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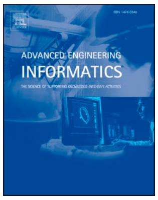

Full length article

# Collaborative CAD in engineering design: a systematic literature review and a taxonomy of collaborative CAD activities

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A B S T R A C T

Collaborative Computer-Aided Design (CAD) plays an important role in engineering design by enabling simultaneous multi-user work on design tasks. However, the absence of a unified framework to describe collaborative CAD and associated design activities has resulted in inconsistencies in research findings and challenges in synthesising existing knowledge. This paper aims to develop a taxonomy that describes the usage of collaborative CAD and identifies research opportunities based on the current state of the art in collaborative CAD and related design activities. Using Activity Theory, six top-level taxonomy categories are proposed to structure collaborative CAD activities: Subject, Object, Tools, Community, Division of Labor and Rules. Following the PRISMA methodology, a systematic literature review of collaborative CAD activities was conducted and combined with the grounded theory to derive the third- and second-level taxonomy elements and subcategories. Additionally, five research opportunities that highlight emerging challenges, including the integration of AI tools, the need for interdisciplinary collaboration, and the development of standardised evaluation metrics are identified. The findings have practical implications for researchers, software developers, and educators by providing guidance on future research directions and collaborative CAD tool development. By offering a comprehensive taxonomy based on both the theory and existing literature, and research opportunities, this study contributes to the ongoing evolution of collaborative CAD in engineering design, paving the way for more structured research in this field.

## 1. Introduction

Engineering design is a process that transforms the information from the initial state of needs, requirements and constraints into the description of the designed artefact [1]. At each stage of the engineering design process, new information is generated and modified, resulting in information models of the design artefacts. The transformation is executed by means of designing, which encompasses all activities performed by a designer [2]. In addition to human designers, the usage of computers is also essential in support of the design process [3]. Referred to as design informatics, as a subset of engineering informatics, design activities supported computationally involve creating, communicating and sharing information models of the designed artefacts [4]. Despite current automation endeavours driven by the advancements in information technology [5], the usage of computers themselves cannot directly lead to the development of the designed artefacts [3]. Therefore, in addition to the importance of a designer's design abilities and skills, being skilled in using computer tools is also essential for the process itself [6]. In the context of computational support for the design process, Computer-Aided Design (CAD) plays a ubiquitous role [7]. Since the introduction over 50 years ago, CAD has evolved from using computers for simple digital drawing [8] into a dominant computer support of designing engineered artefacts. CAD is defined as the use of computers to assist in the creation, modification, simulation, analysis and optimization [9] of an information model of a design artefact [10,11]. This model is typically a three-dimensional digital information object, known as CAD model, which captures both the structure and physical attributes of the designed artefact [11]. Therefore, CAD serves to support the

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activities a designer undertakes to create both the shape and function of a designed artefact [3,12]. These activities are referred to as *CAD activities*. Over the past decades, research has focused on improving the technical capabilities of CAD. Examples include geometric simplification [13], automatic disassembly and assembly sequence generation [14,15], and the integration of FEM-based analyses into CAD workflows [16]. Such endeavours enhance the efficiency and reliability of CAD but remain focused on CAD technically. What is still missing, however, is an understanding of CAD as a tool within design activity, where technical and social aspects are intertwined.

This shift in perspective is particularly important because engineering design itself is inherently collaborative, requiring the integration of diverse expertise, knowledge, and responsibilities [17]. As a result, collaboration becomes essential at every stage of the design process, whether within a single team, across departments, or even between organisations. Effective and efficient collaboration is a prerequisite for a successful design process [18]. Although CAD was initially developed to support designers in individual CAD activities [19], typically through standalone CAD, it has always enabled collaboration [20], thus supporting *collaborative CAD activities*. Such collaboration was facilitated when the previously mentioned standalone CAD was integrated with a data management system that enables multiple designers to work geographically distributed and asynchronously [21]. What followed distributed CAD was the introduction and development of collaborative CAD that, like distributed CAD, supports multiple designers and enables them to interact. However, collaborative CAD additionally supports synchronicity, which allows designers to view, edit, and manipulate a model that updates for each CAD user in real-time. Therefore, the key difference between distributed CAD and collaborative CAD is the multi-user synchronous work. This advancement addresses common collaboration challenges, such as the inability to edit synchronously, seamless file sharing, and visibility of design changes [21]. Despite these activities, current research on collaborative CAD remains fragmented due to the absence of a comprehensive theoretical foundation, hindering comparisons and the synthesis of findings.

What distinguishes collaboration from other forms of shared work is its focus on achieving a shared goal [22]. To define collaborative CAD activities, we adopt a definition based on Bedwell's [23] concept of collaboration. Beyond merely aiming to achieve a shared goal, a collaborative CAD activity involves two or more designers who actively and reciprocally engage with each other through collaborative CAD to accomplish that goal. The active nature of collaborative CAD activities implies that they involve interpersonal interactions and relationships that change over time [24]. Additionally, the reciprocal nature of collaborative CAD activity means that it requires mutual engagement of all involved social entities. In the context of collaborative CAD activity, the social entities are two or more designers involved in the activity, who together form a de facto team working jointly toward a shared goal [25]. This necessitates the integration of both social (team) and technical (design, CAD) aspects. However, the findings from these analyses have focused on isolated components of such aspects, often generalising their findings across the entire domain of collaborative CAD activities' research. This fragmentation indicates a lack of consensus among researchers regarding the defining aspects of collaborative CAD activities, which hinders the comparability of findings and the synthesis of evidence to build cumulative knowledge [26]. Moreover, this issue is not only methodological, but also stems from the absence of a comprehensive overview and conceptual synthesis of collaborative CAD activities. Without a shared understanding of what constitutes collaborative CAD activity, it becomes challenging to identify research opportunities, research gaps and research questions. Although there are a number of studies related to CAD and collaboration, most of them focus on the technical aspects [7,27]. These contributions are valuable, but they do not conceptualise the work in CAD tools as an activity undertaken by designers or teams of designers. As a result, the engineering design domain lacks the integration of both social and technical aspects of collaborative work in CAD. Consequently, the existing literature remains fragmented, with studies addressing isolated components of collaborative CAD activities that are often difficult to compare or synthesise into a coherent body of knowledge. This study therefore aims to fill that gap by adopting Activity Theory as the theoretical foundation and, beyond synthesising existing findings, conducting a systematic literature review to derive a taxonomy that classifies and describes collaborative CAD activities. The taxonomy aims to provide a framework to be utilised for comparison between studies, planning rigorous empirical research, and aiding the accumulation of insights while identifying opportunities for further exploration. To further clarify how the present SLR differs from prior review contributions in the domain of collaborative CAD and collaborative design, and to strengthen the justification for this study, Table 1 contrasts earlier reviews and developed taxonomies with the one developed in this study based on the Activity Theory. In addition to the two prior reviews of collaborative CAD [7,27], the comparison also includes the taxonomies of collaborative design activities [22,44–46]. The reviews adopt a technology-oriented perspective focused on collaborative CAD systems and their technical characteristics, but do not employ a systematic literature review or any theoretical classification framework. Similarly, although the mentioned taxonomies [22,44–46] provide a valuable basis for conceptualising collaborative design activities, they are limited in the context of collaborative CAD. For example, they address communication but not coordination, do not include any performance measures related to team- and taskwork, and treat design tools mainly through usage frequency rather than through their mediating role in the activity. Therefore, none of these contributions provides a comprehensive and theoretically grounded framework that integrates both the social and technical aspects of collaborative CAD activities.

Therefore, to address the lack of unified conceptual consolidation in research on collaborative CAD activities, this study has three objectives. First, to systematically identify and synthesise research on collaborative CAD activities in engineering design. Second, to develop a taxonomy of collaborative CAD activities grounded in Activity Theory and finally, to identify research opportunities emerging from the reviewed literature. These objectives are addressed through the following research questions:

1. How does the existing literature conceptualise and study collaborative CAD activities when structured through Activity Theory categories (Subject, Object, Tool, Community, Division of Labor, and Rules)?
2. What second- and third-level taxonomy subcategories and elements can be derived from the literature under the Activity Theory categories?
3. Which Activity Theory categories are underrepresented and what research opportunities follow from these gaps?

The key contributions of the study are as follows:

- A PRISMA-based systematic literature review of collaborative CAD activities in engineering design
- A taxonomy of collaborative CAD activities grounded in Activity Theory, with top-level categories derived deductively and subcategories and elements derived inductively from the literature
- The identification of underrepresented activity categories and corresponding research opportunities for future research on collaborative CAD activities

The paper is therefore structured as follows. The next section provides the theoretical background on collaborative CAD, collaborative CAD activities and Activity Theory. Section 3 outlines research methodology, including systematic literature review and taxonomy development. Section 4 presents the results in relation to the first and the second research questions. Sections 4.1 and 4.2 provide an overview of the reviewed literature, while Section 4.3 addresses the mentioned

**Table 1**
Comparison of prior reviews and taxonomies, and the present PRISMA-based systematic literature review and Activity Theory taxonomy of collaborative CAD activities

| | Adediran et al. [7] | Li et al. [27] | Ostergaard and Summers [22,44–46] | This study |
|---|---|---|---|---|
| **Primary focus** | Overview on the transition from CAD to cloud and related digital developments | Overview of collaborative CAD from a technology and CAD technical solution perspective | Taxonomy of collaborative design activities | Activity-based synthesis of collaborative CAD research: what collaborative CAD users and teams do and how it is studied |
| **Methodological approach** | Review (not reported as PRISMA with explicit screening process) | Review (not reported as PRISMA with explicit screening process) | Taxonomy development without systematic literature review | PRISMA SLR with search strings, inclusion criteria and screening process |
| **Unit of analysis** | Digital transformation of CAD into a collaboration tool | Collaborative CAD software solutions and approaches and their technical characteristics | Collaborative design activity | Collaborative CAD activity structured by Activity Theory (Subject, Object, Tool, Community, Division of Labor, Rules) |
| **Theoretical framing** | Not organised around any theoretical classification framework | Not organised around any theoretical classification framework | Not organised around any theoretical classification framework | Deductive AT top-level categories and bottom-up derivation of subcategories and elements via GT |
| **Main outputs** | Technology-oriented categorisation and directions | Technology-oriented categorisation and directions | Taxonomy of collaborative design activities | Taxonomy (categories, subcategories and elements) and research opportunities |

research questions by structuring the literature through the Activity Theory categories and reporting the derived taxonomy subcategories and elements. Building on these results, Section 5 addresses the third research question by discussing underrepresented categories and the research opportunities, while also outlining limitations and implications of the study. Finally, Section 6 concludes the study, summarising the findings and contributions.

## 2. Background

Collaborative CAD and the associated activities have been a focus of engineering design research for over 25 years, long before the technological prerequisites to develop a feasible, comprehensive collaborative CAD tool. This focus arises mainly from the need to address the complexity of collaborative CAD activities and the specific characteristics and requirements of CAD tools. The goal has been to facilitate collaborative CAD activities in two ways: vertically, by connecting design and manufacturing [28], and horizontally, by enabling design teams, whether from the same or different disciplines, to engage in synchronous or asynchronous collaboration for a CAD design activity [29]. Early research efforts were mainly concentrated on developing models that outlined how collaboration should be facilitated and managed within the standalone CAD tools [30,31]. Additionally, these efforts included the creation of collaborative CAD prototypes, which were constrained by technological development of that time [32]. Researchers also addressed specific technical aspects of collaboration within existing standalone CAD tools, such as coordinating multi-user assembly modelling actions in real time [33] or tracking the history of part creation as well as modification by multiple users [34,35].

Over the years, advances in information technologies have shifted CAD from standalone to distributed and eventually collaborative CAD [21]. Early advances in Product Data Management (PDM) enabled distributed CAD, supporting asynchronous collaboration by allowing designers to share models, manage versions, and coordinate work across dispersed teams. More recently, the advent of cloud-based technologies, has enabled collaborative CAD, most prominently Onshape [36], supporting synchronous collaboration in which multiple designers can view, edit, and manipulate a CAD model in real time. As a result, researchers began to turn their attention toward collaborative CAD activities, emphasising not only the resulting outputs, which corresponds to those before the era of collaborative CAD [37,38], but also placing increased emphasis on the social or team aspects [39].

### 2.1. Collaborative activities in CAD

Although the adoption of collaborative CAD is in its early stages [21], the development and release of commercial collaborative CAD tools enabled studying and exploring collaborative CAD activities [40]. Studies on these activities have provided preliminary insights into how collaborative CAD activities may impact design outputs in CAD, from the effects of diverse working modes on the efficiency and quality of outputs of collaborative CAD activity inspired by pair programming [20] to influence of communication on team performance [41]. Another study attempted to determine the optimal number of users for specific collaborative CAD activities [42], while another examined the emotional responses of users engaged in collaborative CAD compared with those using CAD individually [43]. Although these studies yield interesting empirical results and insights into the various aspects of collaborative CAD activities, they remain fragmented and as such, limits the comparability of findings and hinders the synthesis of evidence. In other words, the current research on collaborative CAD activities generally is insufficient for building a comprehensive understanding of collaborative CAD activities, or does not provide comprehensive structure of defining aspects of these activities.

Furthermore, what could possibly be used as theoretical foundation to conceptualise and describe collaborative CAD activities could stem from collaborative design and associated activities. Efforts to provide a conceptual framework for collaborative design have led to the development of taxonomies of collaborative design activities [22,44–46]. However, they also present several shortcomings. For instance, those taxonomies address communication at the top level and leadership styles at the second level, but it does not include coordination at all. Also, they lack in objective parameters and performance measures, which in the context of collaborative design activities, aligns with team performance elements: performance of team- and taskwork [47,48] and their evaluation. Furthermore, their treatment of design tools is limited to measuring usage frequency without delving into how these tools influence the associated activities. In other words, while design tools are recognized as important to collaborative activities, their contextual and mediating roles remain under-theorised in these taxonomies. To bridge this gap, Activity Theory provides a theoretical framework that can be applied to collaborative CAD activity research. According to Activity Theory, any activity is defined by the interactions among subjects, the objects they aim to transform, and the tools that mediate these interactions. Viewed through this lens, collaborative CAD tools are not merely passive tools.

### 2.2. Activity theory

Activity Theory (AT), developed by Vygotsky [49], provides a theoretical framework for analysing human practices or “what people do” within complex systems [50]. The theory includes the concept of mediation by referring to the idea that humans’ interactions with their environment cannot be direct but instead mediated by using tools [51]. Therefore, the initial AT triangle model emphasises the interconnectedness of a *subject* (individuals engaged in activity), an *object* (goals of the activity) and a *tool* (physical, conceptual, and symbolic). Engeström [52], furthermore, expanded a triangle model to reflect the collective and collaborative nature of human activity. He proposed the new elements: *community*, *division of labor* and *rules*. Community puts the analysis of the activity being under investigation into the social context of the environment in which the subject operates. The community is organised according to the division of labor, and rules, which are horizontal and vertical informal practices and norms governing the relations between or within the subject and community, affecting how the activity is carried out. In addition, by integrating the technical, social, and organisational aspects of any human activity, it also enables an exploration of the relationships among subject, tools, object and the community in contexts of collaborative design and collaborative CAD activities. In contrast to other commonly used theoretical frameworks in engineering design, such as socio-technical systems [53], which focus on human-technology interactions at the system level, and design cognition [54], which emphasises individual cognitive processes in engineering design, AT provides a comprehensive framework for analysing activities and how tools mediate these activities. This understanding is crucial for examining collaborative CAD activities, where the tool of collaborative CAD plays a significant role in influencing both the collaboration and the outcomes of the activity.

In engineering design, the AT has been utilised to describe design work at three distinct levels (activities, tasks, actions [55] and cognitions [56]), and as such provides a coherent structure for analysis of individual design work at different scales [55]. AT is also used as a qualitative framework [57,58], or as a design tool, for example, to identify the specific problems and contradictions on the organisational level [59]. Furthermore, Engeström and Miettinen [52] highlighted the collective nature of the object-oriented and the tool-mediated activity, suggesting that the elements of AT can serve as a unit of analysis that bridges the gap between individual subjects and societal structures. Indeed, in the field of the computer supported cooperative work (CSCW), the AT serves to describe teams working on the software development tasks [60], as well as interdisciplinary teams engaged in creative tasks within the design domain [57]. Therefore, given its emphasis on activity as the primary unit of analysis and its ability to integrate social, technical and organisational dimensions, AT provides a comprehensive theoretical framework for this study. By bridging individual and societal components, along with the technical aspects, it is well-suited for describing and examining collaborative CAD activities.

## 3. Methodology

To achieve the study objectives to systematically review the literature on collaborative CAD activities in engineering design, to develop a taxonomy based on Activity Theory and to identify research opportunities of collaborative CAD activities research, this study employed a hybrid approach [61]. It combined a deductive approach, which involves top-down categorisation based on the established theoretical model or framework, with an empirical approach, which relies on bottom-up synthesis from the existing literature.

The proposed taxonomy consisted of three levels: categories, subcategories and elements. The top-level of the taxonomy or the taxonomy categories were derived deductively using AT as the theoretical framework. AT is a well-established model of human activities in socio-technical environments and is particularly suited for studying collaborative CAD activities due to the components it involves: *Subject*, *Object*, *Tool*, *Community*, *Division of Labor* and *Rules*. However, while AT provides a high-level structure, it does not explicitly define subcategories and elements that can be utilised to study research on collaborative CAD activities. To define elements and subcategories of the taxonomy, a bottom-up approach was employed through a systematic literature review (SLR) and Grounded theory (GT). Therefore, the study was designed as desk-based research [62] using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) as a methodological framework to ensure a comprehensive and replicable dataset of relevant research studies [63], along with snowballing [64]. To ensure replicability of the data collection, the databases, search terms, and the time frame for literature retrieval are all detailed in the study. Additionally, the inclusion criteria were clearly defined and systematically applied, with all decisions documented to ensure that the process can be replicated. Once the dataset of relevant studies is established, GT [65] is utilised as the methodological framework to synthesise the identified research, focusing on the extraction and categorisation of elements and subcategories under the top-level taxonomy categories derived from AT.

The procedure consists of four steps: 1) Identification of studies, 2) Definition of inclusion criteria, 3) Screening the studies, and 4) Taxonomy development. Steps from 1) to 3) incorporate the SLR, described in the PRISMA checklist (Fig. 1). The step 4) incorporates the GT to develop the taxonomy elements and subcategories.

### 3.1. Identification of studies

The search for relevant studies started with defining search string. These, outlined in Table 2, include *collaborative CAD*, *CAD* and *collaboration* perspective combined using the AND operator. The researchers initially tested this search string, checking whether the string captured the studies researchers were already familiar with (13 studies in total). As a result, the search string was considered sufficient to provide an overview of the field. Additionally, since no prior work has focused on reviewing literature on collaborative CAD activities, this study included all publications without restrictions based on publication type or year. The search string was applied in Web of Science and Scopus databases due to their biases. Namely, those databases represent relevant studies, particularly in the natural sciences and engineering [66]. Additionally, these databases differ in coverage. Web of Science has a broader timespan, while Scopus includes a larger number of publications [67]. Thus, these two databases provide adequate coverage for conducting a systematic literature review in the engineering domain.

The final search was performed on 10th of February, 2025, yielding 50 studies from Web of Science and 111 studies from Scopus. After removing 56 duplicates derived from the both databases, the total number of studies for the screening process was 105 (Fig. 1), which were further screened based on the inclusion criteria.

### 3.2. Inclusion criteria

The criteria according to which the studies were included in the study relate to several key elements: publication type, language, and study content (Table 3). The first criterion required that the identified study must be a research paper. This encompassed both journal and conference studies, while excluding lecture notes or technical reports, as well as introductions to journals' special issues. The second criterion addressed language restrictions, as some studies were written in languages other than English. Finally, the study content criteria consisted of two parts: 1) the paper must include the usage of collaborative CAD tool, or 2) it must present the application in the engineering domain. The former was derived from the definition of collaborative CAD activity presented in the introduction of the paper. The former included studies that proposed solutions for development of collaborative CAD tools or its components, or that suggest developed collaborative CAD solutions without testing them with two or more collaborative CAD users. Furthermore, the latter part of the paper content criteria focused on the application of collaborative CAD specifically in the engineering design domain. Therefore, if a paper met any of content criteria, it was taken into consideration. Also, to minimise bias, the inclusion criteria were defined prior to the systematic literature review and applied consistently across all studies [68]. Additionally, all decisions were documented, and the studies were re-screened to confirm these decisions, which helped mitigate the risk of bias [69]. Based on the three inclusion criteria, a

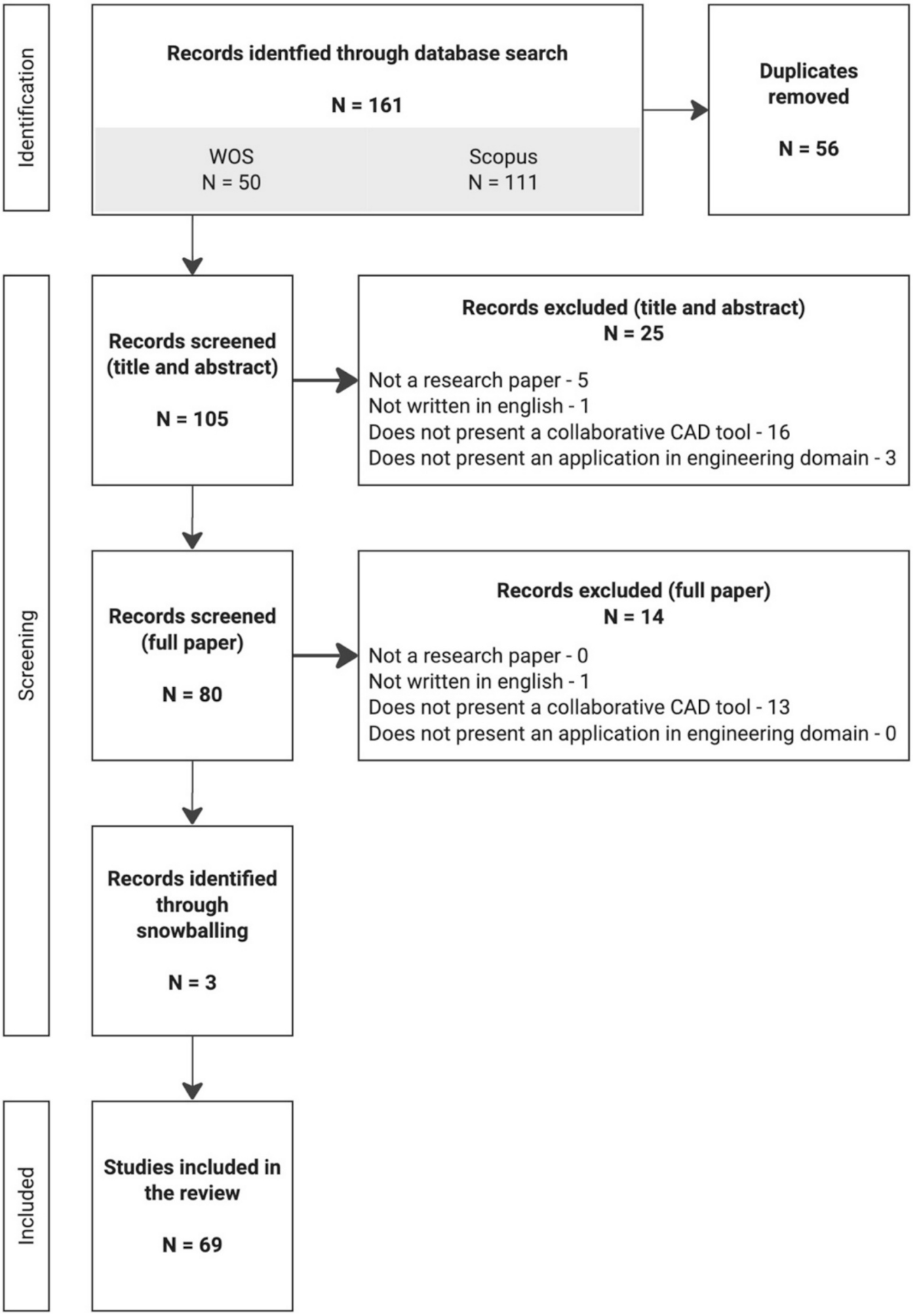

**Fig. 1.** Flow diagram of the systematic literature review, based on [63]

**Table 2**
Keywords and the search string

| **Search terms** | CAD “computer-aided design”<br>“computer aided design” | “collaborative CAD”“collaborative computer-aided design”MUCAD“multi-user CAD”“synchronous CAD”“online CAD”“cloud CAD” | “collaboration”“team*”“group*”“pair*” |
|---|---|---|---|
| **Web of Science** | TS=(CAD OR “computer-aided design” OR “computer aided design”) AND TS=(“collaborative CAD” OR “collaborative computer-aided design” OR MUCAD OR “multi-user CAD” OR “synchronous CAD” OR “online CAD” OR “cloud CAD”) AND TS=(“collaboration” OR “team*” OR “group*” OR “pair*”) | | |
| **Scopus** | TITLE_ABS_KEY(CAD OR “computer-aided design” OR “computer aided design”) AND TITLE_ABS_KEY(“collaborative CAD” OR “collaborative computer-aided design” OR MUCAD OR “multi-user CAD” OR “synchronous CAD” OR “online CAD” OR “cloud CAD”) AND TITLE_ABS_KEY =(“collaboration” OR “team*” OR “group*” OR “pair*”) | | |

**Table 3**
Inclusion criteria and examples of excluded study papers

| **The included paper:** | | **Exclusion examples** |
|---|---|---|
| a) is a research paper | | Lecture notes, technical reports |
| b) is written in English | | Paper written in other languages, Chinese for example |
| c) presents: | 1. collaborative CAD tool | Studies that propose the prescriptive models for the development or developed solutions for standalone and distributed CAD |
| | 2. an application in engineering design | Studies that present the application in business domain |

two-step screening process was applied to the identified studies.

### 3.3. Screening process

The screening process began with a review of titles and abstracts to eliminate studies that did not satisfy the inclusion criteria. The initial screening resulted in the exclusion of 25 studies. Among these, five were not research studies, one was written in a language other than English, 16 did not focus on collaborative CAD tools, and three lacked a proposed application in the engineering domain (Fig. 1). Consequently, 80 studies advanced to the next screening step.

In the second screening step, the researchers downloaded all the remaining studies. The full studies were then reviewed against the content inclusion criteria. During this phase, only one study was found to be written in a language other than English, even though its title and abstract were in English. Additionally, 13 studies were excluded because they did not present a collaborative CAD tool or its application in engineering domain. As part of the second screening process, snowballing was also employed as a method to uncover relevant literature that had not been identified through the initial database search [64]. This involved examining the references cited in the selected studies to identify additional studies that met the inclusion criteria. A total of three studies were identified through this method. Overall, a final set of relevant studies was 69. These studies were then analysed to develop subcategories and their elements for the top-level categories derived deductively from the AT, which, in turn, together with the systematic literature review analysis, was used to identify research opportunities related to collaborative CAD activities. The distribution of studies according to the source, whether scientific journals or conferences, is shown in Appendix B. In addition to that, the Sections 4.1 and 4.2 of the *Results* section provide the distribution of studies according to the published year and the author's affiliation country.

To strengthen the trustworthiness of the evidence base, the included studies were subjected to a quality appraisal. The appraisal was conducted after the final inclusion decision and in parallel with screening process. Given the heterogeneity of studies, which included both the empirical and non-empirical studies, two complementary appraisal tools were applied. Empirical studies were appraised using the Mixed Method Appraisal Tool (MMAT) [70]. In line with MMAT guidance, criterion-level ratings were utilised as the appraisal output, rather than an overall score. Each MMAT criterion could be rated as "Yes", "No", or "Can't tell". Criteria rated as "No" were treated as unmet, whereas criteria rated as "Can't tell" were excluded from the score calculation because they reflected insufficient reporting or information for a judgement. Therefore, the number of MMAT criteria rated "Yes" was converted into a percentage of the total of five criteria and grouped into four categories: very low (0-25%), low (26-50%), moderate (51-75%) and high (76-100%). Non-empirical studies were appraised using the Quality Assessment Tool for Theory-Based and Literature Review Studies (QATTL) [71], which is suitable for assessing the clarity and substantiation of conceptual contributions. QATTL item ratings were interpreted using the QATTL scoring guidance (0 = not at all, 1 = partially, 2 = mostly, 3 = completely, and 4 = irrelevant). Items coded as irrelevant were excluded from the calculation of the overall score for each study, and the total score was converted into a percentage of the maximum possible score and grouped into the same four categories: very low (0–25%), low (26–50%), moderate (51–75%), and high (76–100%). These categories were used to summarize the overall appraisal outcomes across the evidence base.

In addition to the methodological appraisal, and because the taxonomy is structured by Activity Theory, each included study was also assessed by examining whether it could be mapped to at least one Activity Theory category (*Subject*, *Object*, *Tool*, *Community*, *Division of Labor*, *Rules*). This step ensured alignment between the review objectives and the theoretical structure used for taxonomy development, while still capturing the breadth of the field, including studies that address only a subset of activity components. The appraisal was performed by a single author. To strengthen reliability and to reduce the risk of individual interpretive bias, a subset (13 or 18.8% studies) of the included studies was independently appraised by a second researcher (partial cross-check). The assessments were compared, and any ambiguous cases were resolved through discussion.

### 3.4. Taxonomy development

The taxonomy development method involves defining a meta-characteristic aligned with the purpose of describing and analysing research on collaborative CAD activities, and iterating through cycles of taxonomy development until predefined ending conditions are met [61]. The taxonomy development process follows a hybrid approach, combining top-down or theory driven and bottom-up or empirical synthesis approach based on the existing literature. Initially, top-level categories are defined deductively using AT, which serves as a theoretical framework for understanding collaborative CAD activities. The categories of *Subject*, *Object*, *Tool*, *Community*, *Division of Labor* and *Rules* establish a high-level structure but lack specific subcategories and elements. To refine the taxonomy further via a bottom-up or empirical synthesis approach, a SLR, as previously described, is coupled with Grounded Theory (GT) [65], to define taxonomy's elements (third level) and subcategories (second level). Instead of conducting traditional open coding (since top-level categories already exist), the subcategories and elements identification begins with axial coding, in which themes from the selected studies are systematically examined and categorised within the existing AT top-level categories. These subcategories and elements are then iteratively refined through selective coding, ensuring they align with the overarching meta-characteristic of the taxonomy [72]. Furthermore, although GT is often used to generate new theories, selectively applying its coding procedures (particularly axial and selective coding) can effectively organise and integrate empirical findings without fully committing to building a comprehensive theory [73]. This makes GT particularly suitable for developing a taxonomy that is dynamic in nature, or one that can evolve by capturing insights from new and additional data, as well as accommodate refinements to existing subcategories and elements. The development process continues until no new elements or subcategories emerge, fulfilling first objective ending condition. Another ending condition is that at least one element must be classified under every subcategory of every category, and that each subcategory within a category is unique (i.e., there is no duplication). The resulting taxonomy of collaborative CAD activities developed through systematic literature review is then presented in the subsection 4.3. of the *Results* section.

## 4. Results

This section presents the results of the systematic literature review, which provide the evidence base for the taxonomy of collaborative CAD activities and the identification of research opportunities. First, Sections 4.1 and 4.2 provide an overview of the reviewed studies, including their yearly distribution, authors' affiliation countries, and research objectives. Section 4.3 then presents the core findings of the review by analysing the studies through the top-level Activity Theory categories, thereby addressing first research question and deriving the second- and third-level taxonomy subcategories and elements relevant to research question 2. The distribution of studies across the Activity Theory categories also provides the basis for identifying underrepresented dimensions and research opportunities, which is discussed in Section 5 to address the third research question.

### 4.1. *Yearly distribution of research studies*

The distribution of identified studies by publication year is illustrated in Fig. 2. The graph depicts an increasing trend in the number of published studies. From 2001 to 2016, the number of studies ranged from zero to four. Since 2016, there has been a consistent upward trend in research studies addressing collaborative CAD activities, with a higher number of publications observed over the last four years, namely 6 studies in 2020 and 2021, 5 studies in 2023 and 8 studies in 2024. This indicates a growing interest in this field.

### 4.2. *Categorisation of reviewed research studies*

A substantial portion of reviewed research focused on developing solutions to enhance collaborative CAD capabilities. Some studies proposed solutions and prototypes for collaborative CAD tools or their components [35,74,75], while others developed frameworks and methods to enhance collaborative CAD activities [76–80]. Examples of such studies include frameworks to support collaboration in standalone CAD [77,79], the framework developed to support an analysis of collaborative CAD user behaviour using backend data [76], the teaching method for collaborative CAD [78] or proposing different modes of collaborative CAD activities [80]. Furthermore, within the final set, one study provided a review of digital advancements on collaboration and CAD [7], and one proposed a theoretical model of human interaction in collaborative CAD activities [30].

Another portion of research explored collaborative CAD activities empirically. Seventeen studies adopted practice-based research approach, including professional teams of designers working collaboratively [78,81] and student teams in educational settings engaged in university courses [84–96], project-based learning courses studies [97,98] and student competitions [76] and [41]. Furthermore, studies [82] and [83] assessed potential benefits and challenges of collaborative CAD activities in engineering design, based on the experience of users across different collaborative contexts. In addition, some of the studies assessed the usability of proposed proof-of-concept collaborative CAD tools, modules, or methods [75,87,99–101].

Finally, eleven studies used controlled experimental settings to isolate specific variables and gain detailed insights into different aspects of collaborative CAD activities, such as efficiency and the resulting CAD models' quality [42,102–104], communication [20,105–109], or emotional aspects [43]. All these studies were short-term experiments conducted over limited timeframes. Notably, none of the identified studies adopted longitudinal or extended-duration study designs. Taken together, these findings contribute to the first research question by showing how collaborative CAD activities have been conceptualised and studied across different research objectives, contexts, and study designs. The results of the systematic literature review on collaborative CAD activities were further used to develop a taxonomy that describes these activities.

### 4.3. *Taxonomy of collaborative CAD activities*

Building on the structural foundation derived from AT in the form of top-level taxonomy categories, a bottom-up approach was applied, leading to the emergence of second- and third-level taxonomy subcategories and elements, respectively. The complete taxonomy is provided in Appendix C.

The number of categories addressed per study is illustrated in Fig. 3. The distribution reveals that most studies, specifically 25, addressed only one category. Furthermore, there are 23 studies that addressed five categories, seven of them addressing four categories, ten studies that addressed three categories and four studies addressing two categories. Notably, none of the studies included in the systematic literature review addressed six categories.

Furthermore, the distribution of studies addressing each category is shown in Fig. 4. *Tool* category was widely covered with 67 (97.1%) studies addressing this category. *Division of Labor* category was not addressed by any of the studies included in the systematic literature review. Among the represented categories, the *Rules* category was the least addressed, appearing in 23 studies (33.3%). The *Subject*, *Object* and *Community* categories received attention in between the previously mentioned categories, with 34 (49.2%), 36 (52.2%) and 41 studies (59.4%) concentrating on these categories, respectively.

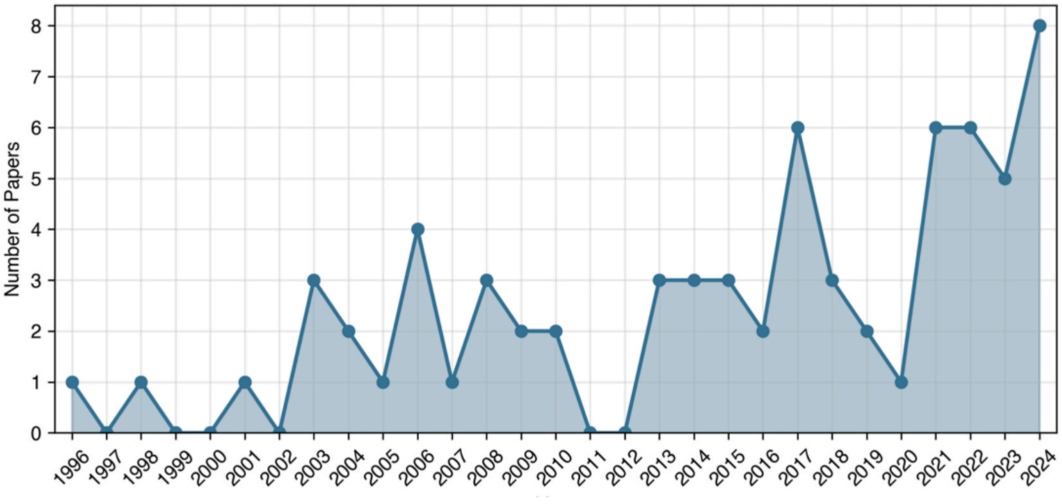

**Fig. 2.** Temporal distribution of identified studies

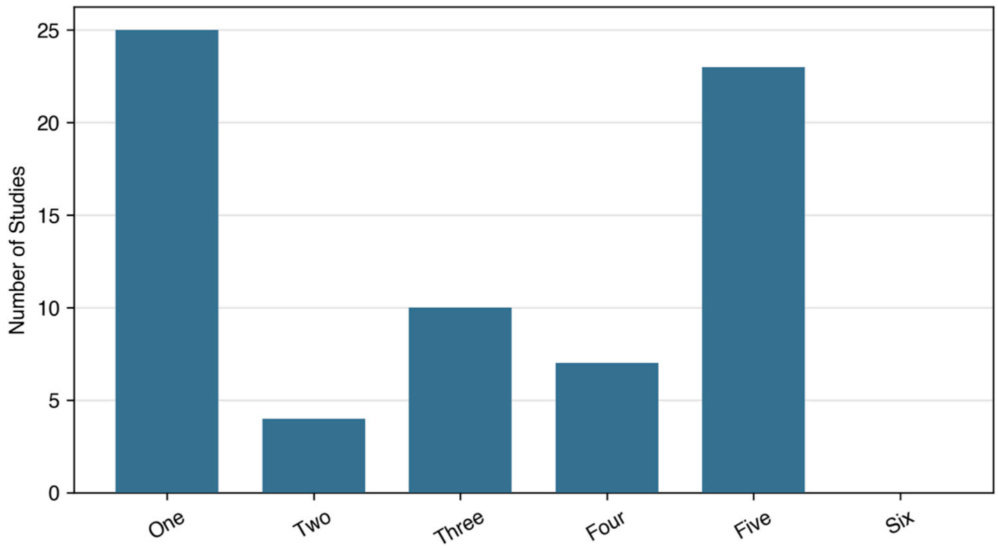

**Fig. 3.** Number of categories addressed per study

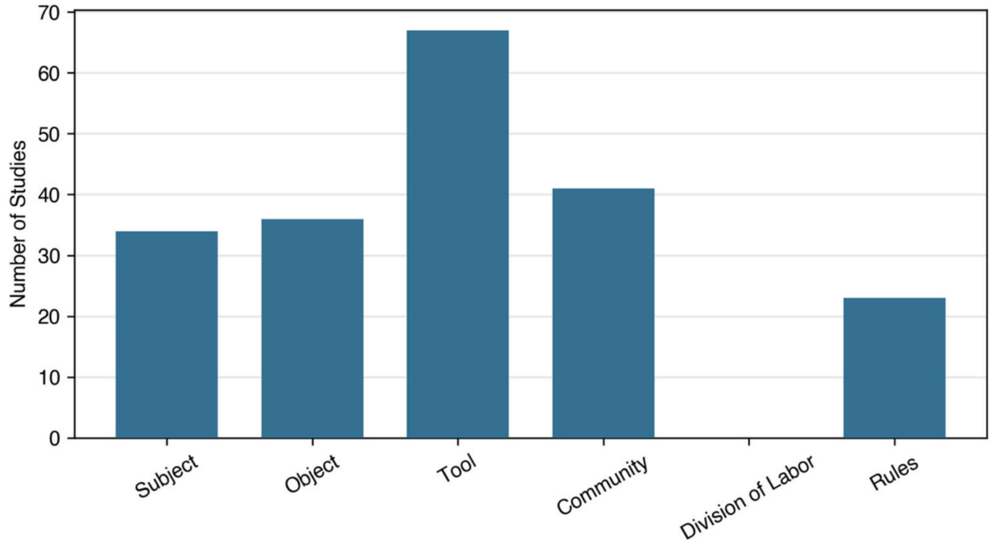

**Fig. 4.** Distribution of studies in each of top-level category

The following paragraphs present the identified subcategories and elements for the top-down AT-derived categories, along with a review of the literature that informed the newly derived element and subcategories.

### 4.3.1. *Subject*

A total of 34 studies focused on the *Subject* category (Table 4). Through a bottom-up, inductive approach, this category addressed differences of individual team members involved in collaborative CAD activities. As a result, the *Subject* category was divided into three distinct

**Table 4**
Studies within Subject category

| Subcategory | Element | Description | Identified references |
|---|---|---|---|
| Individual Experience | Task-specific experience | Practical application of knowledge over time or "knowing how" | [41–43,84–90,92,93,95–98,102,106,111] |
| | CAD-specific experience | Practical application of knowledge in the context of CAD | [20,74,76,78,80,103–105,108–110] |
| Individual Knowledge | Task-specific knowledge | Information, understanding, and theoretical concepts that the individual acquired through learning or to "knowing what" | [81,96,108] |
| | CAD-specific knowledge | Theoretical understanding of principles related to CAD model creation | [81,87,91,94,95,98,105] |
| | Collaboration-specific knowledge | Understanding of working with others, including teamwork, communication, coordination in a shared work environment | [81,83,96] |
| Individual Personality | CAD personality | The unique patterns of behaviours that distinguish one individual's approach to CAD work from another | [78,110] |

subcategories: *Individual Experience*, *Individual Knowledge* and *Individual Personality*.

A total of 31 studies focused on the experience of individual participants involved in collaborative CAD activities. Based on the identified studies within the *Individual Experience* subcategory, it is further categorised into two elements: *task-specific* and *CAD-specific experience*. In total, 19 studies informed *task-specific experience*. Participants had little to no *task-specific experience*, primarily because they were either students or novice users of collaborative CAD. The majority of participants were undergraduate and graduate students [43,84,86,87,89,90,94–96,106] majoring in mechanical engineering [41,42,85,88,97,98,102], followed by those in manufacturing engineering [41], civil engineering [41], engineering science [102], chemical engineering [102], students who had not yet declared a major [41], and high school students [92,93]. Furthermore, eleven studies specifically detailed the students' *CAD-specific experience*, noting that most had at least one year of CAD experience [20,103–105,108,109]. While most studies assumed that the participants were novice users based on their formal education backgrounds, some relied on self-reported CAD experience, where participants categorised themselves as beginners (never used CAD) [76]. In contrast, experts or individuals with professional CAD-specific experience were included in four studies. Some of these participants worked for companies without specifying the specific experience [78,110], while others specified their experience within engineering and manufacturing departments [74,80]. Additionally, some identified themselves as intermediates (having used standalone CAD but never collaborative CAD) or experts (a collaborative CAD professional) [76].

The review of the literature also highlights different aspects of knowledge that individual participants involved in collaborative CAD activities possess, in addition to their *task-* and *CAD-specific experience*. Seven studies differentiated individual participants involved in collaborative CAD activity based on their *CAD-specific knowledge* [81,87,91,94,95,98,105], while from three studies emerged *task-specific knowledge* as another element, related to areas like engineering design [81,108] or manufacturing [96]. There was also a focus on *collaboration-specific knowledge*, which pertains to communication [81,83] and teamwork [81,96]. Additionally, while a single study indicated that participants engaged in collaborative CAD activities possess varying levels of knowledge without specifying the exact aspects involved [107], another assumed overall knowledge based on their task-specific experience [109]. Furthermore, based on the analysis of collaborative CAD usage, two studies proposed specific personality traits of individual team members involved in collaborative CAD activities, referred to by the authors as *CAD personality* [78,110], which constitutes a third subcategory within *Subject* category of collaborative CAD activities.

### 4.3.2. *Object*

In total, 36 studies address the *Object* category. In the context of a collaborative CAD activity, the aim is to transform design information into a CAD model. Thus, the *Object* category not only considers the output but also includes the input to the activity. The category comprises three subcategories and their elements, as shown in Table 5.

Related to input of the collaborative CAD activity, a total of 29 studies examined the element of *Design input information*. Among these, 20 studies utilised graphical representations. These included initial or pre-modelled CAD models representing parts that are further modified [20,35,43,80,90,104,105,108,109] or assembled [100,102,103], sketches from patent databases [85–87], concept sketches [98], product figures [106], detailed technical documentation [94] and 2D mechanisms [89,91]. Another element of input information in collaborative CAD activities is the semantic or textual representations, which were addressed in 15 studies. These included lists of design requirements [81,85–88,96,97,106], instructions for open-ended challenges [76], feedback from design reviews [105], and written instructions for modification of an existing CAD model [20,43,104,108,109]. Additionally, the analytical design input information has been discussed in three studies, such as walking mechanism for a robot [89,91] or aeronautical parameters for a glider being design utilising collaborative CAD [95]. There is also one study addressing the physical representation of input information [41], which served as the basis for creating the assembly.

For outputs, the subcategory *CAD output type* refers explicitly to forms of CAD representations generated through collaborative CAD activities. A total of 36 studies explored these types, categorised as *part*, *assembly*, and *technical drawing*. Thirteen studies examined collaborative CAD activities that resulted in creations [96,107] or modifications [80] of CAD models of individual parts. Some studies focused on tasks such as executing assigned changes to a CAD model [43,105,108], or modifying a CAD model [20,101,104,109]. In other examples, collaborative efforts aimed to create CAD models of specific parts [42,84,95]. Furthermore,

**Table 5**
Studies within Object category

| Subcategory | Element | Description | Identified references |
|---|---|---|---|
| Design Input Information | Graphical input information | A sketch, CAD models, drawings, renderings | [20,35,43,80,85–87,89–91,94,98,100,102–106,108,109] |
| | Semantic input information | The verbal or textual representation of the information | [20,43,76,81,85–88,96,97,104–106,108,109] |
| | Analytical input information | The equations or rules representing the form or function of the object that the information represents | [89,91,95] |
| | Physical input information | The hardware or a physical model of the object being represented by the input information | [41] |
| CAD Output Type | Part | An individual 3D model representing a single, distinct component of a design | [20,42,43,80,84,95,96,101,104,105,107–109] |
| | Assembly | A collection of multiple parts combined to create a complete product or a technical subsystem or a system | [41,76,81,84,87–94,97,98,100–103,106,112–114] |
| | Technical drawing | A 2D representation of parts or assemblies made for manufacturing or documentation purposes | [112–114] |
| CAD Output Purpose | Conceptual design purpose | Rough design representations in CAD that illustrate potential design solutions | [76,81,89–91,96,106] |
| | Embodiment design purpose | Created, refined and detailed concept as a viable and functional design representation in CAD | [20,43,81,85–88,97,98,102–105,108,109] |
| | Prototyping and testing purpose | Virtual prototypes utilised for evaluation of design performance | [81,92–95,103] |
| | Detailed design purpose | Finalised representation of design and detailed drawings with exact tolerances in CAD | [112–114] |

output in the form of an assembly was addressed in 22 studies. Examples included assigning appropriate mates to pre-modelled parts [90,101–103] or assembling parts created during the same collaborative CAD activities [41,87–91,94,97,98,100,106]. Some studies explored the assemblies stemming from student competitions [76,81,84,92,93]. Also, three studies addressed technical drawing as a result of collaborative CAD activities [112–114]. Furthermore, the subcategory *CAD output purpose* highlights how the collaborative CAD activity outputs are intended to support different stages of the engineering design process. In total, 23 studies addressed this subcategory. Among these, seven studies focused on *conceptual CAD output purpose* [76,81,89–91,96,106], 15 on *embodiment CAD output purpose* [20,43,81,85–88,97,98,102–105,108,109], six studies addressed element of *prototyping and testing purpose* through the virtual or physical prototyping of the design resulting from the activity [81,92–95,103], and three studies emerged supporting the detailed design stage [112–114].

### 4.3.3. Tool

The *Tool* category was addressed in 67 studies (detailed in Table 6). All of them focused on *Design and engineering tools*, specifically *CAD tools* [35,74,81,84,94,95]. Most of the studies utilised commercially available collaborative CAD software, such as Catia [115], Solidworks [105,108] and Onshape [20,43,76–78,80,85–90,92,93,96–98,101–105,108–110,115]. Prior to the technical prerequisite for the development and availability of collaborative CAD, such as Onshape, research studies focused on proposing and developing solutions that enable standalone and distributed CAD to operate as collaborative CAD [30,32,33,116–119]. These also include collaborative plugins like NXConnect for Siemens NX [41,42,75,99,106,107,115] and CyberCAD [79,120] designed for part modelling, or e-Assembly [100] for assembling parts pre-modelled in commercially available standalone CAD. Another element of design and engineering tools is *Computer-Aided Engineering (CAE) Tools* that facilitate engineering analysis and optimisation of the collaborative CAD activity object [7]. Furthermore, *Collaboration tools* is also a subcategory identified within *Tool* category. Within those, twelve studies addressed *Communication Tools*. These included Zoom [76,102,103], Google Hangouts [20], MS Teams [97,98], and the built-in chat or commenting functionalities of collaborative CAD software, such as the one provided by Onshape [101,108,110]. The rest have not mentioned specific communication tool except that the one was used in the studies [95,101,106,107]. The other element concerning collaboration tools are *Coordination Tools*, such as task management [107] or document management [7] tool. Moreover, one study addressed the use of *AI-based Tools*, specifically *Generative AI tools* and *AI assistive tools*, suggesting that emerging technology such as AI has the potential to revolutionise the approach to designing and engineering products, including collaborative CAD activities [7]. *Extended Reality Tools* represent another subcategory of *Tool* category, as mentioned in six studies. Among those, three studies compared design reviews that followed collaborative CAD activities and were conducted using virtual reality (VR) tool [85,86,97]. One study [84] specifically focused on using VR to evaluate and enhance the design of artefacts within collaborative CAD activities. Furthermore, [79] discussed how integrating VR into collaborative CAD activities could help reduce design time and cut costs. Also, one study mentioned the capability of empowering designers by allowing them to observe their designs at scale and execute real-time modifications utilising both the virtual (VR) and augmented reality (AR) tools [7].

### 4.3.4. Community

The *Community* category of the activity places it within the social context of the environment in which collaborative CAD users operate [52]. The subcategories and the elements of this category, addressed in 41 studies, derives from the way the teams involved in the activity are organised (detailed in Table 7).

*Team Configuration* emerged as a first subcategory within the *Community* category, discussed in 41 studies. It consists of two elements: *Team size*, referring to the number of members involved in the activity, and *Team familiarity*, which refers to the history among team members, distinguishing between established teams with a shared history and future, and newly formed teams formed for a specific task. Regarding *Team size*, most teams involved in collaborative CAD activities consisted of pairs or teams of two members [42,43,76,80,95,96,102–105,107,109,110,115], followed by teams of three [41,42,76,85–91,100–103]. Additionally, there were also teams with four [42,76,102,103], eight [78,97], and ten members [98]. Furthermore, 20 studies addressed the familiarity of team members. Among these, the majority addressed newly formed teams [20,41,43,76,82,92,94,95,100,102–104,106,107,109]. The remainder referred to established teams, such as those from industry settings [78] or educational environments, which worked together for at least three months [84,87,97,98].

*Team Distribution* subcategory emerges as another subcategory within *Community* category, as identified in 38 studies. This subcategory encompasses three elements: *Geographical team distribution*, *Temporal team distribution and Expertise-based team distribution*. Firstly, *Geographical team distribution* refers to whether team members work distributed or co-located. The majority of studies (27) focus on distributed collaborative CAD activities, where team members interact from different physical locations [43,76,77,79,80,84,85,87,90,92–95,97–103,106,108,115]. While most of these studies explicitly stated that the activities were organized in a geographically distributed manner, some mentioned this implicitly. For instance, in study [102], the activity was conducted

**Table 6**
Studies within Tool category

| Subcategory | Element | Description | Identified references |
|---|---|---|---|
| Design and Engineering Tools | CAD tools | Computer-based tools that assist in the creation, modification, simulation, analysis and optimization of an information object that represents a design | [7,20,30,33,35,41–43,74–81,84–134] |
| | CAE tools | Computer-based tools that help in predicting and improving performance of designed artefacts and reducing physical prototyping costs | [7] |
| Collaboration Tools | Communication tools | Digital tools that facilitate exchange of information between individuals or teams | [20,76,95,97,98,101–103,106–108,110] |
| | Coordination tools | Digital tools that help manage and align tasks, schedules, and workflows in tasks | [7,107] |
| AI-based Tools | AI assistive tools | Tools that utilise AI to assists in performing tasks | [7] |
| | Generative AI tools | Tools that utilise AI to create new content based on existing dataset containing text, image or other data types | [7] |
| Extended Reality Tools | Augmented reality tools | Digital tools that encompass immersive technologies to merge digital and physical environments | [7] |
| | Virtual reality tools | Digital tools that encompass immersive technologies that create fully virtual spaces | [79,84–86,97] |

**Table 7**
Studies within Community category

| Subcategory | Element | Description | Identified references |
|---|---|---|---|
| Team Configuration | Team size | The number of collaborative CAD users in the activity | [41–43,76,78,80,85–91,95–98,100–105,107,109,110,115] |
| | Team familiarity | A configuration of a team based on a shared history, distinguishing between established teams with a shared history and future, and newly formed teams formed for a specific task | [20,41,43,76,78,82,84,87,92,94,95,97,98,100,102–104,106,107,109] |
| Team Distribution | Geographical team distribution | Activities that involve subjects interacting from different (distributed) or the same (co-located) physical locations | [20,41,43,76,77,79,80,84,85,87,90,92–104,106,108,115] |
| | Temporal team distribution | Collaborative CAD activities occurring at the same time (synchronous) or at different times (asynchronous) | [20,41,43,76,79–81,84–86,94,95,98–109,115] |
| | Expertise-based team distribution | Collaborative CAD users are engaged in the collaborative CAD activity from a same (single-domain) or different disciplines (multi-domain) | [20,41–43,78,80,81,84–87,91,94,95,97,98,104–106,108–110] |
| Interaction Mode | Collaborative working mode | Collaborative CAD users work independently in real-time on the same CAD model (parallel) or share control of the CAD model, with only one user having control at a time (shared) | [20,41,43,76,77,79–81,85,90,93,95–106,108,109] |
| | Communication mode | Communication occurs through written text (textual), via spoken interaction (verbal) or relies on visual cues (visual) | [20,41,43,79,81,82,90,94–96,98,99,101–103,105,107–109,114] |

using a digital communication tool, what the authors interpreted as though

collaborative CAD users were geographically distributed. In contrast, only four studies focused on co-located collaborative CAD activities, where team members work together in the same physical space [20,41,96,104]. Secondly, *Temporal team distribution* differentiates between synchronous team distribution and asynchronous team distribution. Synchronous collaborative CAD activities, where team members interact in real-time, is the focus of 22 studies [20,41,43,76,80,85,86,94,95,98–109,115]. In contrast, only four studies investigate asynchronous collaborative CAD activities, where interactions occur independently of time, where users do not engage simultaneously [79–81,84]. Lastly, *Expertise-based team distribution* refers to disciplinary backgrounds among team members and differentiates single-domain teams and multi-domain teams. Single-domain teams refers to teams composed of members from the same discipline or with the same expertise. A total of 18 studies focused on such single-domain teams, where all participants shared a common mechanical engineering background [20,41,43,78,81,85–87,91,94,95,97,98,104,105,108–110]. In contrast, multi-domain teams encompass teams consisting of users from different disciplines or with different expertise. Only four studies examined such teams. Some mentioned users from various engineering fields [42,106], while others examined broader interdisciplinary projects, such as design project involving participants from both engineering and project management [84] or participants from different engineering disciplines, including aerospace engineers [80].

Third subcategory emerging within the *Community* category is *Interaction Mode*, analysed in a total of 25 studies. This subcategory defines how collaborative CAD users engage in collaborative CAD activities and is further classified into two elements: *Collaborative working mode* and *Communication mode*. The *Collaborative working mode* element describes how team members interact with the CAD model during activity. In a parallel working mode, collaborative CAD users work independently in real-time on the same CAD model. This approach is addressed by 22 studies [20,41,43,76,77,79–81,90,95,97–106,108,109]. Conversely, in a shared working mode, users share control of the collaborative CAD interface and the CAD model, with only one user actively making modifications at a time while others observe and contribute through guidance. This mode was explored in five studies [20,85,93,96,104]. Another element, *Communication mode*, explores how collaborative CAD users exchange information during the activity, regardless of whether or not they utilise built-in features of collaborative CAD tools. Among the 20 studies addressing *Communication mode*, the majority (13 studies) reported that users communicated verbally [20,41,79,81,82,94–96,98,102,103,105,109]. Additionally, nine studies indicated textual communication, where participants exchanged messages in a written format [43,79,81,90,98,99,101,107,108]. Notably, one of the studies in this subcategory mentioned the use of visual communication by utilising communication tool with the video-conferencing functionality [114].

### 4.3.5. *Rules*

The *Rules* category is addressed in 23 studies (shown in Table 8). Within this category, there is only one subcategory that aligns with the definition derived from the AT, which is *Strategies*. This subcategory pertains to the practices involved in creating or modifying CAD models, as well as the design methods employed, addressed in three studies. Two of these explored *CAD modelling strategies*, such as parametric modelling [77] and strategies for assembling in CAD [96]. The third study focused on *design methods*, specifically addressing how to design a part in CAD to comply with design for manufacturability rules [74].

Furthermore, some subcategories pertain to the implications that rules have on the execution of activities, which are informed by evaluation metrics and criteria. In the context of collaborative CAD activities, these implications relate to elements of team outcomes, or the “byproducts of team activity” [135], such as taskwork (what team

**Table 8**
Studies within the Rules category

| Subcategory | Element | Description | Identified references |
|---|---|---|---|
| Strategies | CAD modelling strategies | Best practices employed in CAD for efficient, effective and accurate model creation | [77,96] |
| | Design methods | Methods for structuring and guiding the design process | [74] |
| Taskwork Measures | Efficiency measures | The extent to which the gains are achieved in the proportion of the resources used, such as time | [20,42,84,89,91–93,105,107,108] |
| | Productivity measures | The volume of work completed within a specific timeframe | [41,102,103,108] |
| | Quality measures | The extent to which a CAD model is valid, complete, consistent, concise, simple, and capable of conveying design intent | [20,42,87,104] |
| | Effectiveness measures | The degree to which the output meets the intended objective of the activity | [92,93,98] |
| Teamwork Measures | Behaviour measures | Measures evaluating what team members do, such as communicating and coordinating | [20,41,90,95,102,103,105–109] |
| | Attitude measures | Measures evaluating what team members believe or feel | [20,41,43,76,95,105,106] |
| | Cognition measures | Measures evaluating what team members think or know | [41,91,106] |

members have done together) and teamwork (how they have done it) [47,48]. Therefore, these subcategories are designated as *Taskwork Measures* and *Teamwork Measures*.

The *Taskwork Measures* subcategory focuses on assessing the outcomes of collaborative CAD activities, including measures of efficiency, productivity, quality, and effectiveness. Among the 16 research studies that evaluated taskwork, majority focused on the measures of *Efficiency* (ten studies), followed by measures of *Productivity* and *Quality* (four studies each), whereas the element of *Effectiveness measures* was addressed by three studies.

In general, the efficiency of an activity is often expressed as a ratio between the gains achieved and the resources used to obtain them. All studies within this systematic literature review measured efficiency using time as a resource. One metric for evaluating time efficiency is by assessing the time spent per collaborative CAD user [92]. Furthermore, research has shown that the time spent on collaborative CAD tasks is influenced by the collaboration working mode. Specifically, parallel CAD pairs tend to be slower than individual users, but faster than shared CAD pairs [20]. Compared with individual participants, pairs were slower [105,108], mainly due to coordination efforts through communication. Another efficiency metric is related to the iterations. High-performing teams tend to execute more and smaller, evenly spaced iterations rather than larger, unevenly spaced, concentrated iterations [93]. Interestingly, more active collaborative CAD users are not directly associated with iteration levels or cadence [89]. The number of collaborative CAD users also plays a role in time efficiency, with larger teams generally reducing activity completion time [42]. Additionally, studies highlight the advantages of implementing collaborative CAD activities, particularly in reducing design and production time [84]. Furthermore, using a task management system during collaborative CAD activities enhances time efficiency, according to [107]. Finally, team structure and knowledge levels influence both individual and team efficiency in collaborative CAD activities [91].

The productivity of collaborative CAD activities refers to the volume of work done in a specific timeframe. In the studies within the systematic literature review was assessed using metrics mainly related to CAD modelling, such as mates added per collaborative CAD activity time through calendar time and individual collaborative CAD user time. Collaborative CAD teams outperformed single CAD users in productivity when measured by calendar time [102,103], but slightly worse when measured in individual collaborative CAD user time due to added communication overheads. Nevertheless, collaborative CAD teams of all sizes became more productive as assembly complexity increased [102]. Conversely, single participants were found to be more productive than pairs when measured by the total number of implemented CAD changes [108]. Furthermore, collaborative CAD teams showed an increase in productivity, scoring over twice as many points per minute, a measure used in the study, as single CAD users [41].

The quality was measured using four CAD model quality categories of completeness, conciseness, consistency, and validity [37]. Collaborative CAD teams working in a shared working mode consistently created the highest quality outputs in collaborative CAD activities, outperforming both individual CAD users [20] and collaborative CAD teams working in parallel working mode [20,104]. Another study showed that collaborative CAD teams created higher quality models than individual CAD users [42]. Furthermore, an analysis of collaborative CAD activities in the study [87] revealed two distinct approaches between teams producing higher and lower quality outputs. Finally, *effectiveness* in collaborative CAD activities is assessed by the degree to which the output meets the intended objective [136]. It is addressed by three studies [92,93,98], pertains to whether an activity produces the desired output presented before the activity [137], regardless of resources used.

*Teamwork Measures* are addressed by 15 research studies, further categorised into evaluating behaviours (what team members do), attitudes (what team members believe or feel) and cognitions (what team members think or know).

In terms of *Behaviour measures*, eleven studies primarily focus on measuring communication and coordination. Analysis of communication frequency reveals that high-performing teams exhibited communication patterns with spikes at the beginning and end of activities [41,102,103]. In contrast, low-performing teams tend to communicate uniformly [41,102,103]. When measuring the amount of activity time spent communicating, one study found that collaborative CAD pairs working in shared working mode communicate almost twice as much as those working in parallel mode [20]. Additionally, a survey assessing communication satisfaction indicated that team members using standalone CAD experience greater communication difficulties compared to those using collaborative CAD [95]. Post activity feedback in another study revealed that geographically distributed teams were more reserved when working with unfamiliar team members [90]. Moreover, when examining the proportion of communication relative to total activity time, it was discovered that communication in pairs adds overhead compared to individual CAD users [105]. Also, teams utilising collaborative CAD spent more time communicating than teams using standalone CAD [106]. Another study indicated that novices communicated less than experts [109]. It was also noted that expert-novice pairs showed higher overall communication time, as novices sought advice and experts provided guidance. In contrast, when measuring the share of communication used for activity planning and assisting each other, expert pairs relied primarily on communication for planning, while a significant portion of the communication in expert-novice pairs was dedicated to helping and advising [108]. Lastly, to evaluate coordination, an analysis of chat messages sent by teams with and without the task management system revealed that the use of such tools significantly reduces the number of confusion messages [107].

*Attitude measures* have been recognised as another subcategory within *Rules* category and have emerged in seven studies. Emotional responses were measured by calculating the average duration that emotions were present during collaborative CAD activity, based on data from facial recordings and emotion detection of participants. One study found that pairs exhibited more emotional responses overall, including higher levels of joy, anger, and contempt per person, compared to single users, who primarily showed disgust and surprise [43]. Using the same measurement approach, another study revealed that pairs expressed more positive emotions than single users [105]. Additionally, a survey assessing frustration levels showed no significant differences between teams using collaborative and standalone CAD [106]. In another post activity survey participants were asked to rate the strength of their relationship with each member of their team. Teams composed of members who knew each other prior to the activity performed better than those composed of complete strangers [41]. Lastly, four studies measured team satisfaction, all using surveys for measurement [20,76,95,106]. Team satisfaction was found to be high during collaborative CAD activity, with participants appreciating the diverse knowledge and ideas introduced through teamwork [76]. Another study has revealed that CAD users utilising standalone CAD reported higher team satisfaction compared to users utilising collaborative CAD [95]. However, other studies found no significant differences in satisfaction between teams utilising collaborative and standalone CAD [20,106].

*Cognitive measures* were addressed in three studies. The first study assessed team members' visualisation skills measured by the Purdue Spatial Visualization Test [41]. It found that having similar skill levels among team members may be more important than relying on one or two highly skilled individuals. However, another study [106], which also used the same test, concluded that the visualisation skills' assessment may not be the best for evaluating CAD skills in a population already familiar with CAD software. Furthermore, participants self-evaluated their analytical thinking through a survey, highlighting the cognitive processes of problem identification, strategy formulation, and problem decomposition as highly significant. In contrast, the processes of finding relationships and evaluating solutions were the least recognised [91].

## 5. Discussion

In line with the research objectives, the study develops a taxonomy of collaborative CAD activities by deriving the first-level categories deductively from Activity Theory and by deriving the second- and third-level subcategories and elements inductively from the evidence synthesised through the systematic literature review. This synthesis also provides an overview of the current evidence and where research attention has been concentrated, thereby supporting the identification of research opportunities in studying collaborative CAD activities to address the third research question.

The systematic literature review highlights the growing research interest in collaborative CAD activities, particularly in recent years. This trend suggests an increased recognition of collaborative CAD as relevant to the outputs of related activities, on both the taskwork and teamwork, which are important aspects of engineering design [138]. Also, the developed taxonomy provides a structured approach to describe and understand the technical and social interplay of collaborative CAD activities. Moreover, the insights gained from the systematic literature review, along with the development of this taxonomy, have led to the identification of several research opportunities. The importance of a conceptual understanding of collaborative CAD activities emerged from the analysis of the literature. Specifically, identified opportunities are derived from the lack of research involving professional CAD users and designers, insufficient exploration of multi-discipline team configurations, and from the integration of emerging technologies into the study of collaborative CAD activities. Additionally, there is a need for a unified evaluation measure corresponding to the research motivations behind this study, which would provide a foundational framework for investigating and describing collaborative CAD activities, allowing for generalisation and comparison across different studies. Finally, refining and building upon the proposed taxonomy presents another research opportunity, as also described in the motivations for this study.

### 5.1. Research opportunity 1: The importance of conceptual understanding of collaborative CAD activities

One of the key findings is the fragmentation in how collaborative CAD activities are defined and studied. Although researchers are addressing the same phenomenon, they explore it by studying varying aspects of phenomenon. Without a conceptual foundation of collaborative CAD activities, it becomes challenging to compare findings or systematically build on previous research. A clearer understanding of collaborative CAD activities may encourage researchers to move beyond isolated or anecdotal findings and may align individual studies towards a broader objective, thereby creating a body of knowledge about collaborative CAD activities. Additionally, conceptualisation of collaborative CAD activities could prevent duplicative efforts and supports comparisons across different setups and domains, such as industrial design [139] or construction [140].

The taxonomy presented in this study addresses this fragmentation by providing a framework for the description of collaborative CAD activity, thus providing a starting point for the conceptualisation of such activity that ensures both theoretical coherence and empirical validity [26]. It also offers a common language for studying these activities, integrating both the social and technical aspects, which is often a limitation of existing taxonomies in collaborative design [22,44,46]. Therefore, the taxonomy provides a base for defining consistent terminology, cross-study comparisons, and serving as a foundation for future research on collaborative CAD activities.

### 5.2. Research opportunity 2: Towards professionals and interdisciplinarity in collaborative CAD activities

As engineering design increasingly relies on interdisciplinary collaboration [28,84] and practice [141], it is important to understand how individuals with high level of task- and CAD-specific knowledge and experience, as well as diverse expertise, influence collaborative CAD activities. Although studies that informed the proposed taxonomy yield some insights mainly based on novice collaborative CAD users and single-domain teams, users of professional task- and CAD-specific knowledge and experience bringing different levels of expertise and highly specialised knowledge can reshape collaborative CAD activities [142]. Interdisciplinary settings can reshape the matter further, introducing task-specific knowledge, tasks, objectives and tools, which were only partially captured in the taxonomy's *Community* element of *Expertise-based team distribution*. Regarding the developed taxonomy and the extendibility of the taxonomy, professional and interdisciplinary teams can validate whether existing taxonomy elements, such as *Team size*, *Team familiarity*, or *Interaction mode*, remain sufficient or require further differentiation. New subcategories or elements may emerge around leadership roles or the parallelisation of work [143], which could inform potential subcategories and elements to the *Division of Labor*, a AT category that has not yet been addressed by the studies included in the systematic literature review upon which the taxonomy is based.

### 5.3. Research opportunity 3: Integrating AI technologies

The tools used in collaborative CAD activities, as outlined in the taxonomy, play a crucial role in mediating the activity, by providing a means for the subject to interact with the object [60]. Therefore, it is essential not only to explore collaborative CAD and its impact on design activities traditionally focused on standalone and distributed CAD, but also to consider the integration of tools based on emerging technologies. Recently, the emergence of AI-based tools has become one of the most discussed topics. The discussion revolves around whether such tools can act as a human collaborator or a team member, actively contributing to problem-solving [144], or if they simply respond reactively to human queries, serving as support tools instead [145]. However, the proposed taxonomy is informed by only one study [7] aimed at introducing the use of AI-based tools within collaborative CAD activities. Given the evidence suggesting that the utilisation of these tools might challenge both taskwork [146] and teamwork [147], there exists a significant research opportunity to explore how a broader range of AI-based tools influences collaborative CAD activities, far beyond what was covered in that single study. For example, in addition the proposed AI-based design tools in the taxonomy, but regarding CAD activities in general, some of those may be generative AI design tools that can propose design alternatives by analysing vast amounts of historical design and CAD data, potentially enhancing CAD activities by reducing manual work [148]. Similarly, AI assistive tools, by providing contextual design [149] and CAD modelling recommendations [150], may also influence CAD activities, including collaborative CAD activities. Recent work has begun to build the foundations for such AI integration through large-scale CAD datasets. The history-based parametric CAD sketch dataset which includes history of feature-based operations utilised to create sketches [151] enables modelling of how CAD users sequence and constrain their sketches, capturing the process rather than only the final CAD model. Similarly, the parametric and feature-based CAD dataset [152] provides annotated CAD models that support human–computer interaction and learning-based approaches to feature-based operation manipulation. These datasets are valuable because they enable the training of AI models that can learn from actual workflows, generate or recommend modelling steps, and evaluate alternative CAD modelling strategies. By embedding feature-based operation histories, such datasets provide the foundation for developing AI tools that not only manipulate geometry but also support collaboration by anticipating CAD user actions and potentially reducing coordination overhead.

Understanding how AI-based tools impact collaborative CAD activities is crucial in ensuring that AI augments rather than diminishes collaborative CAD activities. Therefore, future research should focus on two main objectives. First, it should investigate the types of AI-based tools and how these tools affect both the social and technical dimensions of collaborative CAD activity, particularly the implications for team dynamics and design quality in CAD [147,153]. Second, insights gained from such exploration should be used to extend and refine the proposed taxonomy, particularly the *Tool* category, as well as the taxonomy as a whole.

### 5.4. Research opportunity 4: Unification of the evaluation measures

The taxonomy’s *Rules* category provides broad evaluation criteria, such as *Taskwork measures* and *Teamwork measures*. However, the absence of unified metrics limits the synthesis and the comparability between different studies. By unifying evaluation measures for collaborative CAD activities, the fragmented findings can be consolidated into a comprehensive body of knowledge for collaborative CAD activities across various conditions. Further research is important to refine metrics derived from a bottom-up approach and to develop standardised benchmarks for evaluating collaborative CAD activities. Studies should aim to establish both quantitative and qualitative measures for assessing the workflow and outcomes of these activities. Additionally, it is important to examine how various subcategories and elements of the taxonomy influence the outputs of collaborative CAD activities. Research should also explore the relationships between various evaluation metrics, examining how improvements in one metric can influence another. Understanding these relationships will facilitate recommendations for prescribing collaborative CAD activities. Furthermore, the taxonomy can be enhanced by incorporating task-specific evaluation measures, such as those related to manufacturability. In conclusion, implementation and refinement of unified metrics can improve both the practical relevance and theoretical rigor of research on collaborative CAD activities.

### 5.5. Research opportunity 5: Refinement of the collaborative CAD activity taxonomy

The developed taxonomy provides a foundational framework for describing collaborative CAD activities. However, on top of the conceptual understanding of the phenomenon, future research should also focus on refining and validating this taxonomy through both the theoretical and empirical studies across different engineering design setups and engineering domains. While the systematic literature review revealed that the short-term experimental studies or design challenges case studies are dominant, it is important to address and explore collaborative CAD activities over longer period by conducting longitudinal studies. Conducting longitudinal studies can provide insights into how collaborative CAD activities evolve over time and how different factors influence the activity output. Regarding the developed taxonomy, by performing the longitudinal studies, researchers can also determine whether the taxonomy requires new subcategories and elements to account for the active nature of collaborative CAD activities [61]. This approach can help establish a more comprehensive understanding of collaborative CAD activities, ensuring that studies capture not just what occurs in such activities, but also how and why those develop over time. Furthermore, applying this taxonomy across diverse engineering disciplines such as mechanical engineering, architecture, and manufacturing can help assess its generalisability and identify domain specific adaptations.

#### 5.5.1. Implications

The proposed taxonomy and identified research opportunities have various implications for researchers, practitioners, and educators. For researchers, this study highlights the need to develop and refine theoretical models of collaborative CAD activities, develop standardised evaluation metrics, by having in mind new technological advancements such as AI. To achieve this, the proposed taxonomy can serve as a foundational starting point. Researchers should conduct empirical studies based on the developed theories, standardised evaluation metrics, and the proposed taxonomy to investigate collaborative CAD activities and what influence them positively. As findings emerge and technology continues to evolve, researchers can expand the taxonomy at the category, subcategory, and element levels. In this way, the proposed taxonomy may become a main source, enabling researchers to identify research gaps and build upon one another's work. This approach is applicable to researchers across various engineering domains where multi-user synchronous work in CAD takes place.

Once a comprehensive body of knowledge is established, both researchers and practitioners will have a better understanding of when and how to utilise collaborative CAD in design activities that typically rely on traditional CAD, but now may include multi-user synchronous work, considering factors such as team structure, object expectations, expertise diversity, and the decision of whether to utilise AI-based or extended reality tools simultaneously. The findings can also guide practitioners in developing collaborative CAD tools that enhance both synchronous and asynchronous collaboration capabilities. Additionally, the collaboration capabilities can also be improved by integrating the AI-based tools and other technological advancements enabled by emerging technologies into collaborative CAD tools. Finally, for educators, the proposed taxonomy can be utilised to create teaching strategies and identify use cases for collaborative CAD. For example, the taxonomy emphasises both technical skills, such as the domain and CAD knowledge and expertise, as well as soft skills such as teamwork or communication. By focusing on those, students can be better prepared for real-world engineering challenges.

### 5.5.2. Limitations and future work

Although the proposed taxonomy provides a structure for analysing and studying collaborative CAD activities, several limitations may affect the presented findings. The systematic literature review depended on published academic literature, which sometimes focuses on short-term experiments or educational settings. As a result, certain subcategories and elements of the proposed taxonomy may not be fully represented. Also, despite employing a systematic search strategy, inconsistencies or incomplete reporting in the identified studies may result in some subcategories and elements being under-documented. Furthermore, because the taxonomy was derived primarily from academic sources, the identified subcategories and elements may not capture all elements of long-term or large-scale professional collaborative CAD activities. Moreover, there is also a difference in the collaboration requirements in other engineering domains utilising CAD or similar tools such as construction or electronics. Since this paper focuses only on the engineering design, the taxonomy may not fully represent all the subcategories and elements of the associated collaborative CAD activities in other engineering domains. It is therefore important not only to expand the taxonomy through systematic literature reviews from other engineering fields to ensure broader applicability, but also to validate it by conducting empirical research both in engineering design and in other domains where CAD is used collaboratively.

Another limitation concerns the lack of real-world industrial data to support and extend the presented findings from the systematic literature review. While the taxonomy is primarily driven by research purposes and aims to provide a framework for defining and studying collaborative CAD activities in engineering design, this study does not evaluate the practical effectiveness of applying the taxonomy in real-world settings and projects. The evidence base identified in this study also provides limited large-scale in-situ validation of classification research approaches of collaborative CAD activities. Since the aim of engineering design research is also to support work in real-world settings, this gap could be addressed by organising experiments in industrial real-world environments or by drawing on diverse sources of data (e.g., PLM, industry internal data, social networks). Such data sources would also enable the application of digital-trace analytics to empirically characterise collaborative CAD activities. In particular, sequence and pattern mining of, for example, modelling logs could be used to analyse how collaborative CAD users apply CAD modelling strategies, thereby mapping onto the *Object* category of the taxonomy, as well as *Rules* category through the identification of CAD modelling strategies and iteration patterns. Social network analysis of for example, communication logs, could be used to analyse the structure and frequency of interaction among collaborative CAD users, thereby mapping onto the *Community* category, specifically the interaction mode and communication mode elements, thus enabling the empirical examination of how team distribution and collaborative working mode influence the activity. Analysis of contribution logs, by capturing who modifies which part in CAD and at what point during the activity, maps onto the *Division of Labor* category. A possible data-driven validation workflow may therefore involve collecting collaborative CAD traces, such as CAD user actions and version or branch histories, alongside collaboration traces, such as communication logs and task-management data, and mapping the resulting evidence to the corresponding taxonomy elements across all six Activity Theory categories. Validation should also include longitudinal deployments and controlled in-situ study designs, including comparative experiments and A/B testing, to quantify whether taxonomy-informed interventions lead to measurable improvements in collaborative CAD activities, such as reductions in task completion time as a measure of efficiency, decreases in the number of conflicting modelling actions or undo events, improvements in quality of the resulting CAD model, improved effectiveness assessed by the degree to which the output meets the intended objective of the activity, or more equitable distribution of modelling contributions across team members. Therefore, future work should aim to validate, refine, and expand the taxonomy within real-world industry settings. To demonstrate the taxonomy's value for guiding future empirical work beyond the limitations of academic datasets, future work includes a study within industrial practice that is informed by the developed taxonomy, preferably embedded into engineering design projects that utilise collaborative CAD. In practical terms, one condition could represent a baseline setting, in which collaborative CAD activities are observed and analysed without taxonomy-informed intervention, while the other could represent a taxonomy-informed setting, in which case selection is structured according to the taxonomy dimensions, subdimensions and elements. For example, cases could be selected to vary in team size and familiarity, geographical and temporal distribution, collaborative working mode, and the combination of collaborative CAD with communication or coordination tools. Across both conditions, data collection should combine collaborative CAD traces, such as CAD user actions, version and branch histories, and modelling sequences, with collaboration traces, such as chat or comment records, meeting data, and task-management data, complemented by surveys and interviews to capture contextual factors that are not observable from the traces alone. The resulting evidence could then be used to examine whether taxonomy-informed distinctions correspond to meaningful differences in collaborative CAD activities and their outputs, and whether particular categories, subcategories, or elements require refinement, extension, or redefinition when applied in real-world settings. In this way, A/B testing or comparative field studies would not serve only to evaluate activity outcomes, but also to assess the practical usefulness, explanatory value, and empirical adequacy of the proposed taxonomy. Such studies would be particularly relevant for underrepresented Activity Theory categories, especially *Division of Labor* and Rules, where industrial settings may reveal additional elements that were not visible in the reviewed literature. In parallel, future work should expand the taxonomy applicability across engineering domains in which CAD is used collaboratively and assess its usefulness in both short-term and long-term collaborative CAD activities. These directions position the proposed taxonomy not as a final solution limited to engineering design, but as a theoretically grounded framework, based on Activity Theory, that can evolve into a universal reference for understanding and supporting collaborative CAD activities across domains and contexts.

A further limitation is that the quality appraisal was not independently conducted by multiple raters across the full dataset, which may leave some degree of subjectivity in the appraisal process. To reduce this risk, an independent partial cross-check was performed on 13 studies or 18.8% of the included studies by a second researcher, and any discrepancies were resolved through discussion. Future work should, therefore, consider independent inter-rater reliability procedures, particularly for the quality appraisal of the studies included as evidence base through systematic literature review.

### 5.5.3. Threats to validity

This study is subject to several threats to construct, internal and external validity that should be considered when interpreting the findings and using the proposed taxonomy of collaborative CAD activities [154].

### 5.5.4. Construct validity

The taxonomy is grounded in Activity Theory and developed through a hybrid approach that combines deductive top-level categories with bottom-up synthesis from the reviewed studies. A potential threat is the operationalisation of AT categories during this hybrid approach process. Primary studies in collaborative CAD do not consistently use Activity Theory terminology and often report constructs in heterogeneously, for example focusing on tools, tasks, or communication without explicitly framing them as elements of an activity construct. Consequently, the assignment of constructs to all level of taxonomy, namely categories, subcategories and elements, involves interpretive judgement, which may lead to misclassification. This threat is most relevant for the *Division* *of Labor* and *Rules* categories, given that the reviewed studies rarely address these dimensions explicitly, making the interpretive step required to map reported constructs onto these categories larger and therefore more susceptible to misclassification than for the more explicitly and consistently reported categories, such as *Subject*, *Tool* or *Community*. To mitigate this risk, the taxonomy development followed iterative coding and refinement cycles, and ambiguous mappings were discussed with co-authors to align interpretations.

#### 5.5.5. Internal validity

Although internal validity is primarily a concern for causal inference in experiments, it is relevant here in terms of whether the reported gaps and research opportunities truly follow from the evidence base. Threats include the possibility that observed underrepresentation of certain AT categories if relevant information is missed due to incomplete reporting in studies. As a result, underrepresentation of certain categories could reflect reporting practices rather than absence in practice. For example, *Division of Labor* and *Rules* elements may be present in collaborative CAD activities, but are seldom documented in the reviewed studies, which means that their absence from the taxonomy may overstate the extent to which these categories are underexplored. In practical terms, this distinction is important for how the identified research opportunities are interpreted, as they may be understood as a gap in reporting and conceptualisation rather than evidence of, for example, role allocation does not occur in collaborative CAD activities. Researchers should not, therefore, conclude from the taxonomy alone that these categories, and corresponding subcategories and elements, are irrelevant to the design and study of collaborative CAD activities. These threats were mitigated through a PRISMA-based screening procedure, pre-defined inclusion criteria, documented decisions, screening refinement cycles, quality appraisal procedures. In addition, this analysis explicitly distinguished what is evidenced in the literature from what is theoretically expected in collaborative CAD activities, and by treating identified gaps as opportunities for future work rather than definitive statements about practice. Nevertheless, some internal validity risk remains because coding and appraisal were primarily conducted by a single author.

#### 5.5.6. External validity

The generalisability of the taxonomy is constrained by the scope of the systematic literature review and by the characteristics of the included study contexts. Majority of studies are short-term studies from educational settings, with fewer industrial studies, which may limit generalisability to professional and long-term engineering projects. This is particularly relevant because the collaborative CAD tasks employed in the reviewed studies, such as assembling pre-modelled parts or executing assigned modifications to an existing CAD model, are not fully representative of real engineering tasks from the industrial settings. As a result, taxonomy categories may be less represented than their actual importance in industrial practice. Specifically, the Rules category, including both the Strategies subcategory, encompassing CAD modelling strategies and design methods, and the *Taskwork* and *Teamwork Measures* subcategories, may not fully capture the range of formal and informal practices, norms, and evaluation criteria that govern collaborative CAD activities in industrial settings, where performance expectations, quality standards, and coordination mechanisms are more varied and demanding than those observed in the reviewed studies. Similarly, the *Division of Labor* category, which is not represented in the reviewed literature, may be more pronounced in industrial settings, where teams are typically larger, more formally organised, and characterised by defined roles and responsibilities that shape collaborative CAD activities. Finally, the *Community* category elements related to team configuration and team distribution may also require extension, as industrial teams often operate across organisational boundaries and involve participants with highly specialised expertise that goes beyond the single-domain student teams that dominate the evidence base in this study. Moreover, the review is scoped to engineering design research and may not fully capture collaborative CAD activities in other domains (e.g., construction, architecture, or electronics). The taxonomy should therefore be understood as a structured representation of the reviewed studies derived through systematic literature review that can be extended and validated through additional reviews and empirical research studies across domains.

## 6. Conclusion

This study made three contributions to research on collaborative CAD activities. Firstly, it systematically reviewed the literature on collaborative CAD activities in engineering design and established an evidence base showing growing research interest in the topic, but also fragmentation in how such activities are studied. The study then developed a taxonomy of collaborative CAD activities grounded in Activity Theory, consisting of six main categories derived from the Activity Theory: *Subject*, *Object*, *Tool*, *Community*, *Division of Labor* and *Rules*. The taxonomy includes 16 subcategories and 41 elements on the second and third levels. Third, it identified research opportunities arising from the coverage of AT categories in the reviewed literature. The reviewed literature indicates he underrepresentation of *Division of Labor* and *Rules*, the limited attention to professional and interdisciplinary settings, the need to examine emerging technologies such as AI, the lack of unified evaluation measures, and the need to further refine and validate the taxonomy. Taken together, further empirical exploration of collaborative CAD activities is necessary. The accumulated evidence from comparative studies on collaborative CAD activities can help synthesise knowledge, provide insights into when, how, and why to utilise collaborative CAD in design activities that traditionally rely on conventional CAD. The main implication of this review is that it serves as a foundational step toward a more comprehensive understanding of collaborative CAD activities. Researchers and practitioners can leverage the proposed taxonomy to enhance both the taxonomy itself and the understanding of collaborative CAD activities, the factors influencing them, and their impact on the design process, of which they are undoubtedly a part.

## 7. Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT in order to support language editing, including vocabulary refinement, sentence phrasing, and text polishing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Code availability: Not applicable.
**Ethics approval:** Ethical approval was obtained for the Croatian Science Foundation projects IP-2022-10-7775.
**Consent to participate:** The authors obtained consent to participate from the participants.
**Consent for publication:** The authors obtained consent for publication from the participants.

## CRediT authorship contribution statement

**Jelena Šklebar:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Tomislav Martinec:** Writing – review & editing, Methodology. **Stanko Škec:** Writing – review & editing, Methodology. **Mario Štorga:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A

Presents the summary of the quality appraisal results across the evidence base.

| Quality Appraisal Tool | Quality Category | Number of Studies | References |
|---|---|---|---|
| MMAT | High | **19** | Horvat et al. [97], Zhou et al. [43], Phadnis et al. [20], Deng et al. [76], Horvat et al. [85], Hepworth et al. [107], Kamrani and Nasr [77], Horvat et al. [86], Celjak et al. [87], Arshad et al. [104], Horvat et al. [88], Vrolijk et al. [93], Šklebar et al. [98], Phadnis et al. [108], Cuperman et al. [91], Vella et al. [109], Cheng and Olechowski [102], Greenholts et al. [95], Cheng et al. [132] |
| | Moderate | **9** | Phadnis et al. [105], Eves et al. [106], Stone et al. [41], Stone et al. [42], French et al. [82], Asuzu et al. [81], Kostic et al. [94], Verner et al. [96], Deng et al. [92], |
| | Low | **5** | Olechowski et al. [89], Leonardo et al. [110], Eigner et al. [90], Leonardo and Olechowski [78], Chryssolouris et al. [84] |
| | Very low | **0** | - |
| QATTL | High | **26** | Cheng et al. [103], Bowman et al. [115], Chen et al. [121], Tay and Roy [120], He and Han [30], Tay and Ming [79], Zissis et al. [74], Kao and Lin [122], Cheng et al. [123], Jing and Zhang [119], Su and Chen [114], Kao et al. [111], Huang et al. [35], Locquet et al. [80], French et al. [83], Su et al. [112], Cheng et al. [117], Cai and Li [118], Xue et al. [125], Zheng et al. [126], Nysetvold and Teng [127], Li [130] |
| | Moderate | **10** | Chen et al. [100], French et al. [75], Liu et al. [124], Adediran et al. [7], Hill and Salmon [99], Lee et al. [101], Cheng et al. [116], Xu et al. [128], Zheng et al. [129], Su et al. [113], Chen et al. [131], Liu et al. [133], Liu et al. [134] |
| | Low | **0** | - |
| | Very low | **0** | - |

## *Appendix B*

Provides the complete list of sources included in the systematic literature review.

| Source Name | No. | References |
|---|---|---|
| Computer-Aided Design and Applications | 8 | Chen et al. [100], Horvat et al. [97], French et al. [75], Phadnis et al. [105], Eves et al. [106], Olechowski et al. [89], Stone et al. [42], Bowman et al. [115] |
| Journal of Computing and Information Science in Engineering | 4 | French et al. [82], Stone et al. [41], Chen et al. [121], Feng et al. [33] |
| Journal of Mechanical Design | 3 | Zhou et al. [43], Phadnis et al. [20], Cheng et al. [103] |
| Advanced Engineering Informatics | 2 | Deng et al. [76], Horvat et al. [85] |
| Computers in Industry | 2 | Tay and Roy [120], He and Han [30] |
| Concurrent Engineering: Research and Applications | 2 | Tay and Ming [79], Hepworth et al. [107] |
| IEEE Transactions on Engineering Management | 1 | Asuzu et al. [81] |
| International Journal of Computer Applications in Technology | 1 | Kamrani and Nasr [77] |
| International Journal of Engineering Education | 1 | Leonardo et al. [110] |
| International Journal of Systems Science: Operations and Logistics | 1 | Zissis et al. [74] |
| Computer Integrated Manufacturing Systems | 1 | Kao and Lin [122] |
| Journal of Computational Design and Engineering | 1 | Cheng et al. [123] |
| Journal of Applied Sciences | 1 | Jing and Zhang [119] |
| Technical Gazette | 1 | Kostic et al. [94] |
| Chinese Journal of Electronics | 1 | Liu et al. [124] |
| Integrated Manufacturing Systems | 1 | Su and Chen [114] |
| Robotics and Computer-Integrated Manufacturing | 1 | Kao et al. [111] |
| Conference proceedings | 37 | Adediran et al. [7], Horvat et al. [86], Celjak et al. [87], Huang et al. [35], Arshad et al. [104], Horvat et al. [88], Vrolijk et al. [93], Šklebar et al. [98], Verner et al. [96], Eigner et al. [90], Leonardo and Olechowski [78], Phadnis et al. [108], Cuperman et al. [91], Locquet et al. [80], Vella et al. [109], Chryssolouris et al. [84], Deng et al. [92], Hill and Salmon [99], Cheng and Olechowski [102], Greenholts et al. [95], Lee et al. [101], French et al. [83], Su et al. [112], Cheng et al. [117], Cheng et al. [116], Cai and Li [118], Xue et al. [125], Zheng et al. [126], Nysetvold and Teng [127], Xu et al. [128], Zheng et al. [129], Su et al. [113], Li [130], Chen et al. [131], Cheng et al. [132], Liu et al. [133], Liu et al. [134] |

## Appendix C

Presents the full taxonomy of collaborative CAD activities, including categories, subcategories, and elements derived from Activity Theory and the systematic literature review.

| Category | Subcategory | Element |
|---|---|---|
| Subject | Individual Experience | Task-specific experience |
| | | CAD-specific experience |
| | Individual Knowledge | Task-specific knowledge |
| | | CAD-specific knowledge |
| | | Collaboration-specific knowledge |
| | Individual Personality | CAD personality |
| Object | Design Input Information | Graphical input information |
| | | Semantic input information |
| | | Analytical input information |
| | | Physical input information |
| | CAD Output Type | Part |
| | | Assembly |
| | | Technical drawing |
| | CAD Output Purpose | Conceptual design purpose |
| | | Embodiment design purpose |
| | | Prototyping and testing purpose |
| | | Detailed design purpose |
| Tool | Design and Engineering Tools | CAD tools |
| | | CAE tools |
| | Collaboration Tools | Communication tools |
| | | Coordination tools |
| | AI-based Tools | AI assistive tools |
| | | Generative AI tools |
| | Extended Reality Tools | Augmented reality tools |
| | | Virtual reality tools |
| Community | Team Configuration | Team size |
| | | Team familiarity |
| | Team Distribution | Geographical team distribution |
| | | Temporal team distribution |
| | | Expertise-based team distribution |
| | Interaction Mode | Collaborative working mode |
| | | Communication mode |
| Rules | Strategies | CAD modelling strategies |
| | | Design methods |
| | Taskwork Measures | Efficiency measures |
| | | Productivity measures |
| | | Quality measures |
| | | Effectiveness measures |
| | Teamwork Measures | Behaviour measures |
| | | Attitude measures |
| | | Cognition measures |

## Data availability

Data will be made available on request.

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