A Systematic Literature Review of Adaptive Learning Systems Based on the Assessment of Collaboration Quality

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Abstract: Advances in information and communication technologies has led to the development of new data analysis methods and strategies used to support remote and co-located collaborative learning. These strategies seek to give meaning to complex data of individual and team interaction with the learning system to inform actionable insights. However, providing teams and teachers with a substantial amount of data during the collaboration process can complicate interpretation and hinder decision-making. Adaptive learning systems bear high potential to assist classroom orchestration and support collaborative learning by providing students with adaptive feedback. This paper systematically reviews existing literature following PRISMA methodology to provide insights into adaptive collaborative learning systems. It specifically puts the light on how learning systems have been adapted by considering the assessment of collaboration quality within teams. The objective is to present common adaptation approaches, practices, and challenges as well as to discuss opportunities to improve future adaptive learning systems.

1 INTRODUCTION

The ability to work in a group to construct knowledge, negotiate, and meet shared objectives is among the critical 21st century skills that promote workforce effectiveness (Lima and de Souza, 2017). However, teams may also face challenges such as conflicts in views, the lack of social skills, as well as the need for support and explanation of tasks (Saqr et al., 2018). Adapting the learning system according to stakeholders' needs can therefore play an important role in supporting collaborative learning.

Adaptation traditionally refers to the process of tailoring the learning content, the system or the interface to individual learners (Brusilovsky et al., 2015; Hocine and Sehaba, 2024). In other studies, it is viewed as a means to support or guide users during the learning process by allowing them to control their learning and choices (Barria-Pineda et al., 2023). In computer-supported collaborative learning (CSCL) studies, adaptation aimed to support collaborative work by recommending or adapting for instance team composition on the basis of group members' characteristics (Lykourentzou et al., 2016). Quite recently, research has been concentrated on various concerns such as supporting orchestration and transitive activities between individual and collaborative learning (Yang et al., 2023), adaptive scaffolding (Splichal et al., 2018), and dashboard design (Zamecnik et al., 2022).

This paper reviews research on adaptive learning systems that assess collaboration quality to support collaborative learning, addressing two key questions. First, the review aims to understand how collaboration quality analysis methods and indicators were used to adapt the learning system and whether this contributed to improving collaborative learning and teaching. **RQ1: What adaptation approaches have been used to enhance collaborative learning based on collaboration quality assessment?**. Second, the review puts the light on collaboration quality analysis methods and indicators. **RQ2: What methods and indicators have been employed to automatically assess the quality of student collaboration for adapting the learning system?**.

Despite numerous literature review studies on assessing collaboration quality through indicators inferred from student interactions with learning systems (Eryilmaz et al., 2021), there is a lack of studies that explore how these indicators contribute to system adaptation. For example, Neumayr and Augstein reviewed personalized collaborative systems across var-

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ious contexts (Neumayr and Augstein, 2020), but did not examine how collaboration indicators informed system adaptation. Similarly, Vogel and colleagues conducted a meta-analysis of socio-cognitive scaffolding techniques (Vogel et al., 2017), but focused on adaptive scaffolding's impact on learners' skills, without addressing how collaboration quality was used to adjust the scaffolds.

The remainder of this paper is organized as follows: Section 2 describes the methodology of the systematic literature review. Section 3 presents the results of the review by answering the two previous research questions. Section 4 discusses the obtained results, current challenges, and some opportunities to advance research in adaptive collaborative learning systems. We conclude this paper by presenting a summary of the review findings, its limitations, practical implications, and perspectives for future work.

2 METHODOLOGY

This systematic literature review follows the preferred reporting items for systematic reviews and meta-analyses (PRISMA) protocol (Page et al., 2021). It is performed in four phases: a comprehensive search of eligible studies using databases, screening the title and abstract of these studies, selection of relevant papers following exclusion and inclusion criteria, and reviewing the full texts of the screened studies to extract data. 27 research papers were included in this review.

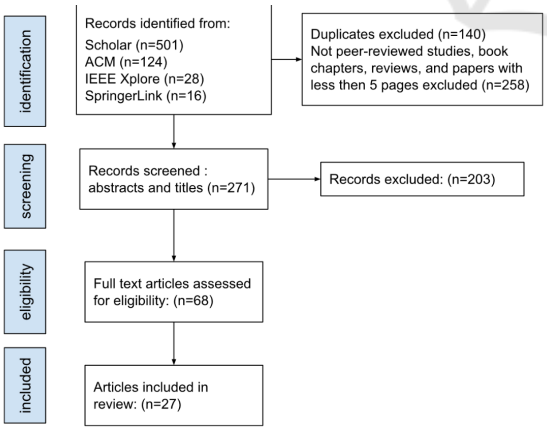

Figure 1: Paper selection flowchart.

The literature review search was conducted using: ACM, IEEE, SpringerLink, and Google Scholar databases. The following general research query was used: (personaliz OR adapt* OR customiz*) AND ("computer-supported collaborative learning" OR "CSCL" OR "collaborative learning" OR "technology-enhanced learning") AND ("Collaboration analytics" OR "collaboration assessment" OR "collaboration quality"). The search was limited to peer-reviewed studies from 2015 to June 2024 written in english.

Figure 1. summarizes the main steps of the search and analysis process. In the eligibility phase of search, the full texts of the 68 articles were reviewed. Given that the review objective is to understand how collaboration quality assessment has contributed to the adaptation of collaborative learning systems, two inclusion criteria of articles were set out. First, the study has to be defined in the context of remote or co-located collaborative learning. Second, the collaboration quality assessment has to be considered to personalize, guide, or adapt learning or teaching. Studies that were limited to the recommendation or the visual representation of educational data and collaboration indicators or models without explainability, collaboration assistance or guidance were excluded. Finally, adaptable systems that are based on manual system configuration by the human, or that deal with human-agent collaboration were excluded. The final list of relevant publications consisted of 27 articles. We analyzed the full text of these articles to address our research questions, RQ1 and RQ2.

3 RESULTS

The results show that research in adaptive collaborative learning systems based on the assessment of collaboration quality has increased over years. A growing interest has been particularly devoted to providing a helping hand to stakeholders in co-located (or face-to-face) collaboration.

3.1 Adaptation Approaches

The following adaptation approaches were suggested to support collaborative learning: adaptive feedback and scaffolding (30% of papers), personalized recommendation (25% of papers), adaptive dashboards (21% of papers), AI assistants (14% of papers), as well as adaptive visualizations of educational data and collaboration indicators (10% of papers). Table 1. presents a brief description of the adaptation approaches used in the reviewed studies, while Table 2. summarizes their main outcomes.

3.1.1 Adaptive Feedback and Scaffolding

Studies suggest that adaptive scaffolding can improve students' reflection on their learning and collabora-

Table 1: Adaptation approaches of collaborative learning systems based on the assessment of collaboration quality.

Approach	Description	paper	ID
Adaptive feedback and scaffolding	Adaptive scaffolding to support students' reflection on their regulatory actions and prompts for the expert to support group monitoring, and the evaluation of individual reflections.	(Splichal et al., 2018)	1
	Adaptive generated textual process feedback for CSCL based on discourse indicators	(Menzel et al., 2023)	2
	Real-time adaptation of the system to support collaboration and generate appropriate action when a group is struggling	(Evans et al., 2019)	3
	An intelligent tutoring system to support learning through step-by-step guidance, adaptive hints and feedback	(Yang et al., 2023)	4
	Adaptive support for group formation and real-time feedback for reflection	(Liang et al., 2023)	5
	Adaptive collaboration script based on prompts and hints	(Rau et al., 2017)	6
	Orchestration scripts that detects everyday work situations in a workplace and suggest strategies (collaborative activities) to attempt during workers' interactions with each other	(Garg et al., 2023)	7
	Collaboration script to regulate the distribution of participation	(Strauss et al., 2023)	8
Personalized recommendation	A teacher-facing orchestration tool based on recommendation of pairing students to work collaboratively	(Yang et al., 2023)	4
	Recommendation of students who needs support and a visual explanation of collaboration indicators using a logical tree	(Anaya et al., 2016)	9
	Recommendation of collaborative activities based on learning style using neural network model	(Troussas et al., 2023)	10
	Personalized recommendation of forum posts to promote collaboration	(Echeverria et al., 2017)	11
	Personalized recommendation of posts based on collaborative filtering and k-nearest neighbors	(Kasepalu et al., 2022)	12
	Personalized recommendation of learning resources using a rule-based approach and a deep neural network model	(Zheng et al., 2024)	13
	Recommendation of roles based on the prediction of student group's collaboration quality using deep-learning models	(Som et al., 2021)	14
Adaptive dashboards	Adaptive multimodal analytics dashboard with adaptive visualization of collaboration quality using a network graph	(Praharaj et al., 2022)	15
	Learning analytics dashboard with adaptive visual feedback for collaborative argumentation according to students' needs	(Han et al., 2021)	16
	Multimodal analytics dashboard with real-time notifications of collaboration issues	(Serrano Iglesias et al., 2021)	17
	Multimodal analytics dashboard with adaptive visualizations (graphs) and automatic feedback about epistemic and social aspects of collaboration	(Chen and Demmans, 2020)	18
	Multimodal analytics dashboard with adaptive visualizations that summarize group indicators	(Martinez-Maldonado et al., 2015)	19
	Learning analytics dashboard to guide orchestration based on Epistemic Network Analysis and an alerting mechanism that fagged critical moments in collaboration	(Amarasinghe et al., 2021)	20
AI assistant	A chatbot with adaptive guidance and feedback on submitted assignments	(Burkhard et al., 2022)	21
	A conversational agent to provide adaptive scaffold for students based on APT(Academically Productive Talk) and an orchestration support for teachers using a concept map and a classification of students activities	(Tegos et al., 2015)	22
	AI assistant for classroom orchestration based on collaboration problems modeling	(Eryilmaz et al., 2021)	23
	AI assistant for collaborative learning using various explainable ML methods	(Tomic et al., 2023)	24
Adaptive visualizations	A feedback tool based on visual analytics using storytelling of the learner model and a rule-based system	(Martinez-Maldonado et al., 2020)	25
	Generated visualizations of of critical sub-processes in teams' activity using a rule-based system	(Venegas-Reynoso et al., 2018)	26
	Visual analytics using social network analysis to support learning, find aspects in need of improvement, and guide an informed intervention	(Saqr et al., 2018)	27

tion processes, while metacognitive prompts help experts monitor group and individual progress. Adaptive feedback and scaffolding strategies were generally suggested in different learning contexts to enhance knowledge acquisition (Menzel et al., 2023), literacy (Liang et al., 2023), and communication skills (Strauss et al., 2023). The assessment of collaboration quality has been primarily used to refine collaborative scripts, support decision-making for orchestration and tutoring, and identify appropriate prompts to enhance learning outcomes and increase group awareness (Rau et al., 2017). By providing adaptive feedback and guiding students through scripts, hints, and prompts, these strategies significantly improved individual learning outcomes (Splichal et al., 2018), satisfaction (Strauss et al., 2023), collaboration skills (Menzel et al., 2023; Garg et al., 2023), perceived collaboration usefulness (Rau et al., 2017), and group awareness (Evans et al., 2019).

However, despite the positive impact of adaptive feedback and scaffolding strategies on individual learning and collaborative skills, a certain amount of concerns have to be addressed. This includes for instance the limited metrics and features considered to assess collaboration quality (Splichal et al., 2018), the dependence of the adaptation strategy on a particular learning context, and the difficulty to considering students' soft skills such as self-regulation and creative thinking (Yang et al., 2023). Some authors also highlighted the need for studies that identify teacher interaction patterns to lend a hand to classroom orchestration (Garg et al., 2023).

3.1.2 Personalized Recommendation

Personalized recommendation systems have been proposed generally in the context of collaborative problem solving (Zheng et al., 2024; Som et al., 2021), project-based learning (Christos Troussas and Voyiatzis, 2023), as well as creative and reflective learning (Eryilmaz et al., 2021). They were based on recommending collaborative activities (Christos Troussas and Voyiatzis, 2023), discussion forum posts (Kasepalu et al., 2022), learning resources (Zheng et al., 2024), and roles (Som et al., 2021). Personalized recommendation has also been deployed in classroom orchestration to assist group formation (Yang et al., 2023) and suggest assistance to students who face collaboration and learning difficulties (Anaya et al., 2016). Research studies showed the usefulness of personalized recommendation systems in increasing for instance students' participation in collaborative activities (Echeverria et al., 2017), creativity, group awareness (Kasepalu et al., 2022; Anaya et al., 2016), as well as individual learning outcomes (Christos Troussas and Voyiatzis, 2023).

However, studies raised different concerns about the consideration of individual students' skills such

Table 2: Summary of samples, research designs, and main studies outcome following the adaptation approaches, (n) the number of students (m) the number of teachers.

Approach	Sample	Research design	Study findings	ID
Adaptive feedback and scaffolding	n=48 m=5	Post analysis of a questionnaire and posts	Improvement of students who augmented their scripts	1
	n=408	Experimental group (generated feedback) vs. control group (simple feedback)	Generated personalized feedback were helpful	2
	n=11	Experimental group (adaptation) vs. control groups (without adaptation)	The effectiveness of the detection of collaboration issues	3
	n=199	Post analysis of the learning system traces and interviews	Utility of dynamic transitions between activities in personalizing learning	4
	n=25	Post study analysis of the learning system traces	The grouping strategy can predict group performance	5
	n=69	Experimental group (adaptive script) vs. a control group (without adaptation)	Improvement of learning outcomes and perceived collaboration	6
	n=17	Pre-post tests and post-study interviews	Situated scripts usefulness in supporting students	7
	n=150	Experimental group (adaptive scripts) vs. an awareness tool vs. control group	Positive impact on students' satisfaction	8
Personalized recommendation	n=23	A survey to evaluate the user experience	The explanation enhanced collaboration issues perception	21
	n=80	Experimental group (personalized recommendation) vs. control group (simple recommendation)	A high degree of pedagogical affordance and the positive impact on learning	10
	n=57	Experimental group (personalized recommendation) vs. control group (other recommendation algorithms)	The effectiveness of predicting students preferences and increasing participation	11
	n=70	Experimental group (personalized recommendation) vs. control group (without recommendation)	Increase the number of messages, cultivated a sense of collective agency and creativity	12
	n=135	Between-subject pre-post test design and interviews	Improved socially shared regulated behaviors	13
	NA	Post study analysis of the performance of representations of students roles	The effectiveness and accuracy of the model of collaboration quality	14
Adaptive dashboards	n=14	Post analysis of team discourses and log data	Positive impact of influential role-role interactions on collaboration	15
	n=22 m=88	A within-subject design to evaluate two conditions: personalized dashboard and without dashboard	The improvement of participation and argumentation	16
	NA	A use case of the system integration	The adoption of MD for the smart learning environment	17
	n=15	Post-study questionnaire and interviews	The dashboard enhanced students' post-hoc reflection about their activity	18
	m= 1	Post-hoc activity: writing reflection		
	n=150 m=4	Post-study interviews and questionnaires	Presented the teachers perspectives and issues to orchestrate a multi-tabletop classroom	19
	m=6	A within-subject design to evaluate 3 conditions: guidance, mirroring, and control condition	The guidance enabled teachers to perform more, orchestration actions, interactions, and announcements	20
AI assistant	n=11	Post evaluation of the chatbot through structured interviews	The perceived usefulness of the guidance	9
	n=43	Experimental group (with agent) vs. control group (without agent)	Improved engagement in a productive dialogue, reasoning, and argumentation	22
	m=20	Wizard-of-Oz protocol founded on interviews	The utility of the virtual assistant in co-regulation understanding	23
	n=252 m=6	Post study interviews and analysis of methods performance and explainability	Fuzzy rules and decision trees combined with neural networks make best performance and explainability	24
Adaptive visualizations	n=44 m=8	Qualitative studies based on interviews	Assistance of student reflection on their activity, stress management, and errors made	25
	n=60	Post study structured interviews	The meaningfulness of the generated visualizations	26
	n=164	A repeated measurement design (pre-intervention vs. Post-intervention)	Enhancement of student-student and teacher-student interactions	27

as critical thinking and social skills (Zheng et al., 2024; Kasepalu et al., 2022). There is also still a need for studies to evaluate the recommendation quality (Som et al., 2021) and its effect on collaborative learning and teaching. Several opportunities can be discussed, including the consideration of multiple aspects and metrics to assess collaboration quality (Christos Troussas and Voyiatzis, 2023; Som et al., 2021), as well as improving the explainability of recommendation methods (Som et al., 2021), especially in co-location collaboration. In fact, due to the significant amount of real-time interaction data, both teachers and students may have difficulty understanding the system's recommendations and how they can influence the collaboration process and students' performance.

3.1.3 Adaptive Dashboards

Adaptive dashboards have been used to support students in different contexts, including collaborative problem solving, co-located project-based learning (Echeverria et al., 2017; Praharaj et al., 2022), and argumentation (Han et al., 2021). They were also used to guide classroom orchestration by altering collaboration issues (Amarasinghe et al., 2021). Moreover, adaptive multimodal analytics dashboards were used to reduce the cognitive load of analyzing collaboration quality indicators that relied on multiple data modalities (Praharaj et al., 2022; Chen and Demmans, 2020). Studies showed the effectiveness of adaptive dashboards in improving learners' participation and argumentation skills (Han et al., 2021), reflective learning (Chen and Demmans, 2020), collaboration skills (Praharaj et al., 2022) as well as teachers' orchestration actions (Amarasinghe et al., 2021; Serrano Iglesias et al., 2021)

However, adaptive dashboards often depend on particular structures of learning activities and scenarios (Amarasinghe et al., 2021; Han et al., 2021). Moreover, as reported by some studies, mining temporal interaction patterns for real-time explanation of indicators (Martinez-Maldonado, 2019) and considering social and epistemic aspects of collaboration to adapt the dashboard (Praharaj et al., 2022) is still challenging. Research opportunities also include the evaluation of the effect of dashboards in different learning contexts (Amarasinghe et al., 2021; Han et al., 2021) and how they can be adapted to improve self-regulation skills.

3.1.4 AI Assistant

Adaptive virtual agents and chatbots were generally used in the context of collaborative project-based learning (Tomic et al., 2023), argumentation (Tegos

et al., 2015), and literacy. The studies showed the usefulness of this approach in improving students' collaboration (Anaya et al., 2016; Eryilmaz et al., 2021), engagement, and learning (Tegos et al., 2015). Adaptive guidance using virtual agents and chatbots mostly focused on individual support of students that stands on a particular learning context and activities. There is also a lack of studies that consider socio-emotional indicators of collaboration to adapt the guidance in the learning system (Liang et al., 2023).

3.1.5 Adaptive Visualizations

Many studies have reported issues with the high cognitive load required to interpret real-time indicators, particularly in co-located collaboration (Gavsevic et al., 2015b). To address this, visual analytics have been adopted to help stakeholders gain insights through data filtering and predictive modeling (Vatrapu et al., 2011). However, despite aiding data exploration, these methods do not always ensure meaningfulness or efficiency in decision-making (Barria-Pineda et al., 2023). The analysis of collaboration processes may require complex datasets, while analytics methods, especially black-box machine learning models, often lack explainability.

Some studies dealt with tailoring visual representation of educational data and collaboration indicators (Yang et al., 2023; Saqr et al., 2018). Studies showed the positive impact of this approach in frosting students' reflection on their activity (Martinez-Maldonado et al., 2020), communication (Saqr et al., 2018), and group awareness (Venegas-Reynoso et al., 2018). These studies often relied on rule-based systems, however, the generation of rules has been seen as challenging to adapt and to capture the intent of team members (Venegas-Reynoso et al., 2018).

3.2 Collaboration Quality Assessment Methods and Indicators

Research on adaptive collaborative learning systems has extensively explored various methods for assessing collaboration quality, leveraging learning analytics (LA, 44%), multimodal analytics (MA, 33%), text analysis (TA, 26%), and social network analysis (SNA, 18%). Collaboration quality assessment using LA was generally used to adapt feedback and personalize recommendations. Common methods include statistical analysis (Menzel et al., 2023), supervised learning (Eryilmaz et al., 2021), neural networks (Christos Troussas and Voyiatzis, 2023) and deep learning (Zheng et al., 2024) using using logs and chat data.

Numerous studies also focused on TA methods based on students' forum posts, questions, and transcribed speech to tailor feedback and scaffolding. Techniques such as thematic similarity (Chen and Demmans, 2020) and question-answer analysis (Rau et al., 2017) enable a detailed examination of communication patterns, while interaction analysis helps reveal the nuances of group discourse (Menzel et al., 2023).

Some studies used SNA to model group interactions and assess collaboration (Eryilmaz et al., 2021) to support personalized recommendations (Chen and Demmans, 2020) and adapt visualizations of learning and collaboration indicators (Saqr et al., 2018).

Finally, recent studies extend the analysis by integrating diverse data types such as logs, audio, gestures, and tabletops touch actions using MA methods. They generally relied on rule-based systems (Evans et al., 2019), predictive analyses of interactions (Serrano Iglesias et al., 2021), and deep learning models (Som et al., 2021). By capturing multiple modalities, MA provides richer insights into both individual and group dynamics.

Across these analytics approaches, research studies identified multiple indicators of collaboration quality, especially knowledge contribution (52%), task participation (30%), collaboration quality models (26%), and group performance (19%).

Knowledge contribution has been generally assessed through the quality of messages, posts, and answers, with metrics such as keyword usage and activity types (Serrano Iglesias et al., 2021). This analysis ties into task participation, where the frequency of actions, speech inputs, and forum interactions highlights the level of engagement (Martinez-Maldonado, 2019). Some studies suggested a collaboration model that depends on connection ratios, readability scores, and machine learning models such as support vector machines and decision trees (Kasepalu et al., 2022). Other studies were limited to the evaluation of group performance as an indicator of collaboration quality. It has been measured through computational models of problem-solving, task completion metrics, and tutor evaluations (Rau et al., 2017). Finally, some studies incorporate individual performance metrics, learning styles, and emotional responses, utilizing psycholinguistic attributes and multimodal data to capture the affective dimensions of collaboration (Martinez-Maldonado et al., 2020).

To sum up, research studies on adaptive learning systems relied on different analytics methods to capture and assess collaboration quality under different group settings. However, despite some similar collaboration indicators revealed in several studies,

their low-level metrics were often different and depend on multiple factors, including the learning context of studies and the collaboration scenario. In addition, some metrics were interpreted differently by research studies as they have been used to compute different collaboration indicators. For instance, the quality of learners' messages and posts measured often by the frequency of keywords and messages length has been used to assess the students' contribution to knowledge construction (Strauss et al., 2023; Praharaj et al., 2022) as well as to evaluate participation and collaboration quality (Eryilmaz et al., 2021).Finally, despite the use of collaboration quality to adapt learning systems, there is a lack of studies identifying and evaluating the most relevant collaboration indicators that can positively influence stakeholders' decision-making.

4 DISCUSSION

This review reveals that research studies proposed various adaptation approaches based on collaboration quality assessment to support collaborative learning and teaching, including adaptive feedback and scaffolds (AF), personalized recommendations (PR), adaptive dashboards (AD), adaptive visualizations (AV), and AI assistants (AIA). Despite their significant positive impact on improving students' learning outcomes and skills, as revealed in the reviewed studies, these approaches were developed in varied learning contexts and utilized different collaboration quality assessment methods and indicators. Some approaches, such as AF, were suggested across different learning contexts. In contrast, other approaches such as AD and PR were generally used for collaborative problem solving and co-located project-based learning.

All proposed adaptation techniques have demonstrated their usefulness in enhancing group awareness and individual learning outcomes. Studies have shown the effectiveness of PR, AD, and AIA in boosting student participation in collaborative activities, while AF, AD, and AV were found to improve students' collaboration and communication skills. AD and AV were particularly effective in fostering students' reflection on their activities. Additionally, PR was found effective in enhancing students' creativity, and AD in improving teachers' orchestration actions.

Although this review can help identify and compare relevant adaptation strategies in certain learning contexts, it does not allow for definitive conclusions about when adaptation techniques are valuable in other learning contexts or under further collaboration indicators. In fact, despite the extensive literature on collaboration quality assessment, there is a notable lack of well-established frameworks for assessing the collaboration process using standardized metrics and measures. Additionally, there is a shortage of studies that identify the most relevant collaboration indicators influencing stakeholders and the decision-making of adaptive systems.

In addition, AF has been seen in the literature as instructional strategies that aim to support collaborative learning (Gavsevic et al., 2015a). However, there is a lack of research on how to effectively adjust scaffolds by addressing collaboration issues. In addition, to improve students' reflection on their actions and collaboration process, other studies have proposed PR to reduce the cognitive load of processing collaboration indicators in real-time. In recent years, research opportunities have been geared towards the explainability of recommendations (Martinez-Maldonado et al., 2020). In the case of co-located collaboration, the stakeholders can be overloaded by the different recommendations of the system and need assistance to evaluate the impact of their actions and decisions on the system decisions. Moreover, there is a lack of studies that consider how the assessment of collaboration quality can improve the decisions of the recommendation system. Finally, despite the potential of dashboards in promoting collaborative learning and teaching, they still lack adaptability by taking into account stakeholders' needs and differences (Han et al., 2021) as well as teacher orchestration strategies (Tomic et al., 2023).

Many research opportunities can be suggested to promote collaborative learning, including the development of new infrastructures of collaborative learning systems that consider multiple learning contexts and collaboration scenarios. There is also a need to develop standardized instruments, measures, indicators and models to assess collaboration quality dimensions while improving their explainability and meaningfulness. This can not only help inform actionable insights but also improve adaptation strategies. Considering individual students' differences can also contribute to improving their skills acquisition, including regulation, social, creative, and critical thinking skills (Splichal et al., 2018; Yang et al., 2023).

5 CONCLUSION

The review highlights the important role of adaptive collaborative learning systems, based on collaboration quality assessment, in improving students' learning outcomes and skills. Despite increasing research

in this area, there is a need for standardized tools and infrastructures to evaluate collaboration quality across different contexts. Adapting learning systems by considering students' collaboration quality, differences, and soft skills can boost engagement and productivity. The review identifies opportunities for improving the explainability of collaboration models and tailoring learning systems to students' needs. However, limitations include restricted database inclusion due to the large number of papers and some access limitations. It also focused exclusively on studies in the context of education conducted after 2015.

Finally, this review provides insights about adaptation in remote and co-located collaborative learning. Practical implications of this review analysis for educators and system designers include the consideration of different collaboration quality metrics that are independent from a particular collaboration scenario and learning activities structures. This also includes examining the impact of collaboration indicators on stakeholders' decision-making to determine adaptation strategies that better address the needs of learners and teachers, as well as targeted competencies.

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