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van Helden, Gitte; Zandbergen, Barry T.C.; Specht, Marcus M.; Gill, Eberhard K.A.

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Collaborative Learning in Engineering Design Education: A Systematic Literature Review

Gitte van Helden, Barry T. C. Zandbergen, Marcus M. Specht, and Eberhard K. A. Gill

***Abstract*—*Contribution:* This article presents a comprehensive overview of characteristics of educational designs of collaborative engineering design activities found in literature and how these characteristics mediate students' collaboration.**

***Background:* Engineers have to solve complex problems that require collaboration. In education, various collaborative engineering design activities have been implemented to prepare students for these professional practices. According to cultural historical activity theory (CHAT), educational activities can be described in terms of interrelated elements, i.e., subject, object, tools, rules, division of labor, and community, that influence learning outcomes. A key issue is how these elements mediate students' collaborative efforts and how they contribute to learning.**

***Research Questions:* 1) How is collaborative learning implemented in engineering design education? 2) How do the elements of CHAT and their interrelations mediate collaborative learning? and 3) What is the evidence that the implementation of collaborative learning contributed to the achievement of desired learning outcomes?**

***Methodology:* A systematic literature review following preferred reporting items for systematic review and meta-analyses protocols guidelines was conducted, including 111 articles published between 2011 and 2021. CHAT was used as analytical framework.**

***Findings:* Collaborative learning was implemented in engineering design activities to develop technical as well as nontechnical skills. For the CHAT elements, it was found that establishing a common object, rules for collaboration, and division of labor are essential for effective collaboration and can be enhanced through digital technologies (tools) and support from a community, for example, educators. Finally, results showed that there is evidence that described implementations contribute to learning. However, this evidence needs to be interpreted with care, due to methodological issues in some included articles.**

***Index Terms*—Activity theory, cooperative learning, educational technology, knowledge gain, team-based learning.**

I. Introduction

THE PROBLEMS that engineers face are growing increasingly complex [1]. Successful problem solving in engineering requires a skill set that includes not only technical skills but also personal and interpersonal skills and awareness of the economical, societal, and environmental context [2], [3], [4]. To prepare students for contemporary and future engineering practices, educational institutes increasingly make use of engineering design exercises that are collaborative in nature, to address not only technical, and personal skills, but also the interpersonal skills needed to allow multidisciplinary teams to solve complex problems [5]. Historically, collaborative learning has been broadly defined as "a situation in which two or more people learn or attempt to learn something together" [6, p. 1] and was presented as an alternative to traditional lectures. There are numerous variations in how collaborative learning can be implemented in engineering design activities. The extent to which learning objectives are achieved greatly depends on the characteristics of the educational design [7], [8], [9]. A well-established theoretical framework for identifying and analyzing the characteristics of an (educational) activity is cultural historical activity theory (CHAT) [10]. According to CHAT, the development and outcome of educational activities can be described and understood through six interrelated elements: 1) subject; 2) object; 3) tools; 4) rules; 5) division of labor; and 6) community. Until now, there is no comprehensive overview of how these elements and their interrelations contribute to the achievement of learning outcomes.

This article addresses this gap by conducting a systematic literature review on the implementation of collaborative learning in engineering design education. The aim is to: 1) describe variations of CHAT elements in the implementation of collaborative learning in engineering design activities; 2) describe how these variations and their interrelations mediated collaborative learning; and 3) present an overview of the evidence that the described implementations contributed to the achievement of learning objectives. Conclusions will inform practitioners on how to design educational activities to prepare students for professional engineering practice of the future and provide researchers with an overview of the state-of-the-art and suggestions for future research.

II. Theoretical Framework

A. Engineering Design Competencies

Contemporary challenges, including rapid technological development, globalization, and a need for sustainable solutions, create complex engineering problems [1]. Educational institutions face the challenge of adequately preparing their engineering students for this changing landscape. As a result,

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Gitte van Helden, Barry T. C. Zandbergen, and Eberhard K. A. Gill are with the Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS Delft, The Netherlands (e-mail: g.vanhelden@tudelft.nl).

Marcus M. Specht is with the Faculty of Electrical, Engineering, Mathematics, and Computer Science, Delft University of Technology, 2628 XE Delft, The Netherlands.

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there has been growing attention for what skills engineers need within the context of the 21st century [4], [5] and how these skills can be trained through educational activities [7], [8].

1) Learning Objectives: Educational institutions aim to prepare their students for designing solutions for complex engineering problems. That is, design is inherent to engineering and is considered the feature that distinguishes learning engineering from, for example, learning mathematics or science [11], [12]. The Accreditation Board for Engineering and Technology (ABET) defines engineering design as "a process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions" [2, p. 4]. Although the engineering design process involves the application of technical knowledge, also a broad range of nontechnical skills is needed for successful problem solving, as engineering problems typically "are embedded in a 'soft context'" [5, p. 174]. Over the past decades, multiple initiatives were launched with the purpose of mapping the skills required for engineering practices [2], [3]. In this review, it was decided to focus on conceiving designing implementing operating (CDIO) [3], as this initiative is widely distributed and applied [13]. CDIO was launched in 2001 and presented a comprehensive taxonomy with learning goals for undergraduate engineering education. Currently, the CDIO syllabus distinguishes the following four areas for development: 1) disciplinary knowledge and reasoning; 2) personal and professional skills and attributes; 3) interpersonal skills; and 4) conceiving, designing, implementing, and operating systems in the enterprize, societal, and environmental context [14].

2) Learning Activities: It is clear that skills, such as collaboration, cannot be taught through traditional talk-and-chalk lectures. Educational institutions often adopt pedagogical approaches, such as collaborative learning, cooperative learning, problem-based learning, project-based learning, and challenge-based learning [15], [16], [17], to create engineering design activities that are collaborative in nature. However, adopting these collaborative pedagogies does not necessarily lead to the achievement of the desired learning objectives. There are numerous design variations possible together determine the extent to which learning objectives can be fulfilled [5], [8]. For example, group size, cultural background, or available tools influence how a learning activity develops. This makes it difficult to uncover what (combination of) characteristics within a learning activity contribute(s) to the achievement of learning objectives [7], [17].

Until now, some systematic literature reviews have been conducted that provided insight in the implementation of collaborative learning in engineering design activities. They either focus on possible variations in the implementation of collaborative pedagogies [18] or intended learning outcomes and team behavior [19], [20]. A key issue that remains is how variations in the implementation of collaborative learning mediate students' design processes and thus lead to the achievement of learning objectives.

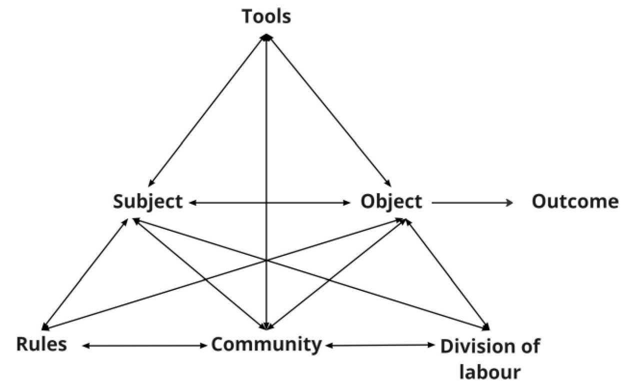

Fig. 1. Activity system.

B. Cultural Historical Activity Theory

When implementing collaborative learning in engineering design activities, one creates a complex environment in which students' behavior is mediated by a variety of social and material resources [21]. *Mediation* in this context refers to the process in which individuals and their socio-material environment mutually shape each other [22]. For example, a tool does not only influence the practice of an individual, but the tool itself also develops through an individual's enactment, as new affordances for action are discovered and created. In order to grasp why an educational activity develops in a certain way, it is essential to understand the mediational structure that underlies this activity. CHAT [10] provides a suitable framework for analyzing complex learning situations, that helps to understand how an activity is mediated by social and material resources.

According to CHAT, an activity is driven by a collective motive (*object*) [23]. The actions that individuals (*subjects*) undertake when working towards this shared object cannot be understood without taking the entire activity system (Fig. 1) into account. The actions of a subject are mediated by different social and material elements. First, *tools* refers to the means that are used while acting on the object, for example, the use of a conferencing tool that allows teams to collaborate in distributed settings. In addition to this, an activity is mediated by implicit and explicit cultural *rules*, for example, design processes and standards. Furthermore, the *division of labor* mediates the activity, for example when each individual in an engineering team is assigned a role with associated tasks and responsibilities. Finally, there is mediation by others that share the same object (*community*), such as educators who share students' object of learning a certain skill. These elements are highly interrelated, and thus the *outcome* of an activity is influenced by variations within elements as well as the connection between elements.

C. Current Study and Research Questions

Collaborative engineering design activities are implemented by educational institutions to prepare students for the challenges of the 21st century. These activities can provide them with valuable learning opportunities. However, it is not clear how the socio-material environment mediates students' collaborative processes and contributes to achieving learning

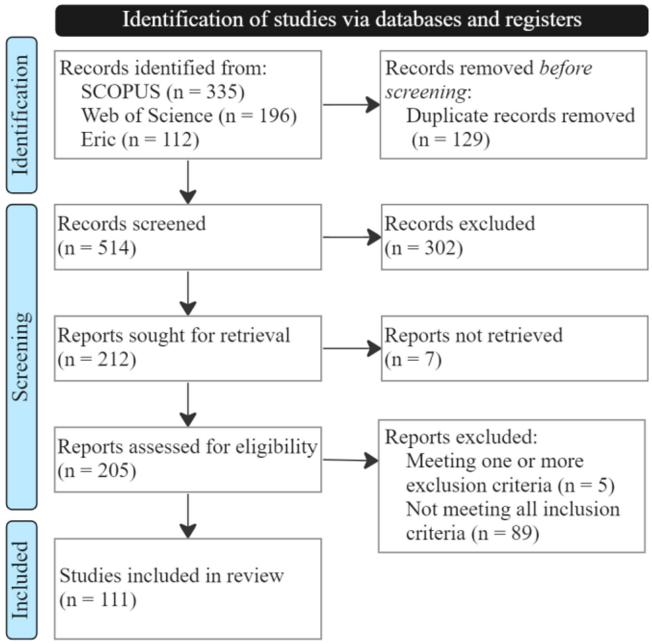

Fig. 2. PRISMA flow diagram.

outcomes. This article addresses this gap by answering the following research questions: 1) How is collaborative learning implemented in engineering design education? 2) How do the elements of CHAT and their interrelations mediate collaborative learning? and 3) What is the evidence that the implementation of collaborative learning contributed to the achievement of desired learning outcomes?

III. Method

A. Research Protocol

For this systematic literature review, PRISMA were followed [24]. The selection process consists of four phases: 1) identification; 2) screening; 3) eligibility; and 4) inclusion, which will be described in the subsequent sections (Fig. 2).

1) Identification: To identify a relevant body of literature, the following search string was used: "collaborative learning" or "cooperative learning" or "team learning" or "group learning" and "engineering" and "design" and "orchestration" or "instructional design" or "pedagogical" or "pedagogy" or "problem-based" or "challenge-based" or "project-based." A systematic search was conducted using the databases Scopus, Web of Science, and ERIC on February 11th, 2021. A date range was set from 2010 onward. The search led to a total of 643 records of which 514 remained after removing duplicates.

2) Screening, Eligibility, and Inclusion: The following exclusion criteria were formulated: 1) document is not written in English; 2) document is not peer-reviewed; or 3) documents does not contain a full article. Documents included should: 1) involve data collection; 2) address collaborative efforts between two or more students; 3) involve solving an engineering design problem; and 4) be in the context of higher education. Articles were excluded when one or more exclusion criteria were met or not all inclusion criteria were met. All documents were screened on the title, keywords, and abstract and eligibility by the first author. When doubts arose about whether an article should be included, this article was discussed with the second and third author and a joint decision was made. During the screening phase, 302 articles were excluded based on title, keywords, and abstract. The full text of seven articles was not available online and could not be retrieved. The eligibility of the remaining 205 articles was assessed through full-text screening and 94 articles were excluded. This led to a final body of literature of 111 articles, of which 57 are journal papers and 54 are conference papers.

B. Qualitative Synthesis of Included Studies

1) Analytical Framework: CHAT was used as the framework underlying the qualitative synthesis of included studies. CHAT used before in other literature reviews (see [25], [26], [27]). Still, their focus was on variations within one element of an activity system. In this review, also the relation between elements is explicated, to reveal how these interrelations mediate collaborative learning.

2) Qualitative Synthesis: For the qualitative synthesis, all included articles were coded. The validity of the qualitative synthesis was increased by using the approach of "negotiated consensual validation," following the example of [28]. This means that all articles were initially coded by the first author using ATLAS.ti. Next, the result of the coding process was shared with the second and third author of this article, who raised issues and suggested alternative interpretation. Discussion continued until consensus among authors was reached. To answer the research questions, the coding process focused on: 1) implementation; 2) mediation; and 3) outcomes.

For implementation, the goal was to distinguish possible implementations within each element of CHAT. First, a top-down coding process was done, using six overarching codes: "subject," "object," "tools," "rules," "division of labor," and "community." Each quote that revealed how an element was implemented in an educational activity was coded. For example, the quote "Meanwhile, they collaborate with the help of digital tools, such as Skype and Google Drive." [29, p. 41] was coded as "tools." Next, for each element, a bottom-up analysis was performed, in which differences in implementation were clustered thematically. For example, from all the quotes on "community," three different parties were distinguished, namely: 1) educators; 2) peers; and 3) external parties. The thematic clustering evolved through weekly meetings in which the first three authors of this article iteratively developed the coding scheme and jointly resolved issues and uncertainties by discussing examples for each subcode. One issue that emerged was that the distribution in themes for the "object" category was very broad and it was difficult to come to an agreement on the thematic clustering. To ensure validity, it was decided to use the four areas of the widely adopted CDIO taxonomy as subcodes for "object" to cross check the authors' interpretation of learning objectives. All subcodes are shown in Table I, codes A–F.

For mediation, all quotes in the result, conclusion, and discussion section that revealed how characteristics of an educational activity mediated students' collaborative processes were coded as "mediation." The next step was to connect the mediational processes to variations in the CHAT elements. This coding process was again executed by the first author, followed by repeated discussion sessions with the second and third author in which consensus was reached. It was found that some mediations occurred as a result of an interrelation between two or more elements. For example, the quote "Students from cultures with a high power distance may feel uncomfortable working autonomously on projects." [30, p. 259] provides insights into how the characteristics of a subject in combination with certain rules mediate an activity and was coded "mediation subject" and "mediation rules." When a quote had two tags, this was considered to be an interrelation between two elements. In the result section, interrelations between elements are indicated by using *italics*. Fig. 3 provides an comprehensive overview of all interrelations that were identified.

For outcomes, evidence that the described implementations contributed to learning outcomes was mapped. For this "data type" was coded. Second, all quotes in the conclusions that revealed evidence that the course design (i.e., implementation) contributed to learning outcomes were coded "evidence for learning." A bottom-up thematic clustering was made of the data sources and evidence for learning that were found (see Table I, code G), using an approach similar to the one followed for codes A–F.

TABLE I
THEMATIC CLUSTERING OF IMPLEMENTATION

Code	Sub-codes
A. Object	1) Learning Objectives a. Disciplinary knowledge and reasoning b. Personal and professional skills and attributes c. Interpersonal skills and communication d. Conceiving, designing, implementing, and operating systems in the enterprise and societal context
B. Subject	1) Group size 2) Student characteristics a. Discipline b. Experience/ academic ability c. Nationality/ culture d. Topic of interest e. Gender f. Personality
C. Tools	1) Functionality a. Enabling collaboration b. Supporting collaboration 2) Implementation form a. Self-chosen vs. teacher-chosen b. Integrated vs. separated
D. Rules	1) Educational theories 2) Design processes and standards
E. Division of labour	1) Roles 2) Jigsaw 3) Disciplinary background 4) Individual and collaborative phases
F. Community	1) Educators 2) Peers 3) External parties
G. Outcome	1) Data type a. Self-report survey b. Couse grades c. Interviews and/or focus groups d. Reflective statements e. Students' work f. Pass rate and/or drop-out rate

IV. RESULTS

This section provides the results obtained with respect to the different CHAT elements organized in Sections IV-A–IV-F. For each section, first the variation of implementation within each element is described, followed by how these variations mediated students' collaborative processes. Section IV-G shows an overview of the outcomes of described implementations.

A. Object

Object refers to the collective motive to engage in an activity. In an educational context the object is to learn, as such the focus is on the learning objectives of included studies.

1) Implementation: Out of the reviewed studies, 63 explicitly addressed one or more learning objectives. These objectives were found to cover all four areas from the CDIO taxonomy. In Table II, an example for each area is given.

TABLE II
LEARNING OBJECTIVES MAPPED TO CDIO AREAS

CDIO areas	Reported learning outcomes
Disciplinary knowledge and reasoning	"An ability to apply knowledge of mathematics, science, and engineering." [31, p. 2]
Personal and professional skills and attributes	"Discriminate between sources of information and recognise the reliability or lack of for multiple source types." [32, p. 257]
Interpersonal skills: teamwork and communication	"The main goal of this project-based course is to have students gradually acquire (…) social competencies such as (…) teamwork and communication skills (...)." [33, p. 2]
Conceiving, designing, implementing, and operating systems	Generate proper design process to produce creative and innovative solution." [34, p. 686].

2) Mediation: Only few articles provided insights into how the object of the activity mediated students' collaborative processes. However, it was clear that students coming to a shared understanding of the learning task at hand, was essential for high-quality collaboration [35], [36], [37], [38]. When the projects' object remained vague, this often came with difficulties with establishing productive *rules* for collaboration and *division of labor,* as it was more difficult to organize collaborative efforts without a shared overarching goal in mind. Additionally, students' (*subjects*) motivation was enhanced when they were able to select a project that aligned with their personal object [39], [40].

3) Summary: Studies claimed to address learning objectives that cover the four areas of the CDIO taxonomy. Only few reported on the mediational process associated with these objects. It was shown that a common object is essential for successful collaboration.

B. Subject

Subjects refers to the individuals that engage in an activity. This section will focus on study participants' characteristics.

1) Implementation: In most of the studies, students worked in small groups that ranged from two to five members. Three studies reported on students who worked in a large project group that was divided into multiple smaller subgroups that each had their own responsibilities [41], [42], [43]. When creating teams, characteristics of students were taken into account, including disciplinary background [29], [34], [38], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], experience or academic ability [34], [40], [41], [42], [45], [46], [60], [61], [69], [70], [71], [72], [73], [74], nationality or cultural background [29], [30], [34], [38], [44], [48], [59], [69], [71], topic of interest [41], [75], [76], [77], gender [34], [45], [69], [71], and personality [44], [78]. Many studies deliberately created diverse teams. Only when it came to students' topic of interest, it was desired to have students with similar preferences.

2) Mediation: Few articles reflect on how group size mediated collaborative learning, but there is some evidence that small group sizes have benefits. This made dividing tasks less challenging (*division of labor*) [79] and made it easier for educators (*community*) to flexibly adapt to students' needs [50], [80] and control interactions among students [60].

Considerably more studies elaborated on how diversity within teams affected collaborative processes. Differences among students can elicit conflicts, as everyone holds their specific set of explicit or implicit *rules* [29], [30], [38], [54], [64], [81]. Conflicts can be due to mismatches in cultural norms (e.g., collectivist and individualist cultures) [30], formal cultural practices (e.g., metric system) [64], disciplinary background (e.g., design processes and standards or work ethic) [38], [54], and personality traits of individuals [29], [54]. Conflicts can negatively affect collaboration during a project. However, they also caused valuable opportunities for learning [30], [64], [78]. Working in diverse teams helped students to practice professional communication [54], [65], to understand each other [78], to acknowledge complementary characteristics [38], to understand how disciplines are interlinked [58], and to improve students' confidence in working with colleagues from different disciplines [64]. To establish successful collaboration in diverse teams, it was essential that everyone works toward the same goal (*object*) [38] and that each student understands how his or her role (*division of labor*) is relevant in achieving this goal [49]. Educators (*community*) can play an important role in facilitating collaboration in diverse teams [81].

3) Summary: Working in large or diverse was generally more challenging. Especially working in diverse groups led to problems in collaboration, but also to valuable learning opportunities. Establishing a common object and division of labor that made each team member feel valued, contributed to successful collaboration.

C. Tools

Tools are the means that subjects use when working toward the object. Although domain-specific engineering tools, such as simulation software, are often used in engineering design education, the focus is on tools for collaboration.

1) Implementation: The included studies described the implementation of (digital) tools with different functionalities. First, there were tools that enabled collaboration. Digital spaces afforded synchronous and/or asynchronous communication through written text, audio and/or video (e.g., discussion boards and conferencing tools), online storage of files and documents (e.g., DropBox), and co-creation of shared knowledge objects (e.g., shared text editor). Collaboration could also be enabled through offering dedicated physical spaces for co-located collaboration, such as makerspaces or laboratory environments [36], [42], [45], [48], [56], [57], [62], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100]. Second, tools can support (parts of) students' collaborative processes. Some tools supported team creation by assigning students to teams randomly or based on student characteristics (*subject*) [40], [77], [81], [90]. Moreover, tools were used to embed a sequence of activities in a digital environment, to guide students into engineering design or problem solving processes (*rules*) [72], [101], [102], [103], [104] or scripts, to facilitate productive collaborative interactions [105], [106]. In addition to this, some tools assisted students in dividing tasks and responsibilities among team members (*division of labor*), for example, through assigning roles [102], [104]. Furthermore, there were tools for establishing and managing connections (*community*) among peers [68], [70], [77], [103] and between students and educators [101].

The form in which these tools were implemented differs. In most studies tools were preselected. However, in some studies students were allowed to select their own preferred set of tools [29], [43], [94]. Often multiple of the functionalities described in the previous paragraph were combined. This can be done by offering a selection of separate tools that each support different functionalities [30], [38], [47], [64], [65], [68], [107], or the use of an integrated environment for digital collaboration [43], [70], [72], [77], [101], [102], [103], [104], [106], [108], [109], [110].

2) Mediation: Digital tools focused on enabling collaboration were mostly implemented in settings with (partial) remote collaboration. Trust among team members, which is essential for successful collaboration, was more difficult to establish during remote collaboration [38], [64]. On the other hand, it was found that some students felt safer expressing disagreement in virtual settings [111] and students valued the flexibility to work from any time and location [112].

Some tools provided additional support for collaboration. Results show that the embedding of *rules* through scripts, scaffolds, or prompts positively impacted collaborations and elicited effective collaborative behavior [101], [106], [110]. The addition of visualizations of collaborative processes promoted reflection [105]. Additionally, [101] created the opportunity to request early feedback from educators (*community*) on meetings with external customers. This led to improved and more consistent communication during meetings with customers. Finally, it was shown that in collaborative interactions, tools became seamlessly integrated with students' (*subjects*) bodily resources (e.g., gestures and utterances) and thus are an important resource for collective meaning making [99].

The extent to which tools were adopted was highly influenced by students' experiences and preferences (*subjects*). That is, the learning space is not predefined by educators (*community*), but co-constructed by students who flexibly use and transform the tools at hand [94]. When students are familiar with a tool, they can make effective choices on what, when, and how to use it [38]. New tools can hold numerous functionalities and identifying and using these new capabilities can be challenging [108] or can even be experienced as overwhelming [64]. For students to adopt new tools, it is important that the tools meet their needs and that it is clear how the tools can contribute to achieving their goals (*object*) [57], [64], [102]. When this was not the case, students did not use certain functionalities as intended, rejected tools, or searched for alternatives themselves [57], [109]. In the example of [109], only tools for asynchronous collaborations were provided. Students felt there was a need for synchronous collaboration and started using conferencing tools. These self-chosen tools created the advantage that students were already familiar with the tools. A downside was that the lecturer had no access to these tools, and thus could not see students' discussions to provide feedback [109].

3) Summary: Implemented tools differed in function and form and were used to enable communication as well as to support collaboration. There were examples in which tools successfully supported positive collaborative behaviors, such as embedding *rules* for collaboration, and promoting feedback processes (*community*). However, the extent to which tools were adopted was heavily influenced by *subjects*' characteristics, such as previous experiences, perceived usefulness, and preferences.

D. Rules

There are various implicit and explicit rules that influence students' collaborative learning. In addition to this, students can formulate rules for collaboration themselves.

1) Implementation: Different types of rules were implemented in the design of learning activities. First, educational theories were leveraged to design learning activities. With two exceptions, all articles referred to educational literature. Most used were references to pedagogical approaches that are characterized by being hands-on and student-centered: project-based learning (55), collaborative learning (37), problem-based learning (31), cooperative learning (22), and active learning (20). Less often studies referred to educational theories on cognition, instructional design, assessment, digital tooling, motivation, or regulation. Second, engineering processes and standards were embedded to structure students' activities. Often similar phases were followed: problem selection/exploration, requirement definition, generating solutions, analyzing solutions, design of a solution, and the evaluation of a designed solution. Occasionally, the design phase is split into a conceptual and detailed design phase [46], a prototyping phase [50], [75], [113], or a launch, maintenance, or re-evaluation phase [60], [75], [87]. This sequential outline of the design process does not mean that the activities students engaged in followed a linear path, as iterations or smaller problem solving cycles were embedded within each phase of a design sequence.

2) Mediation: Many of the pedagogical approaches that were implemented were hands-on and learning-centered. The freedom associated with these pedagogical approaches was often perceived as motivating and engaging by students [31], [58], [85]. Moreover, educators are no longer the primary source of information, which required students to search for and critically assess resources [114], [115]. However, for some students (*subjects*) the ill-structured and uncertain nature of pedagogies such as problem- or project-based learning elicited feelings of discomfort and insecurity [104], [114], [115]. Collaborative problem solving could be structured by making phases of the problem solving process explicit, which students used to regulate their collaborative workflow [114].

Still, there were some indications that implemented engineering design processes fostered students understanding of engineering design sequences [116] and the pros and cons of different design processes [117]. Moreover, it provided opportunities for the practical application of domain-specific content within a realistic setting [41], [85].

Multiple studies pointed out that, when working toward a shared *object*, it is essential for a team to create *rules* that guide collaborative efforts [50], [118], [119]. It is important to note that students were not always able to establish productive collaboration themselves and consequently, action should be taken to support students [35], [36], [38], [103]. Tools or educators (*community*) can guide students to direct the creation or adoption of collaborative rules. However, imposing rules on students can cause the feeling that autonomy is taken away [50].

3) Summary: Rules embedded in the design of a learning activity stem from educational theory as well as from engineering design processes and standards. Typically, the implemented pedagogical approaches were open-ended and ill-structured, which can lead to insecurity for students. Even more, in this type of activity, it is essential to come up with a set of rules to structure collaboration in this uncertain environment. This did not always evolve naturally, but tools and community can provide support.

E. Division of Labor

The division of labor refers to the way that tasks and responsibilities are divided among the subjects in an activity.

1) Implementation: A much used strategy to implement division of labor, was to assign or let students choose roles that determined the tasks and responsibilities of an individual within the team [38], [41], [42], [43], [47], [50], [74], [76], [78], [91], [102], [104], [119], [120], [121], [122]. A second strategy was the so-called "jigsaw" approach, in which group members researched different pieces of information that should be integrated to solve a problem [80], [90], [116], [123], [124]. Third, in multidisciplinary teams (*subject*), the complementary nature of disciplines determined the tasks that should be executed by an individual [48], [57], [59], [60],

[63], [64], [65], [67], [112]. Finally, some studies introduced a distinction between individual and team phases. This was implemented by having a phase of individual background research and idea generation followed by collective execution of a design based on these individual perspectives [37], [40], [42], [62], [71], [75], [77], [92], [111], [114], [125] or by ending a collaborative effort with an individual reflection [69], [98], [126].

2) Mediation: Collaboration was facilitated when interdependency was created, which means that *subjects* needed each other in order to solve a problem [37], [38], [64]. Dividing roles was a useful strategy for students to better collaborate, as it helped to explicate the responsibilities of each individual [114]. In jigsaw, interdependency was created as students performed research on one topic on their own, and then, taught group members about their topic [116]. Also, individual research phases made sure students found new ideas that could be discussed later in collaborative sessions [90]. In all strategies, students developed their own unique expertise or perspective they could bring into discussions with their team and provided opportunities to learn from each other [90], [114], [116].

Interdependence also caused difficulties. When students work in teams, they often alternate between individual and collaborative work. The process of coming back together (i.e., convergence) was perceived as difficult by students [29]. Students working alone rather than cooperatively can be due to not having a clear shared goal (*object*) in mind [36]. Moreover, when rules for collaboration were not in place, difficulties, such as delays, emerged when tasks were dependent on each other [71]. In order to support students, coaches (*community*) should not only be focused on individual and collaborative phases but also on the transition between those phases [29].

Work is not necessarily equally divided among team members and some students took advantage of their peers' efforts [54], [71], [118]. Unequal distribution of work was found to be a characteristic of low achieving teams [118]. A possible solution for avoiding so-called "free riders" is to implement rewards for individual contributions [72].

3) Summary: Approaches, such as role division or jigsaw, were used to facilitate division of labor by creating interdependency. This stimulated collaboration, if work was fairly distributed.

F. Community

Community refers to the ones who share and work toward the same objects as the subject within an activity.

1) Implementation: Educators were involved in all examples and generally took a coaching rather than a directive role. There were variations in the extent to which students were given freedom, but this was often not explicitly specified in papers. Second, peers were involved through peer assessment [34], [62], [69], [71], [78], [81], [83], [84], [89], [92], [95], [103], [105], [106], [113], [119], [127] and role playing [66], [87], [117]. Also, there were interactions with parties from outside of the university environment, for example, industry partners or experts that acted as a customer, provided workshops or attended presentations to give feedback [30], [40], [46], [47], [51], [53], [55], [60], [61], [71], [76], [81], [88], [98], [101], [113], [116], [119], [125], [128], [129], potential users of a product [65], [75], site visits [60], [98], [128], or competitors [55], [130], [131].

2) Mediation: When coaching, educators made use of scaffolding [46]. Process related scaffolding was more effective than content related scaffolding [33]. Scaffolding was used to successfully enhance aspects of students' collaborative design processes (*rules*), including establishing dialogues in teams [116], overcoming anxiety when working on ill-structured problems [79], communicating with stakeholders [101], mediating ideas and proposals [132], bridging multiple disciplines [60], and solving difficulties when collaborating [59]. Furthermore, educators positively influenced students' motivation by providing feedback on group processes, helping to make decisions, and establishing a positive relationship [39]. Reported negative influence of educators included unclear communication about project goals *(object*) leading to confusion [133] and difficulties with balancing between providing structure and freedom, as *subjects* have different preferences. Limited guidance can lead to feelings of uncertainty, the perception that their educator is not interested, or interference with the cultural *rule* that it is impolite to not wait for instructions [30], [39]. However, students can also perceive limited guidance as a sign of empowerment and ownership of their process [39] and too much input from the educator can lead to a tendency to use the educators' ideas rather than formulating their own.

Students learned from each other through peer assessment or teaching. This had a positive impact on students' collaborative process when used as an opportunity to collect feedback for grounding decisions [62], enhanced motivation to improve work to impress each other [62], [115], and helped to create a stronger community feeling [62]. There were also some drawbacks involving peer assessment and peer teaching. When students did not take peer assessment seriously, it could lead to feedback of lower quality [83]. In addition, there are cases in which students removed novel ideas from their product during peer assessment activities because they were afraid their peers would "steal" their ideas [62]. This meant they did not get feedback on all aspects of their product. Finally, during peer teaching, some students felt too insecure or underequipped to take on the role of expert and teach their fellow students new content [57], [123].

Third parties also affected students. Having a customer during an engineering design project created opportunities for students to learn engineering practices (*rules*) [43], [117], involving a customer from industry enhanced students' motivation [53], [61] and gave them an opportunity to create a network [80], and feedback from a customer helped students to improve the quality of their work [53]. When involving external parties for feedback, it was important to clearly communicate assessment criteria and not only pay attention to the product but also to the process to avoid a sense of unfair judgment [81]. Involving users of the developed product helped students to better understand their target audience [65]. For site visits, it was recommended that students first do research and think of questions before the visit [98].

3) Summary: The involvement of educators, peers, and external was beneficial to various aspects of students' collaborative processes. Clear communication and a safe environment are required to avoid negative consequences.

G. Outcome

In this section, the outcome of the implementations and mediations described in previous sections is outlined. First, the quality of data collection and analysis is discussed. Second, the evidence for the achievement of learning outcomes is presented.

1) Quality of Data Collection and Analysis: Out of the 111 included studies, 73 made use of self-report surveys to collect data. Other sources for data collection were course grades (27), interviews and/or focus groups (14), reflective statements (9), students' work (6), pass and/or dropout rate (7), audio and/or video (5), observations (3), log data (2), and time investment (1). Notably, 41 articles included conclusions that were anecdotal or could not be traced back to a data source. The term "qualitative research" was sometimes used when presenting anecdotal results, while qualitative research, just like quantitative research, has a collection of rigorous methods that should be respected in order to reach valid and reliable conclusions. Furthermore, information on the process of data collection and analysis was missing and many studies did not provide a solid interpretation of the data they presented. For example, survey data was presented as averages from Likert scales, which is difficult to interpret without statistical analysis. Finally, only few studies related (educational) literature used in the theoretical framework to their findings.

2) Evidence for Learning: Whereas some articles present insights into mediating processes, for example by focusing on the interplay between a student team and their environment, others evaluate the outcomes of learning activities. The results of these evaluations were consistently positive about their implementation of collaborative learning in engineering design education. Self-report measures revealed that students' perceived gain, satisfaction with (features of) the implementation, and motivation and/or engagement were generally high or higher compared to traditional course designs. Moreover, measures of students' performance, such as grades, pass rates, and observed behavior, presented evidence that implementations contributed to learning. A complete overview of evidence can be found in Table III. Several articles placed a critical note at their implementation, but still only one article considered their implementation unsuccessful due to organizational aspects [84].

TABLE III
EVIDENCE FOR LEARNING

Outcome	Articles that provide evidence
Self-report measures	
Perceived learning gain	[32], [36], [37], [41], [47], [50], [51], [54], [55], [57]–[59], [63], [67], [73], [74], [82], [83], [85]–[88], [97], [100], [106], [110], [112], [115], [117], [119], [122], [123], [125], [130], [132], [134]–[138]
Satisfaction	[32], [40], [41], [47], [48], [55], [57], [58], [60], [62], [66], [68]–[70], [72], [73], [77], [79], [81], [86]–[88], [92], [95], [97], [98], [101]–[104], [107], [113], [115], [116], [122]–[124], [129], [132], [133], [135], [137], [139]
Motivation and/ or engagement	[36], [39], [58], [62], [85], [88], [97], [98], [123], [124], [139]
Student performance measures	
Average grade	[32], [36], [42], [47], [48], [51], [63], [72], [74], [79], [86], [91], [96]–[98], [100], [125], [127], [136]
Pass rate	[31], [58], [86], [87], [96], [97], [123], [133]
Observed behavior	[77], [78], [90], [99]

V. Discussion

How Is Collaborative Learning Implemented in Engineering Design Education? It was found that collaborative engineering design activities are used to foster a broad range of technical and nontechnical skills. The way these activities are implemented varies greatly. This systematic literature review presents an overview of design options that were found in literature (Table I), that mediate students' collaborative efforts in different ways.

How Do the Elements of CHAT and Their Interrelations Mediate Collaborative Learning? The elements that are present in a collaborative engineering design activity together mediate the development of an activity. This systematic literature review contributes to the body of knowledge by distinguishing mediational patterns that were described in literature. A consistent finding was that for successful collaboration it is essential to clarify the common *object* and establish *rules* for collaboration and *division of labor* in order to work toward this object. These behaviors did not always emerge naturally, but the socio-material environment could support students' collaborative efforts. The *community*, for example, educators, could provide process related scaffolds to guide students toward desired collaborative behaviors. Also, *tools* could promote collaboration, for example, through the embedding of scaffolds, prompts, or scripts. However, the extent to which this support is successful depends on student (*subject*) characteristics. Students may react differently to certain supervision styles. Moreover, the extent to which tools are adopted depends on previous experience, preference, and perceived usefulness.

In Fig. 3, an overview is presented of all interrelations found in included studies. For each combination of CHAT elements, at least one interrelation was found with exception of tools and object, which might indicate that this interrelation has not been sufficiently explored.

What Is the Evidence That the Implementation of Collaborative Learning Contributed to the Achievement of Desired Learning Outcomes? With one exception, all studies presented positive evaluations with regard to the implementation of collaboration in engineering design education. Together, they present evidence that this type of educational activity can be used to achieve intended learning outcomes. However, the majority of conclusions are based on self-report surveys filled in by students or anecdotal data,

	Object	Subject	Tools	Rules	Division of Labour
Subject	For successful collaboration all *subjects* should share a common *object* [35]-[38]. A project that aligns with *subjects*' personal *objects* leads to higher motivation [39],[40].				
Tools		*Subject* characteristics influence *tool* adoption [38], [57], [64], [94], [102], [108], [109]. *Tools* can support group creation (*subject)* [40], [77], [81], [90].			
Rules	When working towards a common *object* it is essential to establish productive *rules* for collaboration [50], [118], [119].	*Subjects* hold different *rules*, which can lead to conflict, but also to opportunities for learning [29], [30], [38], [54], [64], [78], [81]. *Subjects* react differently to freedom in some pedagogical approaches (*rules*) [31], [58], [85], [104], [114], [115].	*Rules* for collaboration can be embedded in *tools* through scripts, scaffolds, or prompts [72], [101]-[106], [110].		
Division of Labour	A common *object* is needed to establish productive *division of labour* [35]-[38]	Interdependence among *subjects* leads to *division of labour* [37], [38], [64], [90], [114], [116]. It is easier to *divide labour* in small groups (*subject*) [79]. In (diverse) teams, *subjects* should understand the contribution of their role (*division of labour*) [49].	*Tools* can assist in creating *division of labour*, for example by embedding role division [102], [104].	*Rules* for collaboration and *division of labour* often co-emerge and their quality is reflected in the success of collaborative efforts [35], [36], [38].	
Community	Unclear communication by educators (*community*) on the *object* of a project can lead to confusion [113].	Small groups (*subject*) are easier to supervise for educators (*community*) [50], [60], [80]. Educators (*community*) can facilitate collaboration in diverse teams (*subject*) [81]. *Subjects* react differently to supervision styles (*community*) [30], [39].	*Tools* can assist to establish and manage connections with peers or educators (*community*)[68], [70], [77], [101], [103]. Self-selected *tools* cannot be easily monitored by educators (*community*)[190].	Educators (*community*) can scaffold collaborative *rules* [33], [50], [60], [79], [101], [116], [132]. Involving industry partners (*community*), helps students to understand *rules* from engineering industry [43], [117].	Educators (*community*) can support *division of labour* by guiding the transition between divergent and convergent phases [29].

Fig. 3. Cross-table o the interrelations between CHAT elements. For each interrelation the associated reference is presented. The first row and last column of this cross-table were removed as they presented the object–object and community–community crossing.

which may present a skewed picture. Even more, many studies showcase an implementation of collaborative learning in an engineering design course and conclude that this implementation "works," or "works better" than a traditional implementation (e.g., lectures). Still, few articles engage deeply with literature from educational science and provide insights into why this particular design works well. Thus, the question to be answered in the future is not whether the implementation of collaboration is possible or beneficial in a specific context, but how the (combination of) elements in an educational activity affect collaborative learning in engineering design education and how these elements can be leveraged to promote students' collaborative processes.

Theories that forefront the socio-material nature of collaborative design activities, such as CHAT, can help to answer these questions. Also, the included studies offer some promising alternative theoretical perspectives. For example, [94] uses an ecological perspective to understand the interplay between students and their environment and [99] proposes to use an embodied interaction analysis, in order to understand how students' bodily engagement with their environment shapes collaborative meaning making. The theoretical perspectives mentioned in this paragraph might guide engineering education researchers in investigating how design solutions evolve collaboratively as a result of the complex interaction between students and the socio-material environment.

VI. Conclusion

In this systematic literature review, an overview was provided of variations in implementations of collaborative learning in engineering design activities. Furthermore, an overview was given of how these implementations mediated collaborative learning. These insights can help practitioners to reflect on their practice and make evidence-informed decisions when creating collaborative engineering design courses in their own context.

Finally, it was shown that there is evidence that the implementation of collaborative learning in engineering design activities led to the achievement of learning objectives. However, as most studies rely on self-report surveys and methodological issues arose, conclusions should be interpreted with care. In addition, most studies state whether an implementation "works" in a specific context, but not why this implementation works. Future research should be aimed at investigating how the socio-material environment mediates students' collaborative efforts and how this can be leveraged to promote skills that are needed for 21st century engineering practices.

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Gitte van Helden received the B.S. and M.S. degrees in educational sciences from Utrecht University, Utrecht, The Netherlands, in 2018 and 2019, respectively. She is currently pursuing the Ph.D. degree in engineering education with the Delft University of Technology, Delft, The Netherlands.

Barry T. C. Zandbergen received the Diploma degree in aerospace engineering from the Delft University of Technology, Delft, The Netherlands, in 1986.

He is currently a Senior Lecturer with the Department of Space Engineering, Faculty of Aerospace Engineering, Delft University of Technology.

Marcus M. Specht received the Diploma degree in psychology and the Ph.D. degree in adaptive information technology from the University of Trier, Trier, Germany, in 1995 and 1998, respectively.

He is currently a Professor of Digital Education with the Delft University of Technology, Delft, The Netherlands, and the Director of the Leiden-Delft-Erasmus Centre for Education and Learning, Delft.

Eberhard K. A. Gill received the Diploma degree in physics and the Ph.D. degree in theoretical astrophysics from the Eberhard-Karls-University of Tüebingen, Tübingen, Germany, in 1986 and 1989, respectively.

Since 2007, he has been the Chair of Space Systems Engineering with the Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands.