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Design Science in Engineering Education Research

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My research interest concerns the effects of brief, integrated information literacy education on undergraduate students' research behavior. My teaching experience consists of over 30 years of information literacy education within higher education. Over the years, the content and educational methods have changed greatly. We have moved from library user education to teaching students to understand their information need as part of their research problem. Digitalization has changed teaching methods from plain classroom teaching to using a wide variety of different tools and learning platforms.

Design science in Engineering Education Research

Introduction

Design science, design research, design-based research, design science research, and design experiments are terms used by different research communities to describe a somewhat similar process. In this inquiry process new knowledge is created through application of scientific theories, and systematic design, as well as collecting evidence of the quality and results of the design process. Probably the most known articulation of this process was presented by Herbert Simon in his book *The Sciences of the Artificial* published for the first time in 1969 [1]. Simon suggested that the paradigm of design science is much applied in engineering.

Even though design-based research is included in the taxonomy of keywords for engineering education research as one of the twenty-six terms under the category of research methods [2], [3], one rarely sees the engineering research explicitly described in those terms.
In the early 2000s, the ideas of design science were actively discussed in many disciplines outside engineering. In management sciences, the design science approach was suggested to be a valuable addition to contemporary research methodologies [4], and in information systems research it was argued to be one of the two paradigms characterizing the research in the field [5]. In learning sciences, the concept was introduced already in the 1990s, and a decade later a vivid discussion continued regarding the role and added value of design experiments, design research, and design-based research for educational research [6], [7], [8], [9].

Both in the management science and learning sciences, the need for design science is justified with bridging of practice to theory, thereby advancing practices alongside theories. In learning sciences, the design experiments are seen as a means of studying learning phenomena in the real world instead of the laboratory, thus arriving at better understanding of the contextual aspects or learning and enabling the establishment of better learning conditions. Like educational research in other disciplines, also engineering education research (EER) often aims at improving the learning environments and learning conditions of students.

Although design science may not be an explicitly known research paradigm to many engineering educators, many of its principles are implicitly present in engineering research and thus familiar to them. This creates a potential for bridging not only educational theory and practice, but also practices of engineering education research and engineering research. However, for design science to be a useful tool for engineering education researchers, there needs to be some level of shared understanding about the meaning and use of central concepts and the nature of the inquiry process. Moreover, the differences between design science as a research method and engineering design as the content or method of teaching should be acknowledged. This research aims to contribute to these aspects at both the theoretical and the empirical level.

This paper presents a systematic literature review of the explicit use of the design science methodology in engineering education research. In addition to understanding how widely the approach is known within the community, the study explores how this research approach is used, described, and justified in the EER literature. First, the concept of design research as a research methodology is discussed at a general level and with respect to engineering education research. Then, the methodology applied and the process of inquiry are described. After that, the results of the systematic literature review are presented and discussed. Finally, the paper is concluded with some recommendations regarding the use of the design science approach in engineering education research.

Design, science, and research

Design, science, and research relate to each other in multiple ways. Cross [10] distinguishes between scientific design, science of design, design as a discipline, and design science. In his terms, scientific design refers to the modern design practice, where design activity is based on scientific knowledge. The science of design, on the other hand, refers to activities of scientific inquiry that improve our understanding of design. For Cross, design as a discipline means design studied on its own terms and within its own culture. Finally, by design science he refers to a rational and systematic approach to design, which not only uses the scientific knowledge of artifacts but, in some sense, is a scientific activity in and of itself.

Although Cross states that the concept of design science as a scientific activity is controversial and challenged by many designers and design theorists, it seems to be accepted by many scientists, who have perceived the opportunities of creating scientific knowledge through the combination of processes of systematic design and inquiry. Hevner et al. [5] describe the research on information systems as a process consisting of two complementary phases. First, behavioral science defines the identified business need through the development and justification of theories, and then, design science meets the identified needs through building and evaluation of artifacts [5]. In management science, Van Aken [4] perceives design science research objectives as tested and grounded technological rules, whose creation includes the processes of discovering the rule, by grounding it in scientific knowledge and testing its effectiveness. Holmström, Ketokivi, and Hameri [11] view the knowledge creation process in design science for operations management as a process whereby a solution is first created and then studied to develop a formal theory.

In educational science, the development of a new methodology based on studying educational interventions originated in the 1990s [7]. The methodology was originally called design experiments. Design experiments used a progressive refinement approach in which the original design is revised "until all the bugs are worked out" [7]. However, refining the practice alone was not sufficient, but the study also had to address theoretical questions and aim at simultaneously developing both theory and practice. The Design-Based Research Collective [6] chose to use the term design-based research methods instead of design experiments to "avoid invoking mistaken identification with experimental design, with studies of designers, or with trial teaching methods" [6]. Further, they stress that design-based research goes beyond just designing and testing interventions by having interventions to embody theoretical claims about teaching and learning, and the research of interventions contributing to these theories.

Design science bears many similarities to action research, and it has even been suggested to be totally similar [12]. Action research has been characterized as "an umbrella term for a host of activities intended to foster change on the group, organizational, and even societal levels" [13]. As illustrated above, also design science is a broad term with different foci and emphases depending, e.g., on discipline and type of intervention. Hence, also the question of similarity or dissimilarity between action research and design science depends on how both methodologies are understood and what aspects are considered. In the Lewinian tradition, action research typically involves participants as research teams who address problems in their surroundings, and act as co-researchers who engage in a reflexive dialogue with the actual researchers [13]. This aspect of action research is not essential in design science, where participants may be just users of the created artifacts or pupils engaging normally in class-room activities. In a similar vein, Iivari and Venables analyze the paradigmatic assumptions behind action research and design science research and conclude that there may be no significant overlaps between the two research methodologies [14]

Design science and engineering education research

Engineering design is a central part of engineering curricula and engineering educators constantly design learning environments, learning experiences, and teaching practices. Traditions like Mudd Design workshops have brought together "engineering faculty, with important intellectual content on a variety of topics in engineering design education" for more than twenty years [15]. These communities are likely to be interested in scientific design as the content of engineering education or an instruction method, the science of design in improving the methods of engineering design, or engineering design as a discipline with specific traditions and culture. Nevertheless, design research as a framework to study engineering educators' own teaching (in the field of engineering design) is but one option among the engineering education research methodology.

Design science does not appear to have a strong presence among the explicit research methods or methodologies applied in engineering education research. Neither does it show up in the academic discussions about the methodologies appropriate for engineering education research [16], [17], [18]. It seems, however, not entirely unknown to the engineering education research community and was addressed for example in the special issue of the European Journal of Engineering Education on research methodologies that link theory and practice [19], [20], [21]. In a mapping study of applications of the Maker movement in electrical engineering education, Martinez-Lopez [22] discovered twenty peer-reviewed journal articles or conference papers following the design-based research approach published between 2000 and 2018. However, the interpretation of the research method as design-based research was done by the author of the mapping study and not the researchers reporting the original studies, and hence, it cannot be deducted how explicit the use of the methodology was.

Further evidence of the implicit presence of design science in engineering education research can be found from the research of Malmi et al. [23]. In their methodological analysis of research papers in the European Journal of Engineering Education, they discovered that the most commonly used research strategy was constructive research, which was used in 28% of the papers. The researchers defined constructive research as "research that aims to demonstrate and/or evaluate the feasibility of a proposed idea" [23]. Constructive research was found to be more typical for case reports than empirical papers. The reporting of methodology was considered weak in all the papers, with only 14% of the papers explicitly presenting and discussing methodology, but even weaker in case reports than in empirical papers. [23] All this implies that research strategies with features of design science are employed in engineering education research, but rarely named or discussed explicitly.

Researchers explicitly referring to the use of design science methods in their engineering education research have at least two different rootings of the method: some reference mainly the methodology discussions in educational science [20] whereas others ground their inquiry process more in the design science literature from the engineering design or information systems design research [19]. The extent to which the researchers show familiarity with the use of design research in different disciplines varies.

Methods

The systematic literature search proceeded by steps common to most literature review methods as identified by Dresch et al. [24]. The process started with the definition of the conceptual framework and the review question: How widely and in what manner is design science used as a research method in the engineering education research literature? A research strategy was devised, and the search conducted accordingly. The strategy is outlined in Fig. 1. After the eligibility judgement of the search results, the primary studies were coded, the results were synthesized, and the quality of the results was assessed.

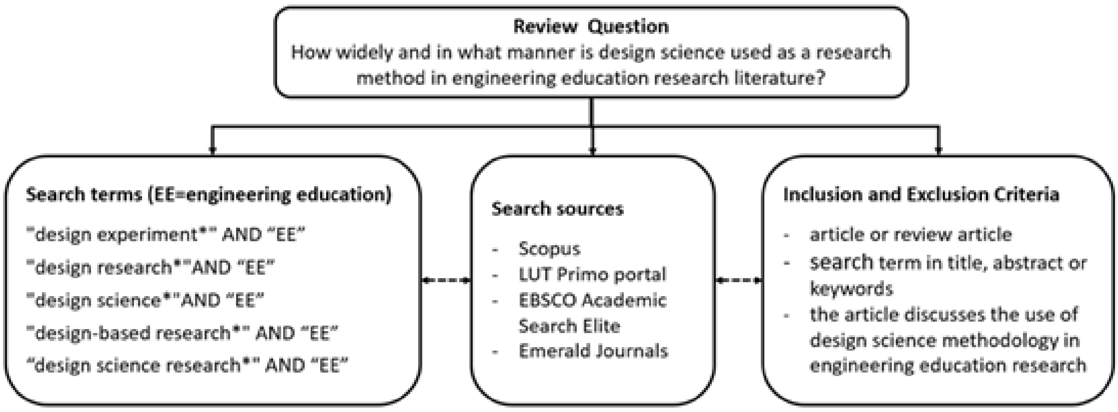

Fig. 1. Information search strategy for a literature review adapted from Dresch et al. [24]

The authors' core organization offers its staff a wide variety of high-quality research databases. Therefore, processing of the literature review started with selecting the most comprehensive search sources. To find applicable research literature, the search was originally planned to cover the Scopus, EBSCO Academic Search Elite, and Emerald Journals databases and the authors' core organization's library portal LUT Primo.

The selected sources have a wide coverage of research literature and engineering science. Scopus is a comprehensive scientific, medical, technical, and social science abstract and citation database. EBSCO Academic Search Elite is a general academic index that indexes thousands of magazines and journals from every academic discipline and provides thousands of full-text articles. Alternatively, Emerald Journals gives access to peer-viewed full text articles on a wide variety of topics including engineering. LUT Primo is the information retrieval portal of LUT University. It offers access to the LUT Academic Library printed and electronic collections and all databases available for the LUT scientific community.

The first searches were performed in Scopus and LUT Primo using five queries:
"design experiment*" AND "engineering education"
"design research*" AND "engineering education"
"design science*" AND "engineering education"
"design-based research*" AND "engineering education"
"design science research*" AND "engineering education"

The search terms were derived from the design research literature in different disciplines.

Scopus and LUT Primo were searched without limiting the time frame. The Scopus search covered the abstract, title, and keywords while the LUT Primo search looked for the search terms in all available data. Scopus, as well, allows the searcher to browse all available data, but that kind of search returns also hits where the search terms are, e.g., in the journal title while the document itself does not discuss the desired topic. Alternatively, LUT Primo does not allow an explicit search in the abstract, title, and keywords. Therefore, “All available data” was the only option to focus the search.

In addition to Scopus and LUT Primo, the same searches were performed in the EBSCO Academic Search Elite and Emerald Journals databases. The retrieved contents of the references in EBSCO and Emerald did not discuss higher education and were therefore classified as irrelevant for the purposes of this paper. Search results showed that Scopus returned significantly more conference papers than peer-reviewed articles in nearly all the queries. However, in LUT Primo results the conference paper/peer-reviewed article ratio was the opposite: there were more articles than conference papers in the result sets. The search results are presented in Table 1.

Table 1. Search results from different databases by the search terms used

AND “engineering education”	Scopus articles	LUT Primo articles	Scopus conferences	LUT Primo conferences
"design experiment*"	19	183	91	24
"design research*"	32	529	163	87
"design science*"	15	246	49	29
"design-based research*"	34	140	101	40
"design science research*"	6	39	6	3

The aim of this research is to discuss the use of design science methodology in engineering education research. To find research papers and to avoid retrieving unrelated documents, such as practice papers, theory to practice papers, and work in progress papers, the searches were limited to journal and review articles.

Scopus offers practical tools for limiting search sets to journal and review articles. However, although LUT Primo allows limiting to peer-reviewed journals and to article as the publication type, the search tool does not support limiting to abstract, title, and keywords, and therefore, the result is not in line with the Scopus result. A comprehensive supply of scientific literature references in Scopus and its effective search tools led to the decision that the searches are performed solely in Scopus.

The database search resulted in 98 peer-reviewed journal articles, which were then screened for the research method used and the educational target group (research scope) to ensure that only papers using design science as a research method and papers dealing with some form of engineering education were included. As computer science and computer engineering are often difficult to separate, also the studies of computer science teaching were considered engineering education. The selection procedure is illustrated in Fig. 2, and the final sample included 32 peer-reviewed journal articles.

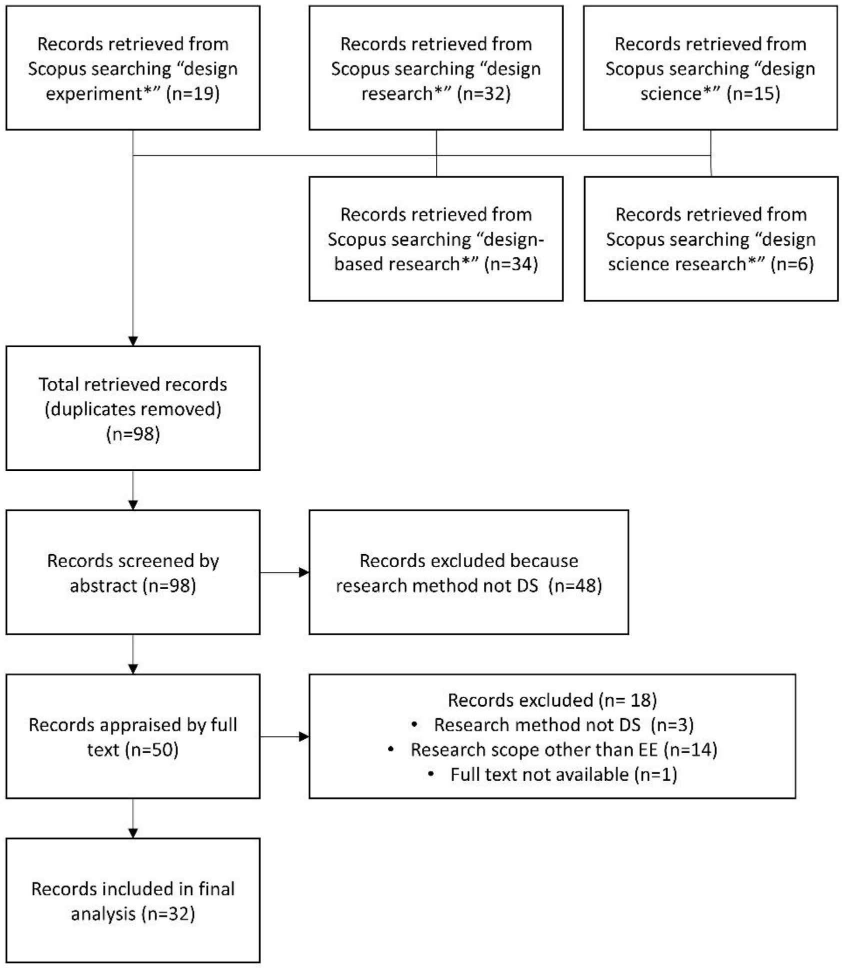

Figure 2. Flowchart for article selection

In the final analysis, the papers were screened for their year of publication, the publication journal, the origin of the authors by the home country of their institution, the target group of the presented educational intervention, and the appearance and use of the design science search terms in the text.

Results

The analysis of the final sample of 32 peer-reviewed journal articles resulted in the following findings. These primary studies are listed in Appendix 1. The timeline of the articles starts from 2005, with only a very moderate growth for more than ten years and a more substantial increase in past three years. As the literature search was conducted in autumn 2020, when all the papers published in 2020 were not yet available, it is likely that the number for 2020 does not represent the full number for that year. Using the Scopus “Analyze search result” tool, the number of yearly published research articles (2010–2019) using the query “design science” AND “engineering education” and the number of articles retrieved by a search using the phrase “engineering education research” were compared. From Fig. 3, we can deduct that some of the growth can probably be related to the growth of the publication volumes. However, the number of articles in the sample is still so small that no reliable conclusions of the publishing trend or the explanations behind it can be presented.

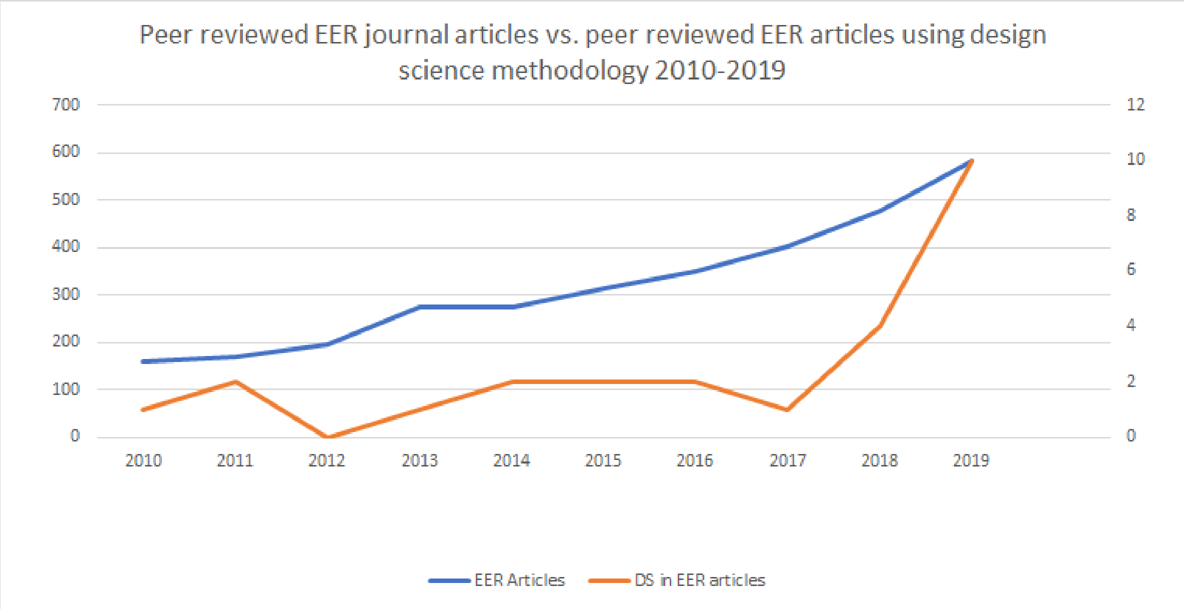

Figure 3. Peer-reviewed EER journal articles (left vertical axes) vs. peer-reviewed EER articles (right vertical axes) using design science methodology for the period of 2010–2019

The articles were published in twenty different journals with six journals having published more than one of the articles in our sample. The journals and the distribution of articles are shown in Table 2. It should be noted that three of the articles were published in a special issue of the European Journal of Engineering Education on research methodologies that link theory and practice. About two-thirds of the articles presented interventions conducted in university-level engineering education. Seven of the studies were related to computer science and six to teaching engineering subjects in primary or secondary education (K-12 engineering). One of the articles addressed a study conducted in higher engineering education and computer science, and one presented a study involving both higher-level and K-12 engineering education.

Table 2. Summary of the final analysis results of the articles included in the study

Publication Journal		***Scope of intervention***	
European Journal of Engineering Education	6	Engineering education	21
Computer Applications in Engineering Education	3	Computer Science	7
International Journal of Engineering Education	3	K-12 engineering	6
IEEE Transactions on Education	2		**34**
Journal of Engineering Education	2		
Journal of Systems and Software	2	***Location of the authors' institution(s)***	
Advances in Engineering Education	1	Europe	13
British Journal of Educational Technology	1	North America	12
Computers and Education	1	Asia	10
Design Studies	1	South America	1
Early Childhood Education Journal	1		**36**
Education for Chemical Engineers	1		
Educational Technology and Society	1	***Terms used for DS***	
IEEE Transactions on Learning Technologies	1	design-based research	20
Journal of Information Technology Education: Innovations in Practice	1	design experiment	10
Journal of the Learning Sciences	1	design research	10
Lecture Notes in Computer Science	1	design science research	4
Mathematics	1	design science	3
Telematics and Informatics	1		**47**
ZDM - Mathematics Education	1		
	32	***Use of DS methodology***	
		Explicit	19
		Implicit or Unclear	8
		Combined	5
			32

The papers came from all over the world. The geographical background of the author was assigned according to the location of the home institution of the authors. In twenty-eight papers, all the authors came from institutions in the same country. Four papers had several authors, from two different countries. Six of the European papers came from the Nordic countries, and with one exception, the North American papers came from the USA. Eight of the Asian papers originated from the Far East and two from the Middle East.

The use of terminology to define or describe the research approach was diverse. All the search terms used were present, with eleven papers featuring more than one of them and twenty-one papers sticking to one of the terms. One paper introduced all five search terms used and explained their usage with respect to each other. The other papers using more than one of the search terms contained several kinds of combinations of usually two of the terms. Hence, no two terms seem to be especially strongly related to each other. The use of different terminology does not appear to correlate strongly with the publication time, although the oldest papers—published before 2011—may contain somewhat more variation and parallel use of several terms than the newer ones. The terminology does not appear connected to the continents or different educational scopes either. However, the K-12 papers are missing the terms design science and design science research.

In nearly two-thirds of the papers, the design science was clearly explicated as the main research approach, methodology, or method. Five papers described the method used as a combination of design research with something else, usually a case study. In two of these papers, the design science seems to refer to a development of an information system or a computer application, which is then studied by means of a case study. In two other papers, the design science terminology appears to relate to a design of a teaching intervention, and in the last paper, possibly to design of both, pedagogical design of a tool and an intervention. Eight of the papers were somewhat unclear as to how the research was actually conducted. These were categorized as implicit or unclear. Most of these papers carried no references to the literature of design science methodology in any scientific discipline. In one of the papers, the term design research seems to refer to "science of design" [10] and in another paper, the term design experiment is used to describe a design task done by the pupils, not the educational design of the intervention. In two of the implicit/unclear cases, the design science terminology seems to refer to an information system or tool used in teaching, in four cases to a pedagogical model or learning tasks used, and in two of the cases the use of the term was expressed so vaguely that it could not be characterized at all.

Discussion

It seems that design science is a research approach or research methodology somewhat known also in engineering education research all over the world. It is used to study higher engineering and computer science education but also the K-12 education of these disciplines. Although the approach is not very widely used—at least by its name—recent years have shown increasing numbers of publications using the methodology. Martinez-Lopez observed a moderate increase in the interest of the academic community in design-based research on Maker activities in electrical engineering education since 2012 [22]. In her study, however, the mapping of design-based research studies was done based on the researcher's interpretation about the nature of the research, and thus, the studies in her sample were not necessarily explicitly conceptualized as design research studies by the authors. Together, these studies suggest a moderate increase both in the use of design research methodology in engineering education research and in awareness of the terminology and the methodological literature around the method.

Many engineering education papers published about a decade ago were observed to follow a constructive research strategy, which aims at testing and evaluating constructs [23]. Another implication of the existence of studies representing design science approach in engineering education research are the conference paper categories reserved for this kind of papers. For example, the ASEE Educational Research Methods division invites evidence-based practice papers, which "provide analysis of one or more engineering education practice, including teaching approaches, instructional technology uses, and institutional strategies to support student success and its implications for engineering educators " [25] and the SEFI Annual Conference invites concept papers "presenting ongoing projects and completed studies of practice in engineering education" [26]. Greater familiarity with design science research methods could help advance this kind of practical studies into more rigorous research.

Currently, the terminology used to describe and define the research approach used in design science studies is diverse and originates from several disciplinary backgrounds. No apparent links between the geographical origin or the intervention scope of the study and the design science terminology used or the disciplinary background could be detected, although the K-12 papers seem to link more often to the design science literature used in educational sciences and do not refer to design science literature in information systems research or management science. In fact, the management-science-related design science methodology literature is not referred in the papers of our sample at all. The use of terminology is further complicated by the issue that in addition to the design science methodology for inquiry, the terms like design experiments or design research can sometimes refer to other things, such as engineering design tasks for students, research on engineering design, or pedagogical approach for teaching design.

One of the major limitations of this study is that the sampling of papers was restricted to those journal articles that contained certain design-research-related terms. Thus, the studies actually using the method but not calling it such were excluded from the search unless they simultaneously used the search terms for some other purpose. In our categorization, these formed the group of implicit or undefined cases, which contained a quarter of the final sample papers. In reality, it is likely that there are many more of these kinds of studies, as can be deducted, e.g., from the Martinez-Lopez study, which found twenty papers only in the realm of electrical engineering education. Excluding the conference papers from our search has most probably also left out many studies applying design science methodology. One more obvious limitation is to restrict the search to papers written in English. This may also distort our observation of the use of the method being relatively evenly distributed globally.

Conclusions and implications

Based on our study, we suggest that design science is a feasible research approach and methodology also in engineering education. Greater awareness of the methodology and the methodological literature around it could help especially many starting engineering education researchers elevate their concept and practice studies into more rigorous research. As contemporary engineering education research often finds itself in the crossroads of engineering design, pedagogical design, information systems, and even organizational management, a systematic development of the design research methodology based on experiences and ideas from other disciplines could result in an efficient tool for engineering education research, which could also be easy to relate for educators with an engineering background. To clear the terminological jungle around the research methodology and other issues combining design, research, and education, we would suggest creating a glossary and hope that our study can be of use in that.

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Appendix 1. Primary papers of the literature review

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