HOW IS SYSTEMS THINKING TAUGHT? A LITERATURE REVIEW

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ABSTRACT
With a growing demand by industry and society for systems thinking skills and capabilities, there is a pressing need to ensure that there are appropriate educational strategies to address this gap in skills. Systems thinking, an integrated approach to understanding complex issues, is essential for stimulating critical thinking and preparing engineering students to navigate contemporary challenges. Despite its recognised importance, few studies provide an in-depth analysis of the efficacy of teaching methods in developing systems thinking competencies. This paper addresses this gap by presenting a systematic literature review of systems thinking educational studies from 2000 to April 2024, specifically focusing on (i) how systems thinking is being taught and (ii) the content and teaching methods that are used to teach this subject. Our review of 57 articles reveals that most systems thinking teaching methods consist of brief, activity-based interventions, typically lasting one to few days, and are predominantly applied in higher education and engineering contexts. These findings are discussed, and we propose a set of guidelines for future research to advance systems thinking in design and engineering education and enable capacity building of systems thinking skills and competencies.

Keywords: System thinking, literature review, education

1 INTRODUCTION
System thinking (ST) is a holistic approach employed to improve the capability for identifying and understanding the interconnection and complexity of a system's elements, rather than analysing them in isolation [1, 2]. ST applied in education is of utmost importance. This integrated approach is essential for promoting meaningful learning, stimulating critical thinking, and preparing students to face the complex challenges of the contemporary world [1, 3].

To support the development of system thinkers, student's characteristics, skills and abilities should be improved when teaching ST. Characteristics refer to dispositional traits such as openness to complexity and tolerance for ambiguity, which shape how students engage with systemic problems. Skills encompass the practical techniques of systems thinking, such as identifying feedback loops, constructing stock–flow diagrams, and using modelling tools. Abilities reflect the capacity to integrate and apply these skills in the real-world [4]. Tools such as stock–flow diagrams (SFD) and system dynamics models are often applied in ST teaching [5]. SFD are visual representations that help illustrate how the different parts of a system are interconnected. System dynamics models are mathematical and computational representations of complex systems that incorporate feedback loops, time delays, and interdependencies among the system's components. These tools, combined, enable students to visualise system structures, convert qualitative insights into quantitative models, and interactively experiment with dynamic scenarios.

Although the theoretical background of ST in education is rooted in studies from the 1950s to the 2000s [2, 4, 6], authors agree that the recent increase in the number of publications on system thinking demonstrates that the interest in the field has also increased [1, 3, 7-9]. The use and research on ST span several domains, such as engineering, business and management, medicine, and social and computer sciences [3, 9]. Several review and bibliometric studies have been carried out, focusing on the use of systems thinking in the general educational context [3, 9], in science education [7], in STEM education [10], in primary education [8] and about curriculum and pedagogy [1].

Despite the importance of ST in education the academic literature on the topic still needs to be improved. Currently, most research focuses on measuring the benefits of ST in education with a clear gap in the literature on how ST is being taught in regard to the curriculum design (e.g. activities, courses, award programmes) and the specific content and pedagogical methods used to teach the topic. This lack of guidance prevents ST from becoming an effective tool for educational transformation. In this context, the present study aims to discuss through an analysis of the current literature, how ST has been applied in education and the content associated with its teaching. A systematic literature review of system thinking studies, from 2000 to April 2024, is presented with a focus on answering how and what is taught in ST education.

2 METHOD

For this research, we adopt the eight-step methodology proposed by [11] for conducting a systematic literature review (SLR). The steps are: (i) Planning and formulation of the research problem; (ii) Literature search; (iii) Data collection; (iv) Quality assessment; (v) Data analysis and synthesis; (vi) Interpretation of results; (vii) Presentation of results; and (viii) Updating the review. This SLR aims to explore the content and methods used for teaching ST. For the second step, our choice of databases fell on Scopus and Web of Science (WoS) as the key databases. The search strategy incorporates two distinct groups of keywords: the first centred on "system thinking" and the second on "teaching": (“system* thinking*” OR “system theory”) AND (teaching OR student* OR curricula OR curriculum OR education). The search was restricted to the titles. The search was conducted on April 2024, considering studies from 2000, the year of Sterman’s seminal work of ST [4]. The initial search yielded 497 results in Scopus and 316 in WoS. After removing duplicates, we were left with a total of 504 papers. The abstracts of these papers were analysed based on predefined inclusion and exclusion criteria, i.e. studies that discuss the ‘what’ (content) and ‘how’ (methods) for teaching ST are included in the final list. Book chapters, studies about grey system theory and/or with a conceptual focus of ST and about grey system theory were excluded as well as were not considered. A total of 123 papers were selected after reviewing the abstracts. After the review of the full papers, using the same criteria as in the previous stage, 57 studies made the final list.

3 RESULTS

The literature review shows a crescent increase in ST papers: about 77% of the studies were developed after 2015 (Figure 1). This finding is aligned with [3, 8, 9]. In 2015, the declaration of "The Education 2030 Framework for Action", highlighted ST as one of the eight key competencies to accomplish 17 Sustainable Development Goals. This had a significant impact on the increase on ST research. The popularity of ST research has increased in the context of concepts such as “sustainability education” and “sustainable development” [3]. This is supported by our review with 63% of the studies (36 papers) directly related to sustainability.

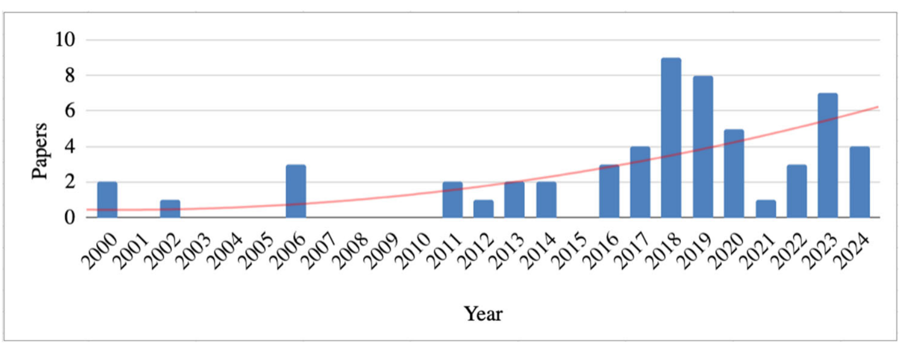

Figure 1. Number of ST papers over the years

The United States of America (USA) is the most prominent country, with 48% of the portfolio studies, followed by Israel (9%) and the United Kingdom (7,7%) (Figure 2a). The academic literature also pointed the USA as the country with the highest number of publications [8, 12]. Overall, the United States' leadership in ST studies stems from a combination of historical and institutional factors that have supported the development and dissemination of this approach. Government policies and the work by leading organisation in this area (e.g. National Aeronautics and Space Administration, Massachusetts Institute of Technology) would partly explain the US's research strength in this area. About level of education, 65% of the studies focus on higher education or university level (Figure 2b).

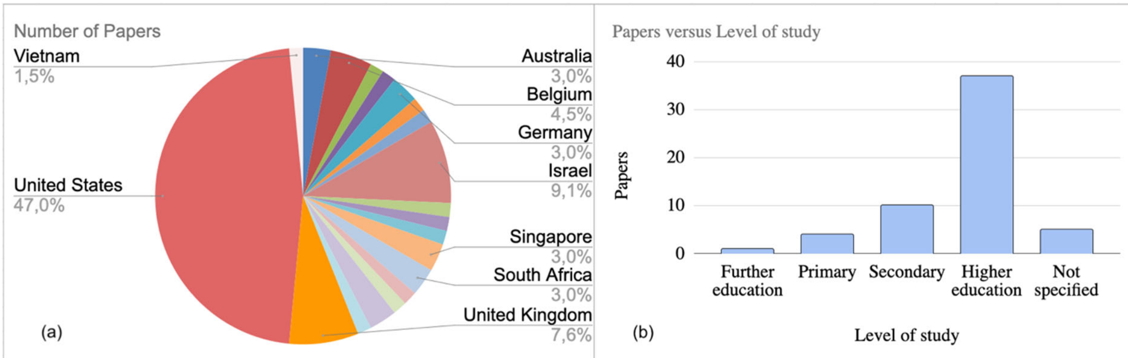

Figure 2. Number of papers by country (a) and number of papers by levels of study

In regard to disciplines, ST is mostly studied in Engineering (23%), Science (15%), and Chemistry (14%) (Figure 3b). These results are aligned with the findings from [3]. According to the authors, chemistry education and STEM (science, technology, engineering, and mathematics) are hot topics in current ST research. Hossain et al. (2020) [12] analysed system thinking literature from 1991 until 2018. At the time, Business, Management, and Social Sciences were the main disciplines contributing to ST research. This shows a change in the disciplinary focus of ST in the last years. Health science as an emergent topic was also cited by [3]. In our study, health science appears in 2% of the review, which indicates that studies about ST and health science are relatively limiter in their focus on the content and methods of teaching ST. In relation to curriculum design, our review shows that ST has been taught using class activities (a day or few days), projects (weeks), modules (semesters) and full courses (years). Our results indicate that activities (40%) are the predominant way of teaching ST, followed by projects (23%) and modules (23%). Courses represent only 7% of the studies (Figure 3a).

Engineering is the discipline that most includes teaching ST (24% of the selected papers). However, differently from the other disciplines, ST in engineering is teaching predominantly through modules (11 papers), i.e. [13, 14], followed by projects (5 papers) (i.e. [15,16]); activities (4 papers) (i.e. [17, 18] and course (1 paper [19]). An explanation for this would the relevance of 'system engineering' as a specific subject area in the design and manufacturing of complex engineering solutions and the need to integrate this knowledge in the curriculum of engineering degrees.

Science and chemistry education (note that the literature makes a differentiation of these two disciplines) stands in the second position in the number of papers. Science addresses a major topic in the primary school years. In science curricula, authors agree that there is a gap of a system perspective for problem-solving. The most ST components are at the introductory level science curricula and textbooks. It does not develop students' skills to understand the aspects of interactions. In chemistry education, studies about system thinking became prominent following the Systems Thinking in Chemistry (STICE) project established by the International Union of Pure and Applied Chemistry (IUPAC). As part of the project, a system thinking special edition of the Journal of Chemical Education was published in December 2019, explaining the increase in publications. Recently, the literature has presented approaches to develop ST in general chemistry [20]. Sustainability challenges are the main focus of ST education in chemistry, science, biology and geography.

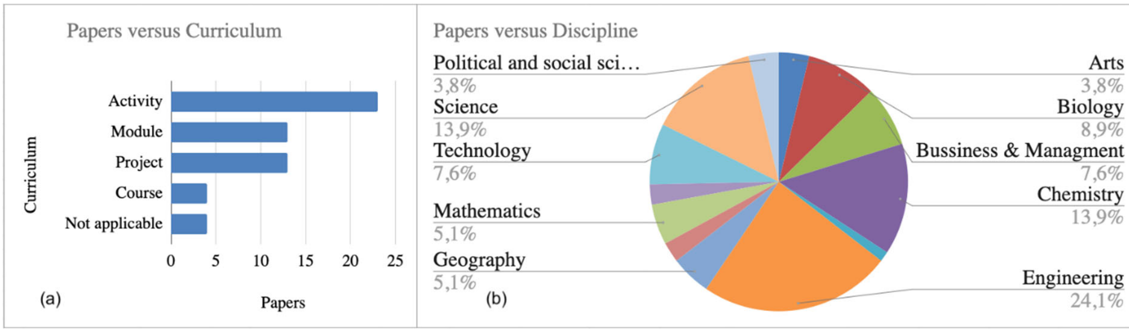

Figure 3. Number of papers by curriculum (a) and of number of papers by discipline

There is only one paper that addresses ST in the design discipline [21]. The authors discussed a cross-disciplinary course for undergraduates from Engineering, Design & Architecture, Education, and Business/Economics. This is an interesting finding given some of similarities between design thinking and ST and the calls for a better integration of these two approaches.

4 DISCUSSIONS

Higher education seems to be an appropriate level of education for developing, testing, and applying ST methodologies, due to the complexity of the subject and its interdisciplinary nature. However, teaching ST from the earliest school years would offer numerous benefits beyond intellectual development. It prepares children to deal with complexity, solve problems creatively and critically, understand global interconnections, develop social and environmental responsibility, and foster collaborative and innovative skills that will be essential in the future. According to [22] continuum of ST teaching from kindergarten through grade 12 is ideal. Starting early builds a shift in student thinking that contributes to recognising and analysing dynamic-multidisciplined scenarios. The author highlights that deeper learning only occurs when students actively engage in constructing their understanding of dynamic behaviour by creating stock-flow diagrams and developing system dynamics models. Therefore, it is essential to have students create models as part of a ST curriculum continuum.

In a context where ST has been taught mostly through activities, evaluating how an isolated activity contributes (or not) to the students' ST skills in the long term is important. However, no studies were found that evaluated the contribution of an activity sometime after its application. Teaching ST in a single activity can be challenging, as this type of approach requires a deep understanding of interconnections, feedback and dynamic interaction. While one activity may introduce the basics of systems thinking, truly developing ST skills demands continuous practice and multiple opportunities to apply the concepts. There is uncertainty in the application of ST and the extent of learning. The terms “characteristics”, “skills” and “abilities” were often used interchangeably [23], which contributes to the ambiguity in defining specific learning outcomes for ST education.

Within the engineering discipline, students should engage with the understanding of systems through the perspective of different lenses in engineering programmes [24]. However, evidence shows that ST is still not extensively taught in undergraduate engineering curricula [17, 25]. This is also reflected in practice, where often engineering and design failures were associate with lack of ST. Those failures were the result of limited understanding of planned and unplanned interrelationships of system components [26].

5 CONCLUSIONS

The literature presented in this paper provides an analysis of the content and methods for teaching system thinking. The study has several limitations, most importantly (1) a broad focus across academic disciplines which can limit the depth of insights and relevance to each discipline, and (2) the analysis of only paper titles in the first stage of the filtering process of the literature given that system thinking as a topic is often dealt with from different perspectives and using different terminology. Whilst the literature review study presented in this paper did not focus on specific academic disciplines, there are several key insights for systems thinking education in design and engineering:

- ST education remains limited in the engineering curriculum even if the literature suggest that it is the academic discipline where teaching of ST is most prevalent. Recent studies from organisations such as the Royal Academy of Engineering UK and Engineers Without Borders highlight the need to better develop and integrate the development of ST competencies to ensure that future engineers can meet the demands on industry and society.

- The literature review shows that specific (and often isolated) activities are the dominant method for teaching ST. A current challenge to ST education is therefore the lack of on end-to-end approach within the curriculum. In that respect, the development of leaning journeys/curriculum maps for ST education in design and engineering can play an important role in ensuring that future engineering graduates gain the required level of ST competencies. Learning journeys are structured, progressive educational pathways designed to build ST competencies over time. Instead of treating ST as a one-off or isolated subject, a learning journey integrates it longitudinally and transversally across the curriculum, allowing students to gradually deepen their understanding and skills in dealing with complex systems. Learning journeys would provide guidance in curriculum design and pedagogical methods at different stages of engineering degrees (ideally from early school years to advanced studies). Future research should focus on the development of such learning journeys.
- Further research is necessary to evaluate the effectiveness of current (and future) provision of ST education within the engineering and design curriculum. In doing so, it will be important to take a long-term approach to the evaluation, looking at the impact of the ST education several years from graduation. Of particular interest would be a more detailed analysis of different pedagogical approaches and teaching methods for teaching ST.
- The integration of design thinking and ST is of particular interest as an area for further research due to the strong complementarities between the two approaches. For designers (and engineers for that matter) to be truly transformational in tackling complex societal challenges it is imperative to develop SR competencies. Future research should focus on the analysis of design curricula with a view of integrating the development of advanced ST competencies.
- There are few studies on ST education from developing countries. These countries often face more complex socio-economic challenges which call for greater ST skills and competencies amongst its population. A better understanding on how ST is taught within the curricula of engineering (and other disciplines) within these countries would be highly relevant.

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