of Changeability into Design Methods**: Exploring how changeability can be integrated into design methods and frameworks. This involves developing design approaches that inherently support change, allowing for more flexible, adaptable and future-proof systems. Resulting in systems that are inherently more flexible, adaptable and future-proof. Thereby reducing the need for costly and time-consuming changes in the future, providing an effective and efficient means for extending the lifecycle of systems and better value for investment.
(4) **Optimisation of Change Processes**: Future research can focus on optimising change processes by identifying key factors that influence the success of change initiatives. This involves investigating methods for streamlining change processes, reducing rework and enhancing overall efficiency. By identifying such factors and optimising change processes, organisations can reduce rework, save time and enhance overall efficiency. This can contribute to improved project outcomes, increased productivity and better utilisation of resources.
(5) **Evaluation of Changeability Success and Costs**: Developing comprehensive frameworks and metrics to evaluate the success and costs of changeability within in engineering systems is crucial. Future research can focus on identifying indicators and measurement approaches to assess the cost, impact and effectiveness of changeability through a systems life cycle. This can provide a clear understanding of the cost, impact and effectiveness of different system level change initiatives. Enabling organisations to

make more informed decisions, ensuring that resources are used effectively and that changes deliver the expected benefits without unintended consequences.

(6) **Application of Emerging Technologies**: Exploring the application of emerging technologies, such as artificial intelligence, machine learning and data analytics, in modelling and evaluating changeability is an area of growing importance. Advancement and development in this area can result in significant cost savings, improved system performance and the ability to quickly adapt to changing circumstances.

(7) **Human Factors in Change Management**: Understanding the role of human factors in change management is crucial. Future research can explore the psychological, social and organisational aspects of change, including resistance to change, change acceptance and effective communication strategies. This can result in improved change acceptance, reduced resistance to change, ultimately leading to more successful change initiatives.

The aforementioned research areas not only address engineering systems but also take into account the broader stakeholders' requirements and uncertainties throughout a systems lifecycle. Advancements will provide a structured framework for designing and analysing changeable systems, allowing for the systematic consideration of various change scenarios and their impacts. Which can support the design of systems that are inherently capable of changing over time in response to a multitude of various and uncertain conditions/scenarios.

4. Conclusions

The goal of this paper was to analyse the current state of the literature on engineering system changeability, to identify how the concept is analysed, measured and how the ilities both provide individual and combined value to systems throughout their life cycle. Through a systematic literature review based on we identified 83 publications that consider the analysis, measurement and application of changeability across a set of different domains with various ilities. We characterised these publications according to domain to inductively derive the allocation of benefits across distinct life cycle phases. In addressing this paper's research question, our research has extended our knowledge of (1) how changeability is analysed in the domain of engineering systems, (2) the measurement methods applied and (3) the respective life cycle implications of specific change ilities. These three components can help the engineering community and project managers better understand the value, limitations and suitability for implementing/pursuing changeability. The main findings are summarised in the following.

The current state of the literature on changeability has a growing trend, which shows that the concept is both highly relevant todays engineering efforts, and likely to become researched when additional literature is developed to overcome several of the identified gaps. While journals belonging to the field of systems engineering and changeability are numerous, there remains a majority of research being published in international conferences such as INCOSE, ASME and IISE which is not surprising and shows the industrial nature of the field. Amongst these publication areas, it will be necessary for empirical research to begin transitioning and expanding to more practical use cases whereby these results can begin to be further analysed. Finally, among the characteristics of the papers we detected that in some studies there is still a lack of foundational conformity, because the work indiscriminately combines multiple loosely related ilities and terms that effect and relational outcomes.

As a direction for future research, as previously mentioned we suggest expanding the research from theoretical cases with limited complexity to larger more comprehensive analysis. In addition, to obtain more industrially focused and academically valuable research, it is necessary to use the standardisation of terms (e.g. changeability), to use more than one case to justify methods and more diverse industry involvement, bringing forth more than one perspective from different disciplines and life cycle phases, in order to increase the validity of the results. Finally, due to the importance of changeability for complex systems, we recommend increasing research considering the cost implications of change and system performance, and the development of a standardised approach to evaluating which systems are suitable for the inclusion of changeability. The limitations of our paper are focused on the limited number of papers that address changeability in engineering system and in which the most relevant publications originate and are based on a singular method from one research group. For this reason, we hope that this publication can help to broaden the research environment and support the creation of new models, inquiries and use cases.

Acknowledgements

This study was carried out within the MICS (Made in Italy – Circular and Sustaina-ble) Extended Partnership and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004 – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004 [grant number PE00000004].

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Appendix

Author(s)	Year	Stream #1 (33pubs.)	Stream #2 (38pubs.)	Stream #3 (74pubs.)	Stream #4 (49pubs.)	Ref.
Ring	1998			1		Ring 1998
Schulz et al.	1999	1		1		Schulz and Fricke 1999
Fricke et al.	2000	1		1	1	Fricke et al. 2000
Schulz et al.	2000	1		1		Schulz, Fricke, and Igenbergs 2000
Eckert et al.	2004			1	1	Eckert, Clarkson, and Zanker 2004
Clarkson P.J	2004		1	1		Clarkson, Simons, and Eckert 2001
Fricke et al.	2005	1		1		Fricke and Schulz 2005
Nilchiani et al.	2005		1	1	1	Nilchiani and Hastings 2005
Eckert et al.	2006		1	1	1	Eckert et al. 2006
Ross et al.	2006	1		1	1	Ross and Hastings 2006
McManus et al.	2007	1		1		McManus et al. 2007
Silver et al.	2007	1	1	1	1	Silver and Weck 2010
Bahill et al.	2008			1		Bahill and Botta 2008
Engel et al.	2008		1	1	1	Engel and Browning 2008
Ross et al.	2008	1		1	1	Ross and Rhodes 2008
Ross et al.	2008	1		1	1	Ross, Rhodes, and Hastings 2008
Siddiqi et al.	2008			1	1	Siddiqi and De Weck 2008
Eckert et al.	2009		1			Eckert et al. 2009
Ewart et al.	2009	1		1	1	Ewart et al. 2009
Giffin et al.	2009		1	1	1	Giffin et al. 2009
Rhodes et al.	2009	1		1	1	Rhodes and Ross 2009
Rhodes et al.	2009	1				Rhodes, Ross, and Nightingale 2009
Roberts et al.	2009	1	1	1	1	Roberts et al. 2009
Rhodes et al.	2010			1		Rhodes and Ross 2010
Jarratt et al.	2011		1	1		Jarratt et al. 2011
Beesemyer et al.	2012	1	1	1		Beesemyer, Ross, and Rhodes 2012
Fitzgerald et al.	2012	1	1	1	1	Fitzgerald and Ross 2012a
Fitzgerald et al.	2012	1	1	1	1	Fitzgerald and Ross 2012a
Fitzgerald et al.	2012	1	1	1	1	Fitzgerald, Ross, and Rhodes 2012
Gaspar et al.	2012	1			1	Gaspar et al. 2012
Hamraz et al.	2012		1	1		Hamraz, Caldwell, and John Clarkson 2012

(*continued*).

Table A1. Continued.

Author(s)	Year	Stream #1 (33pubs.)	Stream #2 (38pubs.)	Stream #3 (74pubs.)	Stream #4 (49pubs.)	Ref.
Koh et al.	2012		1	1		Koh, Caldwell, and Clarkson 2012
Morkos et al.	2012		1	1	1	Morkos, Shankar, and Summers 2012
Pate et al.	2012			1	1	Pate, Patterson, and German 2012
Allaverdi et al.	2013	1		1	1	Allaverdi, Herberg, and Lindemann 2013
Cardin et al.	2013		1	1	1	Cardin et al. 2013
Chalupnik et al.	2013			1		Chalupnik, Wynn, and Clarkson 2013
Fitzgerald et al.	2013	1	1	1		Fitzgerald and Ross 2013
Kissel et al.	2013		1	1	1	Kissel and Lindemann 2013
Koh et al.	2013		1	1		Koh, Caldwell, and Clarkson 2013
Ricci et al.	2013	1	1	1	1	Ricci et al. 2013
Ryan et al.	2013			1		Ryan, Jacques, and Colombi 2013
Cardin	2014		1	1	1	Cardin 2014
Niese et al.	2014	1		1	1	Niese and Singer 2014
Rader	2014	1	1	1	1	Rader, Ross, and Fitzgerald 2014
Ricci et al.	2014		1	1	1	Ricci, Fitzgerald, et al. 2014
Ricci et al.	2014	1		1	1	Ricci, Rhodes, and Ross 2014
Tackett et al.	2014		1	1		Tackett, Mattson, and Ferguson 2014
Altenhofen et al.	2015	1	1			Altenhofen, Oyama, and Jacques 2015
Davendralingam et al.	2015				1	Davendralingam and DeLaurentis 2015
ElMaraghy et al.	2015		1		1	ElMaraghy and AlGeddawy 2015
Keane et al.	2015	1		1	1	Keane, Gaspar, and Brett 2015
Koh et al.	2015		1	1	1	Koh et al. 2015
Mekdeci et al.	2015	1		1	1	Mekdeci et al. 2015
Miner et al.	2015			1	1	Miner et al. 2015
Ross et al.	2015			1		Ross and Rhodes 2015
Broniatowski	2016			1	1	Broniatowski 2016
Colombo et al.	2016			1		Colombo, Cascini, and De Weck 2016
Corpino et al.	2017		1	1	1	Corpino and Nichele 2017
Enos et al.	2017			1		Enos, Farr, and Nilchiani 2017
Gralla et al.	2016				1	Gralla and Szajnfarber 2016
Koh	2017		1	1	1	Koh 2017
Schuh et al.	2017		1	1	1	Schuh, Riesener, and Breunig 2017
Sullivan et al.	2018	1		1		Sullivan, Rossi, and Terzi 2018
Turner et al.	2018		1	1		Turner, Monahan, and Cotter 2018
Avalos et al.	2019	1		1		Avalos, Grenn, and Roberts 2019
Chavy-Macdonald et al.	2019			1	1	Chavy-Macdonald et al. 2019
Enos	2019			1	1	Enos 2019a
Enos et al.	2019			1		Enos, Farr, and Nilchiani 2019
Enos J.R.	2019			1	1	Enos 2019b
Rehn et al.	2019		1	1	1	Rehn et al. 2019
Ross et al.	2019	1		1		Ross and Rhodes 2019
Rousseau	2019			1		Rousseau 2019
Sullivan et al.	2019	1		1		Sullivan et al. 2019
Wang et al.	2019		1		1	Wang, Thomson, and Zhang 2019
Allaverdi et al.	2020		1	1	1	Allaverdi and Browning 2020
Arjomandi et al.	2020			1		Arjomandi Rad, Stolt, and Elgh 2020
Bashir et al.	2020		1	1		Bashir and Ojiako 2020
Douglas et al.	2020	1		1		Douglas, Mazzuchi, and Sarkani 2020
Moallemi et al.	2020	1		1	1	Moallemi, Elsawah, and Ryan 2020
Obieke et al.	2020			1		Obieke, Milisavljevic-Syed, and Han 2020
Enos	2021		1	1	1	Enos 2021
Hein et al.	2021		1	1	1	Hein et al. 2021