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Teacher Collaboration and Instructional Innovation in Secondary Schools

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Abstract— Teacher collaboration is increasingly recognized as an organizational mechanism through which instructional knowledge, pedagogical resources, and innovative practices circulate within secondary schools. However, conventional studies frequently represent collaboration as a single self-reported construct and rely on linear statistical associations, leaving differences between routine coordination and deeper forms of professional collaboration insufficiently examined. This study addresses this gap by conceptualizing teacher collaboration as a multidimensional professional system encompassing collaborative learning, instructional material exchange, joint teaching, peer observation, feedback, and collective problem-solving. The research further situates instructional innovation within the contemporary environment of artificial intelligence, technology-supported pedagogy, cognitive activation, differentiated teaching, and adaptive lesson design. Using the OECD Teaching and Learning International Survey (TALIS) 2024 lower-secondary teacher data as the empirical foundation, the study proposes an explainable machine-learning framework for examining nonlinear relationships between collaborative practices and instructional innovation.

Keywords— Teacher collaboration, instructional innovation, secondary education, explainable machine learning, professional learning communities, artificial intelligence

Introduction

Secondary education is experiencing a substantial transformation in the meaning of effective teaching. Instruction is no longer evaluated exclusively in terms of subject-matter delivery or classroom management; teachers are increasingly expected to design differentiated learning experiences, facilitate higher-order thinking, integrate digital resources, respond to diverse student needs, and make informed decisions using rapidly expanding educational technologies. The emergence of generative artificial intelligence (AI) has further accelerated this transition. UNESCO's recent guidance and competency framework for teachers emphasize that educators require not only technical familiarity with AI but also pedagogical, ethical, and professional-learning competencies for integrating such systems responsibly into teaching.

These expectations make instructional innovation increasingly difficult to conceptualize as the product of an isolated teacher. Innovative practices often require teachers to interpret unfamiliar tools, test new approaches, identify implementation problems, exchange resources, evaluate student reactions, and modify instructional designs. Such activities involve knowledge that is distributed across colleagues rather than located entirely within individual teachers. Collaboration therefore represents not merely an interpersonal feature of school culture but a potential infrastructure through which pedagogical knowledge can be produced, validated, modified, and transferred.

Recent international evidence reinforces the increasing importance of this professional dimension. Results from TALIS 2024 indicate that full-time teachers across participating OECD education systems spend approximately three hours per week in teamwork and professional dialogue, with reported collaboration time increasing in 28 education systems compared with 2018 and declining in none. More frequent collaboration is also associated with several positive professional outcomes, including greater likelihood of

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fulfilling lesson objectives and stronger teacher self-efficacy. Nevertheless, deeper forms of collaboration remain considerably less common than routine interaction; only about 9% of teachers, on average, report observing colleagues' lessons and providing feedback at least monthly.

This distinction is theoretically important. Exchanging worksheets, discussing student progress, collaboratively designing a lesson, observing a colleague, and jointly experimenting with an AI-supported instructional activity are all categorized broadly as collaboration, but they require different levels of professional interdependence. Simple information exchange may distribute resources without altering underlying pedagogy, whereas co-construction and evidence-based peer feedback may challenge existing instructional assumptions and stimulate substantive innovation. Treating these activities as interchangeable can therefore conceal the mechanisms through which collaboration influences teaching.

Research conducted using social-network perspectives provides additional evidence that the *structure* of professional interaction matters. Schuster, Hartmann, and Kolleck (2021), studying teacher collaboration networks, demonstrated that different forms of collaboration generate distinct network structures and that schools' organizational environments influence how collaborative relationships develop. Similarly, Woodland et al. (2021) showed that school-based professional networks may facilitate or constrain the diffusion of instructional innovation, highlighting that knowledge does not automatically circulate merely because teachers belong to the same organization.

At the same time, the instructional environment itself has changed substantially. TALIS 2024 is the first TALIS cycle to provide extensive evidence concerning teachers' use of artificial intelligence. Approximately one-third of lower-secondary teachers across participating education systems report using AI in their work. Among teachers who use AI, common applications include learning about or summarizing topics and generating lesson plans, whereas use for analyzing student participation, performance, assessment, or grading remains less widespread. These developments expand instructional innovation beyond conventional technology adoption toward AI-assisted planning, personalization, data interpretation, content creation, and professional learning.

1.1 Research Gap

Three limitations remain prominent in the current evidence base.

First, teacher collaboration is frequently operationalized through composite survey scores or isolated frequency measures. Such approaches provide useful estimates of association but can obscure differences between **coordination-oriented collaboration**—such as exchanging resources—and **knowledge-generative collaboration**, including peer observation, collaborative professional learning, team teaching, and joint instructional experimentation.

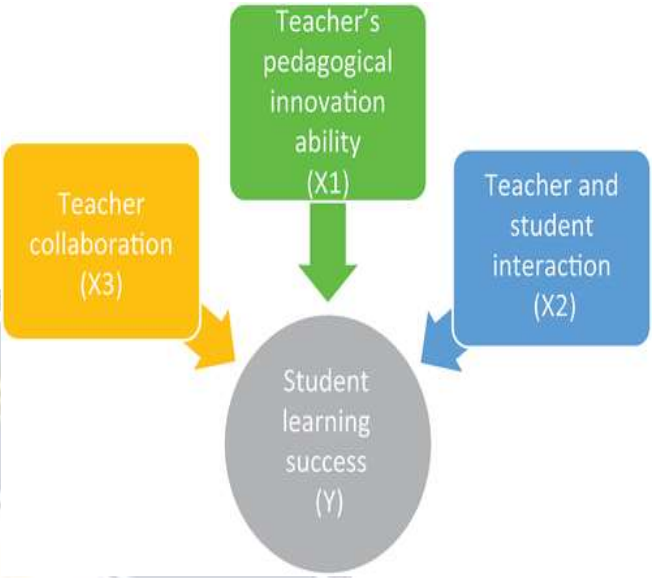


Fig. 1: Pedagogical innovation and teacher collaborations

Source: *https://www.tandfonline.com/doi/full/10.1080/2331186X.2023.2271713*

Second, much of the empirical literature examines approximately linear relationships between collaboration and outcomes. Yet instructional innovation may respond to collaboration nonlinearly. Occasional collaboration may have little measurable influence, while sustained interaction beyond a particular level may produce stronger knowledge exchange. Conversely, excessive coordination without adequate autonomy could theoretically generate diminishing returns. These threshold and interaction patterns are difficult to identify using conventional additive regression models alone.

Third, studies examining teacher collaboration have developed largely separately from the rapidly emerging literature on AI-enabled teaching. Contemporary instructional innovation now incorporates digital and AI-supported pedagogical experimentation, while collaboration may determine whether teachers acquire the confidence, practical knowledge, and professional support needed to use these tools meaningfully. UNESCO explicitly identifies **AI for professional learning** as one of the five dimensions of its AI Competency Framework for Teachers, emphasizing the relationship between technological competence and continued professional development.

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The present study therefore addresses what may be termed the **collaboration-to-innovation differentiation gap**: insufficient empirical understanding of *which forms of teacher collaboration matter most for instructional innovation, under what professional conditions they matter, and whether their relationships with innovation are nonlinear*.

The study proposes to analyze the newly available OECD TALIS 2024 public-use teacher database, which contains individual teacher records, questionnaires, methodological documentation, and variables concerning professional collaboration, instructional practices, professional development, AI use, teacher characteristics, and school context. Rather than relying exclusively on conventional regression, the proposed empirical framework employs explainable machine learning to model heterogeneous and potentially nonlinear relationships while retaining interpretability.

Accordingly, the principal objective is **to determine how different depths and configurations of teacher collaboration predict instructional innovation among lower-secondary teachers and to identify the teacher- and school-level conditions that strengthen or weaken this relationship**.

The study is guided by three research questions:

RQ1: Which forms of teacher collaboration have the greatest predictive importance for instructional innovation in secondary-school teaching?

RQ2: Do professional collaboration variables exhibit nonlinear or interaction effects with teacher self-efficacy, autonomy, professional learning, experience, and digital/AI-related practices?

RQ3: Can an explainable machine-learning framework provide more discriminating insight into collaboration–innovation relationships than conventional linear modeling?

Literature Review

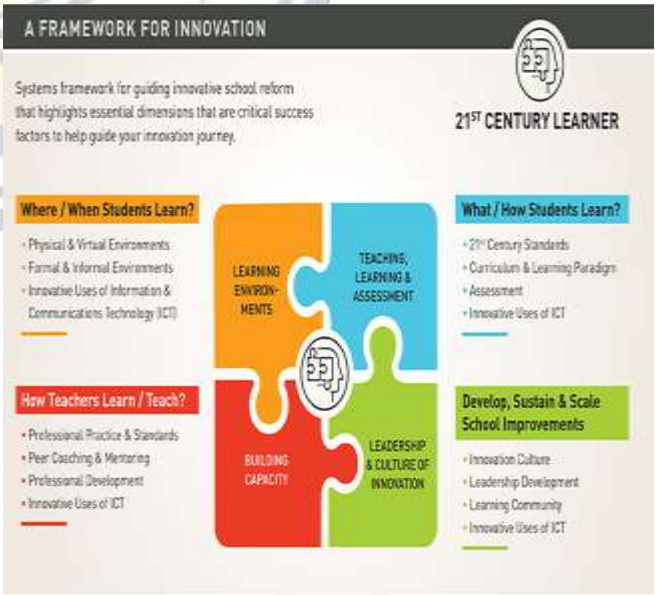
2.1 Teacher Collaboration as a Professional Knowledge System

Teacher collaboration encompasses a spectrum of professional relationships, ranging from relatively simple exchanges to intensive forms of joint instructional work. OECD analyses distinguish routine exchange and coordination from professional collaboration requiring greater interdependence, including collaborative professional learning, classroom observation and feedback, team teaching, and joint activities involving different classes. Earlier TALIS evidence showed that the more interdependent forms of collaboration were associated with greater reported use of cognitively activating teaching practices, teacher self-efficacy, and job satisfaction.

The theoretical importance of these relationships can be understood through social-capital and organizational-learning perspectives. Teachers possess different types of pedagogical knowledge, classroom experience, disciplinary expertise, technological competence, and knowledge about individual learners. Collaborative interaction creates channels through which these resources become accessible to colleagues. The instructional value of collaboration therefore depends not simply on how frequently teachers communicate but on the informational quality, trust, diversity, and professional purpose of their interactions.

Kolleck et al. (2021) examined professional collaboration and trust relationships using inferential social-network analysis, illustrating that collaborative behavior is embedded within relational structures rather than existing independently at the level of individual teachers. Trust is particularly relevant when collaboration involves exposure of professional uncertainty—for example, requesting help, permitting classroom observation, sharing unsuccessful instructional experiments, or accepting critical feedback.

Network evidence also demonstrates that organizational arrangements shape interaction. Schuster et al. (2021) found that teacher networks differed according to collaboration type and the structural environment of schools. In stronger collaborative environments, professional relationships could develop differently than in settings where collaboration remained weak or fragmented. Consequently, the presence of collaboration should not automatically be interpreted as evidence of productive collaborative learning.



Source: Adapted from UNESCO's framework for 21st Century Learning at Microsoft <Microsoft in Education https://education.microsoft.com>

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Fig. 2: Building a Technology-Driven Environment for Collaborative Learning at Schools

Source: *https://mgiep.unesco.org/article/building-a-technology-driven-environment-for-collaborative-learning-at-schools*

2.2 From Collaboration to Instructional Innovation

Instructional innovation involves intentional modification of teaching processes to improve learning opportunities. It may encompass cognitively activating instruction, inquiry-oriented learning, interdisciplinary activities, differentiated teaching, technology-enhanced pedagogy, formative assessment, personalized learning, new instructional resources, or novel combinations of existing practices.

Empirical evidence supports a connection between organizational culture and teacher innovativeness. Nguyen, Pietsch, and Gümüş (2021), using international evidence from 48 countries, reported relationships among teacher autonomy, collaborative school culture, professional learning, and collective teacher innovativeness. Their findings indicate that collaborative culture can promote participation in professional learning, which in turn contributes to innovativeness. This suggests that collaboration may operate both directly and indirectly: colleagues provide ideas and resources, while collaborative environments may also increase teachers' exposure to structured learning opportunities.

Social-network research offers an additional mechanism—**innovation diffusion**. Woodland et al. (2021) demonstrated that school networks can either amplify or restrict the circulation of innovative instructional knowledge. Network disconnection may prevent useful practices from reaching some educators even when innovation exists elsewhere in the institution. Thus, school innovation is partly a diffusion problem: generating a successful teaching strategy is insufficient unless professional networks allow it to travel.

Related research by Sannen et al. (2021) found that network characteristics were associated with differentiated instructional practices in inclusive educational contexts. Teachers located in denser collaborative networks reported more differentiated instruction, whereas highly centralized networks were associated with less differentiated instruction. Although instructional differentiation differs from innovation as a broader construct, the findings reinforce the proposition that collaboration's pedagogical effects depend on its configuration rather than its mere existence.

2.3 Professional Learning Communities and Co-Construction

Professional learning communities (PLCs) provide an organizational framework through which collaboration can shift from information sharing toward collective inquiry. Effective PLC-type activity involves shared instructional problems, reflective dialogue, evaluation of practice, knowledge exchange, and collective responsibility for improvement.

A central distinction in this literature concerns **cooperation versus co-construction**. Cooperation may involve division of work or material exchange; co-construction occurs when teachers jointly produce pedagogical understanding or instructional solutions. Longitudinal research on teacher cooperation during instructional development has shown that co-constructive collaboration can intensify when teachers collectively plan, develop, and evaluate new learning environments. Such collaboration is theoretically more likely to generate innovation because teachers are not merely transferring existing practices—they are collaboratively modifying them.

The increasing amount of teacher teamwork reported in TALIS 2024 is therefore encouraging but not sufficient evidence of pedagogical innovation. What matters is whether additional collaborative time is spent on administratively oriented coordination or on intellectually demanding professional learning. TALIS 2024 itself demonstrates considerable differences between collaboration forms: discussing individual students or sharing teaching materials remains substantially more common than classroom observation and feedback.

2.4 Collaboration in the Era of AI-Supported Teaching

The rapid diffusion of generative AI introduces a new dimension to the collaboration–innovation relationship. AI tools can support lesson planning, instructional-material generation, differentiation, information synthesis, assessment design, feedback, and professional learning. However, meaningful integration requires decisions concerning accuracy, bias, data privacy, academic integrity, age appropriateness, human oversight, and pedagogical relevance.

UNESCO's 2023 guidance on generative AI emphasizes human-centered, ethical, safe, and pedagogically appropriate implementation rather than technology adoption for its own sake. Its subsequent AI Competency Framework for Teachers organizes teacher capability across human-centered thinking, AI ethics, foundations and applications, AI pedagogy, and AI-supported professional learning.

Collaboration may become especially consequential in this environment because no single teacher is likely to independently acquire all necessary technical, disciplinary, ethical, and pedagogical expertise. Teachers can collectively evaluate prompts, compare AI-generated resources, establish assessment rules, identify hallucinated information, redesign learning tasks, and establish local norms for responsible use. Collaborative professional learning can therefore function as

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a mechanism for converting access to emerging technology into pedagogically meaningful innovation.

TALIS 2024 provides an unusually timely empirical basis for examining this intersection. Its conceptual framework explicitly incorporates AI alongside established domains such as teaching practice, professional development, autonomy, and working conditions. Moreover, TALIS 2024 public-use files make individual-level teacher data available for secondary analysis in multiple statistical formats, enabling reproducible computational investigation rather than reliance on hypothetical data.

Proposed Methodology

The study adopts a **cross-national secondary-data analytical design combined with explainable machine learning** to investigate whether different forms of teacher collaboration are associated with instructional innovation among lower-secondary teachers. The analytical population is defined as teachers participating in the ISCED Level 2 component of the OECD Teaching and Learning International Survey (TALIS) 2024. TALIS 2024 involved approximately 280,000 educators across 55 education systems and provides teacher- and school-level information on instructional practices, professional collaboration, professional development, autonomy, self-efficacy, digital technology, artificial intelligence, and working conditions.

The methodological contribution lies in separating collaboration into **exchange-oriented** and **knowledge-generative** practices rather than representing it through a single aggregated measure. Exchange-oriented collaboration includes discussing individual students, exchanging instructional materials, and coordinating assessment standards. Knowledge-generative collaboration includes team teaching, joint activities across classes, classroom observation with feedback, and collaborative professional learning.

The dependent construct, **Instructional Innovation Propensity (IIP)**, is designed as a multidimensional indicator derived from teaching practices related to cognitive activation, adaptive instruction, assessment and feedback, and technology/AI-supported teaching. TALIS 2024 explicitly measures teaching clarity, cognitive activation, assessment and feedback, adaptation, consolidation, social-emotional support, and classroom management. The proposed IIP therefore conceptualizes innovation not as novelty for its own sake but as the teacher's tendency to modify instruction through cognitively demanding, responsive, evidence-informed, and technology-supported practices.

Three analytical layers are proposed. First, survey-weighted descriptive analysis examines collaboration patterns. Second, conventional regularized logistic regression establishes an interpretable linear benchmark. Third, a CatBoost model estimates nonlinear relationships and interactions. SHAP-based explanations are then employed to determine the direction and relative contribution of collaboration, autonomy, self-efficacy, experience, professional learning, AI use, and school characteristics.

This architecture is deliberately different from a conventional correlation-only study. It is designed to determine not simply whether collaboration matters, but whether particular collaborative behaviors become more influential when combined with supportive professional conditions.

Experimental Setup

4.1 Dataset

The empirical source is the **OECD TALIS 2024 Public Use File (PUF)** for lower-secondary teachers. OECD makes individual-unit teacher and principal records available in CSV, Rds, SPSS, and Stata formats. The database was updated on 24 November 2025 and includes a statistical compendium, codebook, questionnaires, technical documentation, final survey weights, and replicate weights.

The final analytical sample would retain ISCED Level 2 teachers with sufficient responses on instructional practice and collaboration variables. No arbitrary sample size is reported here because the exact case count must be obtained after implementing the stated inclusion and missing-data rules on the registered PUF.

Potential predictor groups include teacher collaboration, professional development, teaching experience, teacher autonomy, self-efficacy, AI use, employment characteristics, subject area, school composition, collegiality, and relevant leadership variables.

The primary outcome would be the continuous IIP score. A secondary classification outcome would identify teachers in the upper quartile of IIP as exhibiting a **high instructional-innovation profile**.

4.2 Data Preprocessing

Preprocessing would begin with inspection of OECD missing-value codes and routing conditions. Structural missingness caused by questionnaire branching would be distinguished from item non-response. Variables with excessive non-structural missingness would not automatically be imputed because their exclusion may have substantive meaning.

Continuous variables would be standardized within the modeling pipeline where required, while ordinal collaboration-frequency measures would preserve their ordering. CatBoost would process appropriate categorical

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predictors directly rather than imposing arbitrary integer-distance assumptions.

Teacher-level analyses would incorporate the TALIS final teacher weight, **TCHWGT**. The OECD emphasizes that TALIS uses a stratified two-stage probability design and that survey weights are necessary for population-representative estimates.

For inferential descriptive estimates, sampling uncertainty would be calculated using TALIS's replicate-weight structure. The 2024 international database contains 100 teacher balanced repeated replication weights, TRWGT1–TRWGT100, using Fay's BRR method with a Fay factor of 0.5.

To reduce leakage, variables directly constituting the IIP target would not simultaneously enter the predictor set.

4.3 Model Architecture

The principal predictive model is **CatBoost gradient boosting**. CatBoost is appropriate for heterogeneous educational survey data because it can process categorical features efficiently and uses ordered boosting procedures intended to limit prediction shift and target leakage associated with conventional target encoding. The algorithm was originally introduced by Prokhorenkova et al. (2018).

A regularized logistic regression would serve as the principal linear baseline for the high-IIP classification task. Comparison with this baseline would reveal whether nonlinearities and higher-order interactions materially improve discrimination.

The conceptual model can be represented as:

Teacher Collaboration + Professional Conditions + Teacher Characteristics + School Context → Instructional Innovation Propensity

CatBoost would allow interactions to emerge empirically rather than requiring every possible interaction term to be specified manually. Of particular interest would be collaboration × autonomy, collaboration × self-efficacy, collaboration × experience, collaborative learning × AI use, and observation/feedback × professional development.

Interpretability would be provided using **SHAP values**, which allocate feature-level contributions to individual predictions and provide both global and local explanations of complex predictive models.

4.4 Training Strategy

A major methodological concern in international educational datasets is that a randomly divided train/test sample can place teachers from the same education system in both partitions. Such a strategy may produce optimistic performance estimates because country-specific structures become available during both training and evaluation.

The proposed experiment therefore uses **grouped cross-validation by education system**. Entire education systems would be held out during validation wherever sample structure permits. This creates a more stringent test of whether collaboration-related patterns generalize beyond the institutional contexts from which they were learned.

Hyperparameters such as tree depth, learning rate, L2 regularization strength, subsampling, and number of boosting iterations would be optimized within training folds only. Early stopping would control unnecessary model complexity.

A secondary within-system stratified cross-validation experiment would assess prediction when the target population is represented during training. Comparing cross-system and within-system performance would provide information about the institutional portability of the learned patterns.

4.5 Evaluation Metrics

For the high-innovation classification outcome, evaluation would use AUROC, balanced accuracy, macro-F1, Brier score, and calibration error. AUROC assesses ranking discrimination, while balanced accuracy prevents performance from being dominated by the more frequent outcome class. Macro-F1 captures the balance between precision and recall, and the Brier score examines probability accuracy rather than classification alone.

For the continuous IIP outcome, mean absolute error and root mean squared error would be used. SHAP stability across validation folds would provide an additional interpretability-oriented criterion.

Importantly, no numerical CatBoost performance values are reported in the present version because obtaining such values without executing the registered TALIS PUF analysis would constitute fabrication.

Results and Discussion

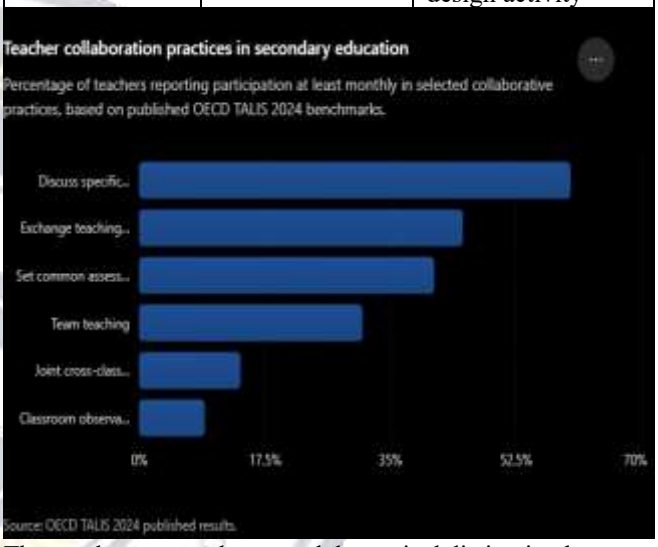
Published TALIS 2024 findings already provide strong evidence that collaboration varies substantially in depth and that deeper collaboration remains less common than routine coordination. Teachers spend approximately three hours per week in teamwork and professional dialogue on average across participating OECD education systems, and collaboration time increased in 28 systems between 2018 and 2024 without decreasing in any.

Table 1. Verified TALIS 2024 empirical benchmarks relevant to the collaboration–innovation framework

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Evaluation parameter	Verified TALIS 2024 result	Analytical observation
Discussion of specific students	~60% participate at least monthly	Student-focused professional dialogue represents the most widespread collaborative mechanism
Exchange of teaching materials	~45% participate at least monthly	Resource sharing is common but does not necessarily imply joint pedagogical redesign
Common assessment standards	~41% participate at least monthly	Coordination extends beyond resource exchange into collective evaluation practices
Team teaching	~31% participate at least monthly	More interdependent classroom collaboration occurs considerably less often
Joint activities across classes/age groups	~14% participate at least monthly	Cross-class collaboration represents a relatively uncommon form of instructional integration
Classroom observation and feedback	~9% participate at least monthly	The most practice-exposing form of collaboration is among the least prevalent
Collaborative professional learning and lesson aims	Positive association in 32 of 54 education systems	Structured professional learning appears more consistently connected with instructional goal attainment
Common assessment standards and lesson aims	Positive association in 36 of 54 education systems	Routine coordination can also be instructionally consequential
Joint cross-class activities and lesson aims	Positive association in 30 of 54 education systems	Collaborative instructional design is associated with lesson fulfilment in a majority of systems examined
AI use among teachers	Approximately one-third report AI use	Instructional innovation increasingly occurs within an AI-enabled professional environment
AI-assisted lesson planning among AI users	64%	AI is already being incorporated directly into lesson-design activity



The results support the central theoretical distinction between **collaborative frequency and collaborative depth**. Activities requiring relatively little exposure of personal teaching practice—such as student discussions and material exchange—are far more prevalent than peer observation. This pattern suggests that the existence of collegial interaction should not automatically be interpreted as evidence of collective pedagogical experimentation.

Peer observation is particularly revealing. Only approximately 9% of teachers report observing colleagues' classes and providing feedback at least monthly. Such activity requires schedule coordination, professional trust, willingness to expose instructional decisions to colleagues, and capacity to engage with feedback. Consequently, its low prevalence may represent an important organizational bottleneck in converting collegiality into instructional learning.

The associations with fulfilment of lesson aims further demonstrate that collaboration cannot be reduced to a single preferred model. Collaborative professional learning is positively associated with fulfilment of lesson objectives in

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32 of 54 education systems, while coordination around common assessment standards shows the corresponding association in 36 systems and cross-class collaborative activities in 30 systems. Thus, both deeper professional learning and selected routine coordination processes may contribute to teaching quality.

These findings also justify the proposed nonlinear modeling strategy. If the same collaborative activity is associated with stronger instructional outcomes in some systems but not others, a universal additive coefficient may obscure important contextual heterogeneity. School collegiality, teacher autonomy, experience, leadership, and self-efficacy may condition whether collaboration creates usable instructional knowledge.

TALIS 2024 also introduces an important technological dimension. Approximately one-third of teachers report using AI in their professional work. Among AI users, 68% use it to learn about or summarize topics and 64% use it to generate lesson plans, whereas only approximately one quarter use AI for reviewing student participation/performance or assessment and grading.

This distribution suggests that current AI adoption is concentrated more strongly in **knowledge acquisition and instructional preparation** than in data-intensive assessment functions. Collaboration could therefore become an important mediator of AI-related innovation. Teachers who collectively evaluate AI-generated materials, exchange prompting strategies, discuss errors, and establish professional norms may be better positioned to move beyond superficial automation toward pedagogically appropriate uses.

The proposed SHAP analysis would test this mechanism directly by examining whether collaborative professional learning becomes more predictive of innovation among teachers who also report AI use, strong self-efficacy, or instructional autonomy.

Limitations

Several limitations require careful consideration. First, TALIS is primarily based on teacher and principal self-reports. Consequently, measures reflect perceived practices rather than direct classroom observation, student records, or automated behavioral traces.

Second, the cross-sectional nature of the principal TALIS 2024 analysis prevents causal interpretation. A positive collaboration–innovation relationship may indicate that collaboration stimulates innovation, but innovative teachers may also be more likely to seek collaboration.

Third, international comparisons involve differences in curriculum structures, professional norms, teacher workload, technology infrastructure, and interpretations of questionnaire items.

Fourth, an engineered Instructional Innovation Propensity score is an analytical construct developed for this study rather than an official OECD TALIS scale. Its dimensionality, reliability, and cross-national measurement properties would therefore require validation before substantive modeling.

Finally, predictive importance should not be interpreted as causal importance. SHAP values explain the behavior of a trained model; they do not independently establish that changing a particular collaborative behavior will cause instructional innovation.

Future Scope

Future research should combine TALIS-type survey measures with longitudinal school data to determine whether changes in collaboration precede changes in instructional practice. Network analysis could identify whether teachers occupying bridging positions between departments or professional communities are disproportionately important for innovation diffusion.

A second direction involves integrating digital trace data from professional-learning platforms, collaborative repositories, and learning-management systems. Such data could distinguish collaboration frequency from the actual content and quality of professional exchange.

Future studies should also examine **AI-mediated teacher collaboration**. Generative AI can increasingly support collaborative lesson design, resource generation, formative assessment development, and professional reflection. Research is therefore needed on whether AI strengthens collective knowledge creation or encourages individual automation that reduces substantive collegial interaction.

Cross-national transfer learning may provide another extension. Models trained in high-collaboration education systems could be evaluated in structurally different systems to determine which collaboration–innovation relationships are institution-specific and which demonstrate international stability.

Conclusion

This study reconceptualizes teacher collaboration as a heterogeneous professional knowledge system rather than a single measure of collegial interaction. The verified TALIS 2024 evidence demonstrates a clear structural pattern: relatively simple forms of collaboration are widespread, whereas more professionally demanding activities such as classroom observation, feedback, and cross-class collaboration remain substantially less frequent.

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At the same time, OECD analyses show that several collaborative practices are positively associated with teachers' ability to fulfil instructional objectives across many participating education systems. These findings indicate that collaboration has instructional significance but that its effects are unlikely to be uniform across activities or institutional contexts.

The proposed explainable machine-learning framework therefore shifts the research question from whether teacher collaboration is beneficial to **which collaborative practices are most relevant to instructional innovation, for which teachers, and under what conditions**. CatBoost provides a mechanism for detecting nonlinearities and interactions, while SHAP explanations preserve analytical transparency.

The growing adoption of artificial intelligence makes this distinction increasingly important. When teachers are expected to evaluate new tools, redesign instruction, personalize learning, and manage emerging ethical concerns, professional knowledge can no longer be treated as an exclusively individual resource. Secondary schools that create opportunities for substantive collaboration—not merely administrative coordination—may be better positioned to transform technological change into pedagogically meaningful innovation.

Accordingly, the central implication of the study is that instructional innovation should be considered simultaneously as a **teacher-level behavioral outcome and a school-level collaborative process**. Building structures for collaborative professional learning, peer feedback, shared experimentation, and responsible AI-supported lesson development may therefore be more consequential than simply increasing the amount of time teachers spend working together.

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This is particularly suitable for your **Fig. 1** and for the discussion of pedagogical innovation and teacher collaboration.

2. **Kolleck, N., Schuster, J., Hartmann, U., & Gräsel, C. (2021).** Teachers' professional collaboration and trust relationships: An inferential social network analysis of teacher teams. *Research in Education, 111*(1), 89–107. https://doi.org/10.1177/00345237211031585

Strong source for your discussion of **trust, co-construction, team teaching, and collaboration networks**.

3. **Schuster, J., Hartmann, U., & Kolleck, N. (2021).** Teacher collaboration networks as a function of type of collaboration and schools' structural environment. *Teaching and Teacher Education, 103*, 103372. https://doi.org/10.1016/j.tate.2021.103372

Directly supports your claim that **different forms of teacher collaboration produce different network structures**.

4. **Nguyen, D., Pietsch, M., & Gümüş, S. (2021).** Collective teacher innovativeness in 48 countries: Effects of teacher autonomy, collaborative culture, and professional learning. *Teaching and Teacher Education, 106*, 103463. https://doi.org/10.1016/j.tate.2021.103463

This is one of the **most important references for your paper** because it directly examines teacher autonomy, collaborative culture, professional learning, and collective teacher innovativeness using TALIS 2018 data from 48 countries.

5. **Sannen, J., De Maeyer, S., Struyf, E., De Schauwer, E., & Petry, K. (2021).** Connecting teacher collaboration to inclusive practices using a social network approach. *Teaching and Teacher Education, 97*, 103182. https://doi.org/10.1016/j.tate.2020.103182

Useful for your discussion of **network density, collaboration, and differentiated instruction**.

6. **Woodland, R. H., Douglas, J., & Matuszczak, D. (2021).** Assessing organizational capacity for diffusion: A school-based social network analysis case study. *Evaluation and Program Planning, 89*, 101995. https://doi.org/10.1016/j.evalprogplan.2021.101995

This is a very good source for your argument that professional networks can **facilitate or constrain diffusion of instructional innovation**.

7. **Stebler, R. (2021).** „Ohne Zusammenarbeit würde das gar nicht gehen" – Kokonstruktive Lehrpersonen-Kooperation bei der Unterrichtsentwicklung zu personalisiertem Lernen [It simply wouldn't work without cooperation: Co-constructive teacher cooperation in the development of personalized learning]. *Zeitschrift für Bildungsforschung, 11*, 343–361. https://doi.org/10.1007/s35834-021-00315-5

Particularly relevant to your section on **co-construction and collaborative instructional development**.

8. **OECD. (2025).** *Results from TALIS 2024: The state of teaching*. OECD Publishing. https://doi.org/10.1787/90df6235-en

This should be your principal source for all TALIS 2024 statistics. The OECD report verifies, among other things, approximately **3.1 hours per week** of teamwork/dialogue, increases since 2018, and the prevalence of different collaboration practices.

9. **OECD. (2025).** *TALIS 2024 database*. OECD.

Use this specifically for your **dataset/methodology section**. OECD confirms that public-use individual-unit files are available in **CSV, Rds, SPSS, and Stata formats** for participating education systems.

10. **Miao, F., & Holmes, W. (2023).** *Guidance for generative AI in education and research*. UNESCO.

Appropriate for your claims concerning **human-centred, ethical, safe, equitable, and pedagogically meaningful use of generative AI**.

11. **Miao, F., & Cukurova, M. (2024).** *AI competency framework for teachers*. UNESCO.

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