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Regular Article

The development of an organizational model for technology enhanced personalized learning (TEPLAN)

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ABSTRACT

Technology-Enhanced Personalized Learning (TEPL) offers new opportunities for adaptive learning, yet its successful implementation requires coherence across teaching practices, school organization, and educational context. Despite growing interest, research lacks an integrated perspective on the organizational dimensions of TEPL. This study develops an organizational model for TEPL (TEPLAN) through an iterative process that integrates research and practice in a continuous cycle of refinement. Based on literature key factors at the micro-, meso-, and macro-levels are identified, which are validated and shaped into an initial organizational model for TEPL by expert validation. An empirical validation tests the model's validity in diverse school contexts, providing insights into its relevance for schools at varying stages of TEPL implementation, while a final theoretical validation ensures alignment with recent scholarly advancements. By adopting a network-based approach, TEPLAN captures the dynamic interrelations between organizational factors, providing a framework for schools to develop TEPL in a way that aligns with their specific context and needs.

1. Introduction

Calls for education to be more closely aligned with the needs of students are not a recent phenomenon. As early as 1997, legislation was enacted in the Netherlands stipulating that every child should have the opportunity to develop at its own pace and according to its own abilities, and that schools should provide a continuous learning trajectory for each child. Schools continue to strive to accommodate and acknowledge diversity among students. This article focuses on personalized learning (PL), considered as learning in which students take shared ownership and responsibility for the learning process, and the education provided is tailored to their needs, abilities, and interests (Bray & McClaskey, 2013a, 2013b; FitzGerald et al., 2018; Van Loon et al., 2016).

Technology-enhanced personalized learning (TEPL) offers new opportunities for adaptive learning through the integration of technology to support personalization. However, successful implementation requires coherence across teaching practices, school organization, and educational context (Demissie et al., 2022; Fullan, 2013; Holmes et al., 2018). Existing research typically addresses either pedagogical design (PL) or technological infrastructure (TEL) (Deacon et al., 2023; Vanderlinde & van Braak, 2010). However, a comprehensive understanding of TEPL requires an integrated, system-level approach that connects pedagogical, organizational, educational change and contextual factors (El-Hamamsy et al., 2024; Krijgsman et al., 2022). Synthesizing recent insights from educational change, PL and TEL, a system perspective, considering all aspects of the system in a holistic matter, is crucial for grasping the complexity of TEPL. Successful implementation of TEPL requires a system transformation (McCarthy et al., 2024). However it remains insufficiently understood which aspects influence the organization of TEPL and how these aspects are interrelated (Ifenthaler & Egloffstein, 2020; Sony & Karingada, 2024). This underscores the need for an organizational model tailored to TEPL.

The urgency arises from three developments: renewed interest in PL (Fitzgerald et al., 2018; Sony & Karingada, 2024); the growing role of

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educational technologies, reinforced by lessons from the COVID-19 transition and the need to sustain their effectiveness (Deacon et al., 2023); and the accelerating pace of technological innovation, such as artificial intelligence, which can support PL but requires organizational embedding (Agélii Genlott, Grönlund, & Viberg, 2019; Holmes et al., 2018; McCarthy et al., 2024). Unlike traditional organizational frameworks that emphasize hierarchy or linear change, this study introduces TEPLAN, an organizational model for TEPL that adopts a network-based perspective reflecting the dynamic and context-specific nature of educational innovation (Czarniawska, 2017). The unique contribution of this study lies in the development and validation of TEPLAN, which integrates relevant factors across system levels and interprets them through a network-based perspective based on Actor Network Theory (ANT). This research focuses on K12 education, where learner diversity is particularly prominent (Holmes et al., 2018), making this context especially relevant for this study. The research question is:

What does an organizational model for technology-enhanced personalized learning (TEPL) encompass in the context of K12 education?

The sub questions are:

- What aspects are relevant for the organization of TEPL on micro-, meso- and macro-levels?
- How can these aspects be integrated into an organizational model for TEPL?

To answer these questions, this study makes three key contributions. First, it introduces TEPLAN as a mid-range theoretical model grounded in ANT, that complements existing approaches such as TPACK, SAMR, and current PL or TEL frameworks. By moving beyond a synthesis of individual factors, it provides an interpretive lens to explain the relational dynamics and organizational configurations that shape digital transformation. Second, it applies a multi-phase, iterative validation process that integrates literature, expert insights, and school-based practice. Third, it demonstrates the added value of ANT by showing how interrelations between human and non-human actants shape the organizational conditions for TEPL implementation.

2. Method

This study employs an iterative research methodology to develop an organizational model for TEPL, progressively refining the organizational model with inputs derived from both research (literature and expert opinions) and practice. This aligns with the concept of interactive research as proposed by Ellström (2008), in which a collaborative production of knowledge from two systems is stimulated (see Fig. 1).

The research consists of several methodological steps: literature exploration, expert validation, empirical validation in practice and theoretical validation. Consistent with middle-range theorizing, this process of empirical grounding ensures the development of an explanatory model that identifies the underlying mechanisms of change, reconciling abstract theory with the specificities of school-based practice

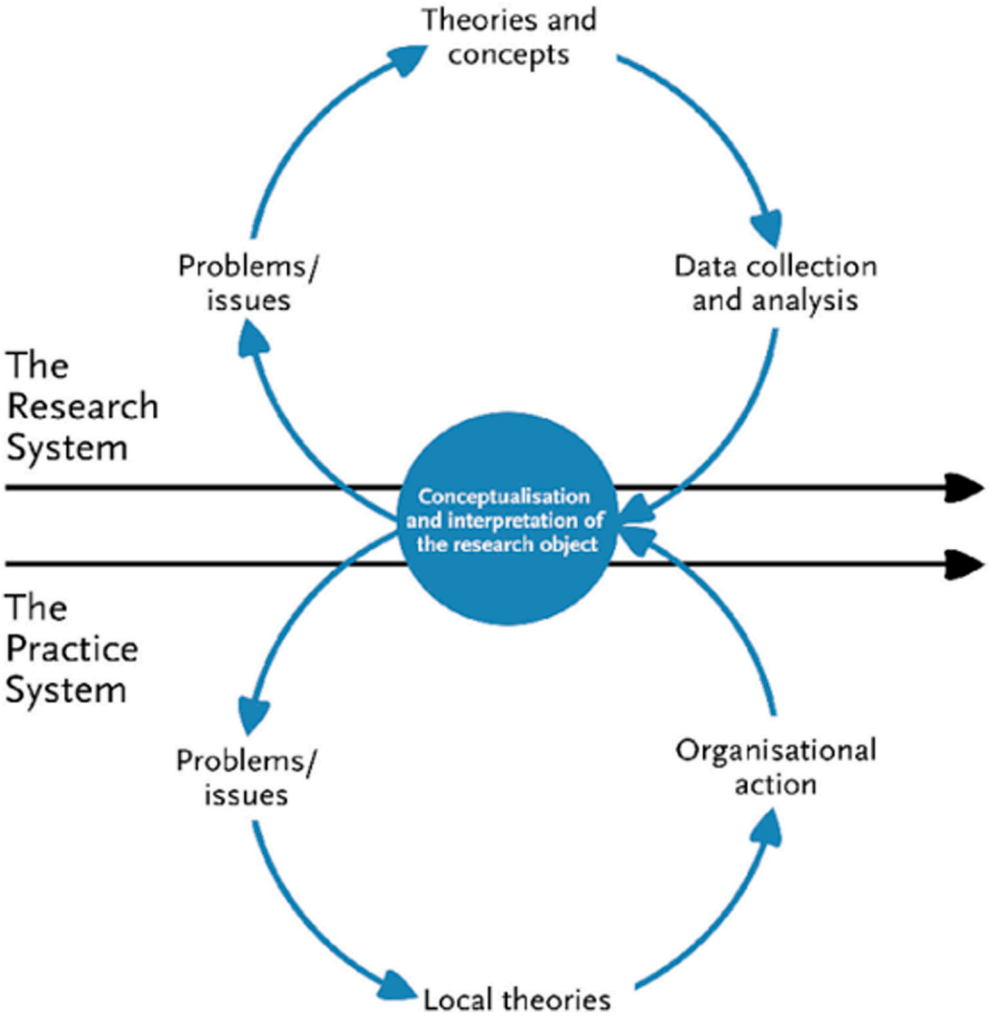


Fig. 1. A Model of Knowledge Creation Through Interactive Research (Ellström, 2008: p.9).

(Davidoff et al., 2015).

2.1. Literature exploration

The literature exploration aims to identify relevant aspects at the micro-, meso-, and macro-levels for the organization of TEPL in K12 education. At the outset of the study, a literature review was intended to identify aspects. However, given the limited availability of scientific literature specifically addressing TEPL at that time, the approach was adjusted to a literature exploration. This exploration identifies relevant aspects for TEPL by integrating insights from two domains: technology-enhanced learning (TEL) and personalized learning (PL). The literature exploration includes papers depicting organizational models for TEL for aspects on micro-, meso- and macro-levels and studies concerning PL for aspects on micro-level. The selection process and sources consulted are depicted in Appendix 1.

The data processing is performed by qualitative content analysis (Schreier, 2012), which involved three coding steps based on Gessler and Siemer (2020):

1. Initial analysis (selecting relevant data from various texts),
2. Critical evaluation (assessing the extracted data), and
3. Synthesis (combining and reanalyzing the aggregated data).

To minimize bias, three researchers independently conducted the first two coding cycles. Each researcher initially analyzed one article separately after which results were compared and coding approaches aligned. The remaining articles were then divided among them, with recurring calibration discussions to check consistency. The final synthesis step was carried out collaboratively to ensure cohesion in the aggregated findings. Agreement was reached through iterative discussion and comparison of coding results. Discrepancies were explicitly documented and resolved by returning to the source material until agreement was reached. This consensus-based approach was preferred over calculating inter-rater statistics, given the exploratory and model-building nature of the study.

2.2. Expert validation

To ensure accuracy and relevance, experts in educational and non-profit organizations validated the initial aspects extracted from the literature. Experts are purposefully selected to ensure that all dimensions of TEPL are represented, including expertise in technology, pedagogy, organizational change, and governance. All selected experts hold doctoral degrees and have substantial research and professional experience in these domains. Candidates were identified within the research team's professional network and national platforms. Over a period of seven months, three structured expert meetings are conducted to move beyond a descriptive synthesis toward a more explanatory model. During this process the experts play a functional role in the decision-making process: they enriched the literature base, substantiated the identified aspects, and validated the model's explanatory value. A detailed description of the experts involved and the audit trail of the agreement procedures is provided in Appendix 2.

2.3. Empirical validation in practice

For the empirical validation, two groups of schools are included. First, Dutch schools with innovative TEPL practices are identified through document analysis of relevant publications, professional networks, and media coverage. On this basis, a list of 35 innovative schools across the Netherlands is compiled and grouped into four clusters, reflecting the main areas in which they are considered innovative: (1) advanced use of ICT, (2) flexible timetables and organizational structures, (3) personalized learning pathways, (4) student-engagement. From each cluster, schools are approached for participation; if a school declines, another school from the same cluster is invited. This process ensured representation across the full spectrum of innovative TEPL practices. Ultimately, six schools agreed to participate, representing diverse yet complementary manifestations of TEPL.

Second, nine regular K12 schools in the South-East region of the Netherlands are selected as part of the NRO-funded research program *Personalized Learning with ICT (OWP PO)*. The selection process is coordinated with school boards and guided by intake interviews. Schools are included if they (a) demonstrate a clear ambition to implement TEPL; (b) embed this ambition in school-wide development; (c) commit time and staff capacity to the three-year design and research process; and (d) show willingness to engage in collaborative research and knowledge sharing. This twofold selection strategy is appropriate, as it incorporates variation in both implementation maturity and contextual characteristics, providing a robust basis for validation across complementary contexts.

Qualitative data collection for the empirical validation consists of at least one semi-structured (group) interview per school with the school leader, supervisors, and teachers, complemented by observations of school practices. The organizational model serves as an analytical framework to document how the aspects of TEPL manifest in practice. The research instruments and a descriptive overview of the participating schools are provided in Appendix 3. For each school, the collected qualitative data were summarized in a matrix containing all aspects, including a brief description of each aspect and its reported interrelations with other aspects. Based on these matrices, individual Actant Network Maps were constructed for each school.

To explore patterns in interrelations and structural complexity of these maps, network analysis is conducted (De Ries et al., 2022), treating human and non-human actants symmetrically. The following quantitative network measures are calculated to characterize the structure of each map: network density, average OutDegree, Eigenvector centrality and Betweenness centrality (Newman, 2018).

- Network density indicates overall connectedness or structural complexity of maps and is calculated as the ratio of observed to possible connections (links) among actants (nodes), using the standard formula $D = L/[N \times (N-1)]$, where L is the number of directed links and N the number of nodes in the network (Newman, 2018).
- Average OutDegree represents the mean number of outgoing ties per actant, revealing the general level of direct influence within the network. Nodes with the highest OutDegree exert the strongest influence, reflecting a node's capacity to actively shape other elements in the network (Newman, 2018).
- Eigenvector centrality measures the relative influence of actants, accounting for the influence of their connected peers. Nodes with highest Eigenvector centrality hold the most influential positions, indicating a state of relational alignment where an actant's influence is reinforced by a cluster of other influential nodes, increasing its overall weight within the network configuration (Newman, 2018).
- Betweenness centrality captures nodes' capacity to connect separate parts of the network. Nodes with highest Betweenness centrality play key bridging roles that coordinate actions and mediate influence by linking otherwise disconnected elements (Newman, 2018).

These measures jointly provide both local and global insight into how influence is distributed, and how roles are allocated within each school's TEPL configuration. Visualizations and calculations are performed using Microsoft Excel Node XL and Python Networkx.

2.4. Theoretical validation

After the empirical validation a final theoretical validation of the model is conducted. The validation primarily served a confirmatory purpose, ensuring the model's alignment with the latest theoretical developments and enhancing its robustness. Given the rapid advancements

in technology (such as AI) and their influence on educational practices (Farias-Gaytan et al., 2023), along with the increasing body of literature on PL implementation and TEPL (Sony & Karingada, 2024), this theoretical validation represents a crucial and timely step. The literature review for the theoretical validation consists of three steps (more thoroughly described in Appendix 1): identification, eligibility screening and check and inclusion (Gessler & Siemer, 2020), as presented in Fig. 2:

Data processing follows Gessler and Siemer's (2020) three-step approach: analysis, critical evaluation, and synthesis. To ensure consistency and transparency, the following procedure is applied:

- Analysis: in this inductive step, three researchers extract relevant data. They initially reviewed one article each to align coding methods before dividing the remaining articles. Throughout this step, coding outcomes are explicitly compared, and differences are discussed until a shared interpretation is reached.
- Critical evaluation: the researchers collaboratively evaluate the relevance of extracted data, ensuring only significant findings are retained.
- Synthesis: this final step combines deductive categorization with exploratory analysis. Data are grouped into predefined actants to validate the model, while new actants are incorporated as needed.

This approach balances inductive exploration with deductive structure while researcher consensus safeguards consistency and transparency.

3. Results

The results are presented per methodological step and organized around two lines of reasoning, reflected in the subheadings: (1) identifying **relevant aspects**, and (2) integrating them into an organizational model or **model development**, concerning the interrelations of aspects.

3.1. Literature exploration

3.1.1. Relevant aspects

The literature exploration resulted in a comprehensive list of relevant aspects for the K12 organizational model (Table 1, 'Literature exploration' column). Some aspects are more straightforward, while others represent a synthesis of various terms. In some cases, an actor is explicitly mentioned (e.g., government), while in others, the focus is on what the actor produces (e.g., policy). Terms for the same factor often vary, such as ICT infrastructure, hardware, technology, and ICT facilities, all referring to aspects of ICT infrastructure. Additionally, certain terms may have different meanings depending on context; for instance, educational organization can refer to the regional or contextual level of a school or to the internal processes within a school. The synthesis of factors was therefore conducted with careful consideration of the context provided in the original articles.

In Appendix 1, a summary table of the literature review is provided (Table A1), listing and defining all factors along with the frequency counts of their occurrence in included papers.

3.1.2. Model development

While these levels and aspects capture a wide range of relevant factors, the literature exploration revealed substantial fragmentation in how the multilevel nature of TEPL is addressed (depicted in Table A2 in the appendix). Twelve studies focus on only two levels, while ten of the twenty-five reviewed articles consider three levels. Among these ten studies, the number of aspects described per level is limited: four out of these ten studies mention only one macro-level factor, another three address merely two macro- or micro-level factors. Nine of these ten studies describe between 9 and 14 actants (roughly 50%) and only one study includes 19 actants (79%). Moreover, none of the studies examine how aspects interact with or relate to one another.

In general, PL literature concentrates on micro- and meso-level aspects, whereas TEL studies emphasize meso- and macro-level conditions. This imbalance shows that current research offers no integrative models

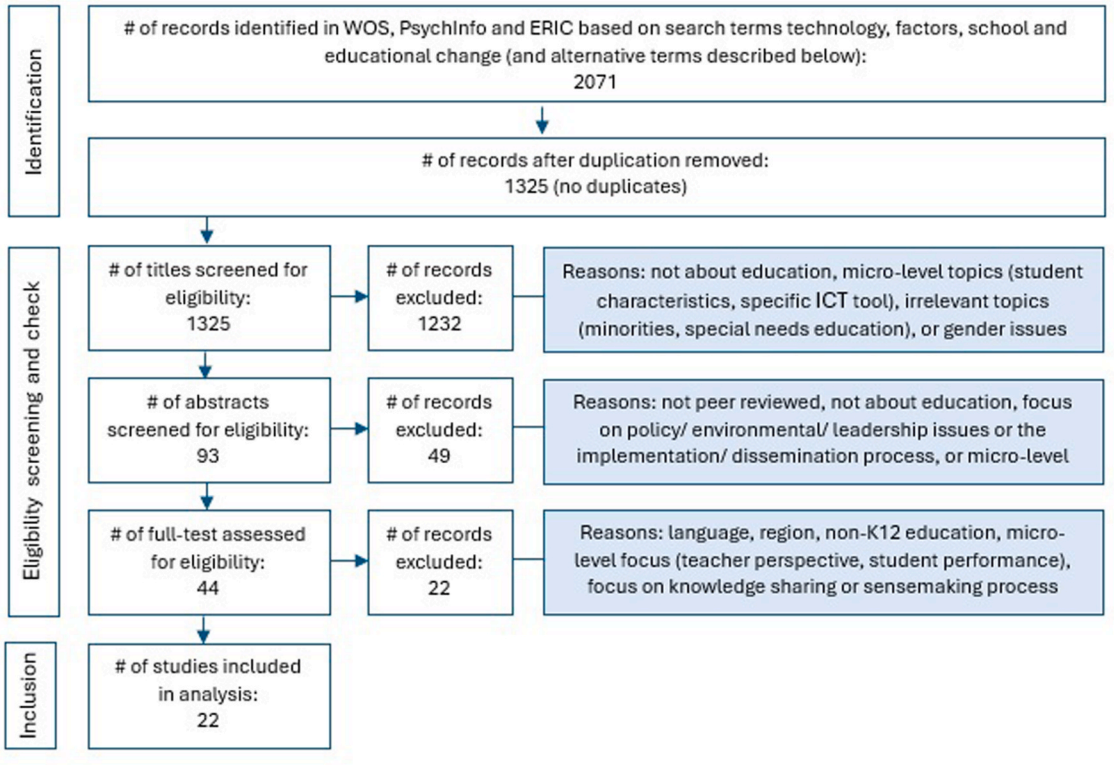


Fig. 2. Flow diagram presenting the literature review process.

Table 1
Comparison table depicting changes over time in aspects for each validation phase.

Literature exploration		Expert validation	Empirical validation
MACRO	Curriculum standards (Inter)national education (ICT) policy Teachers' standards	*Teacher & curriculum standards/policy*	Teacher & curriculum standards/policy
	Board	Board	Board
	Education software developers Educational publishers	*Education software developers & publishers*	Education software developers & publishers
	Educational infrastructure	Educational infrastructure	Educational infrastructure
	Social system and cultural norms Economic system and economic forces	*National contextual influences (social, cultural, economical)*	National contextual influences (social, cultural, economical)
MESO			***Parents***
	Intended curriculum	Intended curriculum	**Educational vision & goals**
	Leadership	Leadership	**School leader**
	School type School location and school layout	*School type & location and layout*	School type & location and layout
	ICT infrastructure ICT policy planning	*ICT policy & infrastructure*	ICT policy & infrastructure
	Support (ICT, pedagogy and innovation)	Support	Support
	Time-tabling Roles of members	**Division of labor**	Division of labor
	Professional development (ICT, pedagogy, innovation)	Professional development	Professional development
	School culture Collaborative climate Networks and collaboration among teachers	*School culture & collaborative climate*	School culture & collaborative climate
	Innovation characteristics	Innovation characteristics	Innovation characteristics
	Grouping	Grouping	Grouping
	Resources	Resources	Resources **(time and money)**
	Monitoring system	*Assessment, monitoring & evaluation*	Assessment, monitoring & evaluation
MICRO	Curriculum content and goals	Curriculum content & goals	Curriculum content & goals
	Learning materials	Learning materials	Learning materials
	Ways of ICT use	Ways of ICT use	**ICT applications**
	Time and space of learning Availability of/access to ICT	*Time and space of learning & availability of/access to ICT*	Time and space of learning & availability of/access to ICT
	Teacher role Type of teacher Teacher knowledge and skills Teacher attitude and beliefs	*Teacher*	Teacher
	Student role Type of students Students' knowledge and skills Students' attitude and beliefs	*Student*	Student
	Assessment		
NANO	Goals, diagnosis, design, performance, monitoring, evaluation		

linking the organizational, pedagogical, and contextual dimensions of TEPL across levels. This discrepancy is also reflected in existing pedagogical models such as TPACK and SAMR, which focus primarily on the micro level of teacher practice and technology use. While valuable, these frameworks remain largely descriptive and overlook the organizational interdependencies that shape implementation. TEPLAN addresses this gap by repositioning these interdependencies as a dynamic, relational process of translation between human and non-human actants. Rather than a static classification, TEPLAN captures organizational 'friction' and 'alignment' over time. This provides the analytical depth necessary to explain how broader organizational dynamics facilitate or hinder technological integration.

3.2. Expert validation

3.2.1. Relevant aspects

During the expert validation, the list of aspects from the literature exploration was refined into actants, according to ANT (explained below the next sub-heading 'model development'), which focuses on the relations and influences among actants. Consequently, overlapping factors were merged where they showed interdependence within the network and did not exert independent influence as separate actants (indicated in *italic* text in Table 1, 'Expert validation' column). The following actants were combined due to their shared influence:

- *Curriculum standards*, *(Inter)national education (ICT) policy*, and *Teacher standards* were merged into *Teacher & curriculum standards/policy*.
- *Education software developers* and *Educational publishers* became *Education software developers & publishers.*
- *Social and cultural norms* and *Economic systems and forces* were combined as *National contextual influences (social, cultural, economic)*.
- *School type*, *Location*, and *Layout* were integrated into *School type, location & layout.*
- *ICT infrastructure* and *ICT policy planning* were merged as *ICT policy & infrastructure.*
- *School culture*, *Collaborative climate*, and *Networks and collaboration among teachers* were unified as *School culture & collaborative climate.*
- *Monitoring system* and *Assessment* were merged into *Assessment, Monitoring & Evaluation.*
- *Time-tabling* and *Availability of/access to ICT* were included in *Time and space of learning.*

In line with ANT's terminology, *Roles of members* was relabeled as *Division of labor*, emphasizing distributed responsibilities rather than fixed functions (relabeling is indicated with **bold text** in Table 1, 'Empirical validation' column). Teacher- and student-related characteristics were integrated into two composite actants, *Teacher* and *Student,* reflecting that attributes such as skills and attitudes emerge through their relations in the network (not as separate actants). Actants from the former nano-level were removed, since personalization is represented within actant characteristics.

3.2.2. Model development

In consultation with the experts, it became evident that traditional organizational perspectives, such as mechanistic, organic, or system-based models, do not adequately fit the dynamic and interconnected nature of TEPL. Therefore, Actor-Network Theory (ANT; Latour, 2005) is adopted, providing a network-based lens to analyze TEPL's interrelations and organizational dynamics. ANT conceptualizes actants, both human and non-human elements, as entities that shape and influence one another (Ammar et al., 2024). This view particularly relevant for TEPL where technology actively mediates learning processes (Tahirkheli, 2022). Through these interactions, meaning and knowledge emerge (Canagarajah, 2018), illustrating how material and social elements jointly shape teaching practices (Law, 2002). Unlike hierarchical

system models, ANT emphasizes connections rather than levels, enabling a holistic understanding of TEPL's organizational complexity and responsiveness to broader societal and technological developments (Leonard, 2023).

The consultations with experts led to the development of the first model depicted in Fig. 3. In line with the ANT perspective, distinctions between levels are disregarded and actants are considered as more contextual, organizational or pedagogical depending on their characteristics and interrelations within the network. The model is also given a name: TEPLAN (Technology Enhanced Personalized Learning Actant Network).

In the visualization of TEPLAN, actants directly related to the learning process are positioned centrally, with broader organizational or contextual actants placed around them. While the literature provides limited information on specific interrelations, the model visualizes actants with content-related connections in close proximity, avoiding explicit representation of concrete relationships. For instance, *Teacher & curriculum standards/policy*, *Intended curriculum*, *Curriculum content & goals*, and *assessment, monitoring & evaluation* are grouped in the upper half of the model. This arrangement reflects their practical interdependencies: curriculum standards inform the intended curriculum, which is translated into curriculum content and student learning goals, and these goals are subsequently monitored and evaluated through assessments. Furthermore, actants such as *Professional development*, *Division of labor*, and *School culture* are positioned near the actant *Teacher*.

3.3. Empirical validation in practice

3.3.1. Relevant actants

The empirical validation aims to validate the completeness of the theoretical TEPLAN model within diverse TEPL practices and whether additional actants should be included. *Parents* are added to TEPLAN as an actant due to their explicit influence on other actants within the actor-networks of the innovative TEPL schools (indicated with ***bold italic text*** in Table 1). They can shape student engagement and motivation, participate in student-teacher assessment meetings, influence ICT availability at home, and support students in their learning. Through these roles, parents can significantly impact the dynamics within the network, making them an integral and autonomous actant.

Another actant frequently mentioned by respondents is *ICT applications*. From an ANT perspective, *ICT applications* is a more suitable actant than *Ways of ICT use*, as it functions more autonomously. This autonomy aligns with ANT's emphasis on the agency of non-human actants (Latour, 1990). From ANT perspective *Ways of ICT use* can be considered as an action of teachers or students using ICT applications. Therefore, the actant W*ays of ICT use* is changed into *ICT applications*. The actant

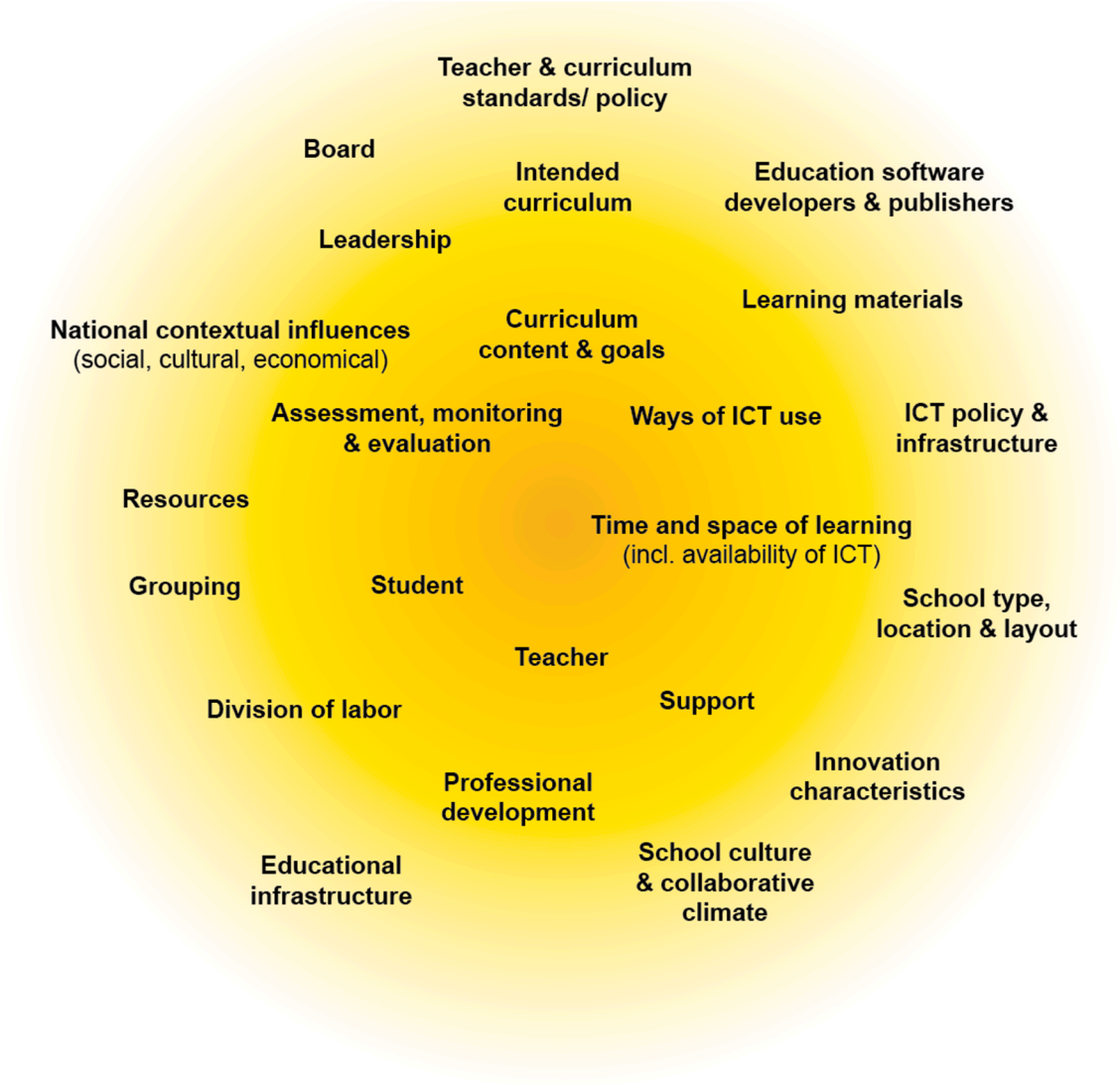


Fig. 3. Initial version of TEPLAN based on the literate exploration and expert validation.

Intended curriculum is revised to *Educational vision and goals*, reflecting its strategic importance and more direct influence on other actants such as professional development and support. While educational vision was identified as a relevant factor in the literature review, it was previously considered as part of *Leadership*. However, its distinct role in shaping strategic priorities and guiding implementation processes warrants its recognition as a separate actant in TEPLAN. The actant *Leadership* is accordingly revised to *School leader*. Another refinement of TEPLAN resulting from the empirical validation is the further specification of the actant *Resources*, which is defined more explicitly as '*time and money*'.

The organizational model serves as an analytical framework to document how the aspects of TEPL manifest in practice, providing insight into contextual variation in their manifestation. All actants are recognized by the participating schools, and most play a distinct role within their TEPL configurations, ranging from 92% to 100% (see Appendix 3, Table A5). *National contextual influences* are mentioned least frequently (73%), being absent among the key actants in four schools at the early adoption stage. *Educational infrastructure* follows (80%), not mentioned in two schools with mature TEPL practices. Across contexts, however, actants exhibit different characteristics. For example, *ICT infrastructure* varies considerably between schools: in most, this includes one-to-one student devices and interactive whiteboards in every classroom, whereas others have only a few desktops per room or a limited number of mobile devices. Another example concerns *Division of labor*. In some schools, teachers assume differentiated roles or functions, for instance, as subject specialists leading domain development or as student coaches supporting self-regulated learning.

3.3.2. Model development

Analyses of the school-based Actant Network Maps, from both mature TEPL practices and schools in the early phases of TEPL adoption, revealed distinct network patterns. The centrality metrics for each school are described in Table 2. Mean scores for three centrality measures (Out-Degree, Betweenness, Eigenvector) are presented as well as *top nodes* columns, to identify which actants holds the highest value for each centrality measure.

Overall, mature TEPL networks show higher density and mean centrality values than EA networks, suggesting that mature TEPL practices are characterized by more interconnected configurations of actants. This higher density reveals an organizational condition of strong cohesion, where ICT integration is facilitated by a continuous flow of influence across the network, rather than being confined to isolated clusters. The mean average Out-Degree is higher in mature TEPL schools, indicating that a greater proportion of actants actively influence others. Notably, in TEPL schools, non-human actants such as *Vision* and *ICT policy* emerge as central initiators with high Out-Degrees (e.g., TEPL1, TEPL4, TEPL6), demonstrating their autonomous agency in guiding organizational dynamics and stabilizing the digital learning environment. In contrast, influence in most EA schools remains more traditionally concentrated within the human actants *Leader* and *Teacher*. While *Teacher* has a high out-degree in both types of networks, closer analysis of the influence of *Teacher* reveals a clear difference in focus: in EA networks, teachers primarily affect actants directly related to classroom practice, such as *Curriculum Content & Goals*, *Grouping*, and *Time and Space of learning*, whereas in TEPL school networks, their influence extends beyond instructional design including among others *School culture & collaborative climate*, and *Educational vision and goals*.

While individual EA networks sometimes show high Eigenvector peaks for *Student* (e.g., EA6 at .715), the mean Eigenvector centrality value is higher in mature TEPL networks (.164 vs.135). This means that actants with high influence, particularly *Teachers* and *Students*, are strongly embedded within influential subnetworks. In EA networks, the high Eigenvector peaks for students result from influential actants (e.g., *Teacher* and *Leader*) directing their actions toward them. In these directed configurations, *Student* functions as a high-status destination of influence while remaining a passive recipient. This is clearly illustrated

Table 2
Network and centrality metrics for each school and mean scores for nine schools in early adoption stage of TEPL (EA) and the six mature TEPL practices (TEPL).

School	Density	OutDegree		Betweenness centrality		Eigenvector centrality	
		mean	Top	mean	Top	mean	Top
EA1	.143	3292	Teacher (10) Leader (9)	.046	Teacher (.419) Leader (.210)	.149	Student (.550) Teacher (.433)
EA2	.107	2348	Leader (11) Teacher (10)	.042	Teacher (.379) Leader (.234)	.146	Student (.682) Teacher (.332)
EA3	.111	2435	Leader (6) Teacher (5)	.023	Teacher (.166) Vision (.081)	.131	Teacher (.501) Grouping (.439)
EA4	.120	2750	Leader (10) Teacher (9)	.056	Teacher (.487) Leader (.322)	.131	Teacher (.575) Student (.486)
EA5	.101	2333	Leader (9) Teacher (6)	.061	Teacher (.466) Leader (.379)	.125	Student (.527) Curriculum (.457)
EA6	.126	2783	Leader (9) Teacher (8)	.027	Teacher (.196) Student (.092)	.114	Student (.715) Curriculum (.366)
EA7	.107	2458	Teacher (7) Leader (5)	.064	Teacher (.468) Leader (.338)	.123	Student (.607) Curriculum (.392)
EA8	.128	2826	Leader (12) Teacher (10)	.041	Vision (.258) Teacher (.238)	.155	Student (.510) Curriculum (.368)
EA9	.107	2348	Leader (6) Teacher (5)	.058	Teacher (.349) Vision (.228)	.145	Parents (.471) Student (.453)
Mean	**.117**	**2619**		**.046**		**.135**	
TEPL1	.185	4250	Teacher (15) Vision (15)	.048	Teacher (.415) Vision (.220)	.161	Teacher (.495) Student (.471)
TEPL2	.221	4636	Leader (12) Teacher (12)	.047	Teacher (.256) Leader (.228)	.173	Student (.458) Teacher (.455)
TEPL3	.208	4565	Leader (12) Student (11)	.047	Leader (.334) Student (.309)	.162	Student (.520) Teacher (.419)
TEPL4	.167	3833	Teacher (12) ICT Policy (10)	.042	Teacher (.326) Leader (.117)	.162	Student (.443) Teacher (.429)
TEPL5	.180	3957	Teacher (15) Leader (8)	.063	Teacher (.488) Resources (.144)	.163	Teacher (.416) Student (.404)
TEPL6	.172	3958	Vision (14) Student (10)	.046	Student (.242) Teacher (.172)	.162	Teacher (.487) Student (.398)
Mean	**.189**	**4200**		**.049**		**.164**	

by school EA3 (Fig. 4), where *Student* holds a high Eigenvector value (.387) but an out-degree of 0, indicating no initiated influence within the network. By contrast, the higher mean Eigenvector values in mature TEPL networks, combined with higher mean Out-Degrees, underscore a structural shift toward greater interdependence. This means that actants with high Eigenvector, particularly *Teacher* and *Student*, are strongly embedded within influential subnetworks of mutual translation. In school TEPL2 (Fig. 5), for example, *Student's* out-degree is 8, revealing a transition where students actively shape the digital learning environment.

Interestingly, despite the increased connectivity in mature schools, Betweenness centrality values show no difference between EA and TEPL networks. However, a qualitative shift is visible in which actants fulfill these roles. In EA schools, bridging roles, that connect disparate parts of the network, are typically assumed by *Teacher*, *Leader*, or *Vision*. This creates a leadership dynamic heavily dependent on formal gatekeepers, posing a risk of relational friction if these actants fail to translate organizational or ICT goals to educational practices. In two TEPL networks, however, *Student* also occupies a connecting position, revealing a more resilient organizational configuration. In these schools, students are actively integrated into the translation process; rather than being passive recipients of a top-down leadership vision, they function as a bridge that allows educational practices to be continuously adapted to their specific learning needs. This shift from a leader-centric perspective to a student-inclusive network stabilizes the integration process by ensuring that technology is anchored in the actual pedagogical interactions of the school.

To illustrate the observed differences, two representative maps are presented below: school EA3 (Fig. 4) and school TEPL2 (Fig. 5). Both networks are visualized using a force-directed spring layout (Fruchterman & Reingold, 1991), which positions actants based on the strength and number of their connections. To enhance visual clarity, actant labels are abbreviated (as described in Appendix 3, Table A1).

In the early-stage network (Fig. 4: EA3), the visual layout reveals a fragmented structure where influence is concentrated in a linear, top-down fashion. *Teacher* occupies the central bridging position, primarily influencing actants related to the learning process (e.g., *Grouping*, *Materials*) while being influenced by organizational roles such as *Leader* and *Vision*. The structure appears open and uneven, indicating limited structural integration and reliance on individual coordination and the teacher acts as the sole gatekeeper to translate organizational goals to the pedagogical practice. In contrast, the mature TEPL network (Fig. 5: TEPL2) shows a denser and more balanced configuration in which *Teacher*, *Leader*, Student, and *Vision* form a cohesive core. This core is characterized by mutual translation, where pedagogical goals and organizational conditions are continuously aligned. Here also *Student* exerts greater influence across the network, moving from the periphery to a central position. This shift reveals a student-inclusive organizational logic: the student is actively integrated into the translation process, allowing the digital practice to be tailored to actual learning needs rather than following a rigid, leader-centric vision. This multi-directional flow of influence stabilizes the network, making the ICT-integration more resilient to organizational changes.

Due to the unique and context-dependent nature of interrelations between actants, explicit connections between actants are not visually represented in TEPLAN, to emphasize relational thinking and encourages school teams to critically explore potential and unique interactions between actants, without being prescriptive. Nevertheless, the model emphasizes the significance of these interrelations by adopting an ANT perspective, which considers actants as part of an interconnected network.

Based on the empirical validation, the final version of TEPLAN is configured as follows (Fig. 6), with adaptations from the previous version highlighted in red.

Another aim of the empirical validation was to examine how TEPLAN, as an analytical framework, supports transformations towards TEPL or TEPL implementation. Teachers reported that TEPLAN helps them visualize the complex interrelations within their school's organization. One teacher explained, *'The organizational model provided a clear overview of what we were working on and how everything related to one another. When we visualized our organizational model we gradually transitioned to thinking about what exactly we wanted to change in daily practice and what that would mean for the organization of our education.'* By comparing the current and desired situations, the model helped school

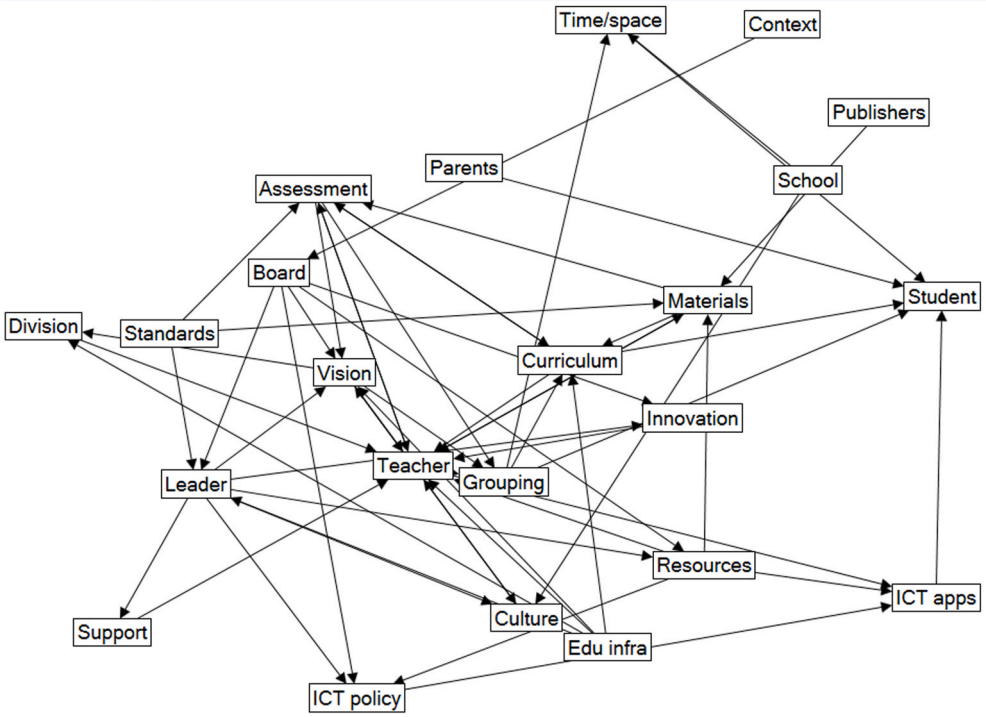


Fig. 4. Force-directed spring layout of an early-stage TEPL adoption network (school EA3).

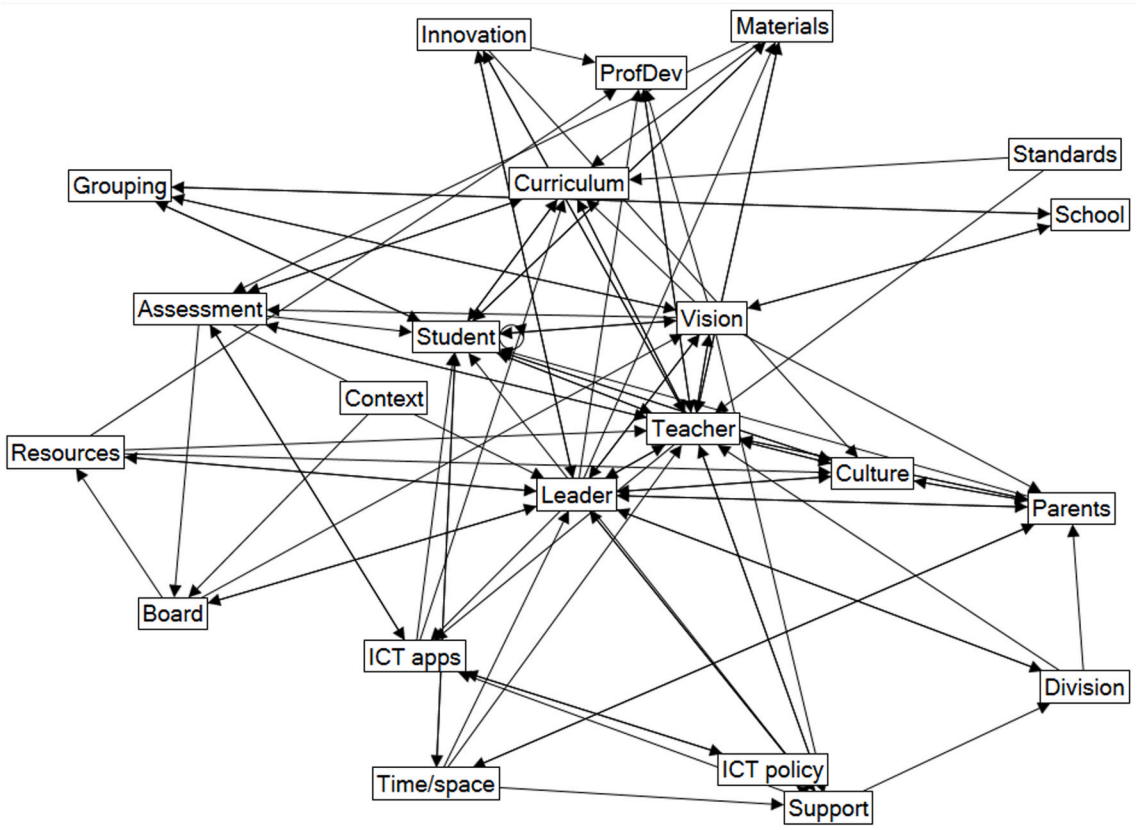


Fig. 5. Force-directed spring layout of a mature TEPL practice network (school TEPL2).

teams clarify their goals and the organizational implications of choices they make. One participant noted, *'It provided clear phasing for me, but also for the team,'* highlighting how the model supports structured planning and alignment within the team. This increases teachers' sense of control and provides a structured approach to addressing challenges, such as role allocation and differentiation as well as team composition. Teams become aware of the necessary organization, can think through these requirements from a holistic perspective, and thereby take steps towards TEPL implementation.

Teachers value the holistic approach stimulated by TEPLAN, which fosters a comprehensive understanding of interdependencies between the actants within the model. Reflection on the changes in the organizational model over time highlight achievements and provides schools with a sense of progress. Furthermore, some schools adopt hybrid implementations of TEPL with TEPLAN, applying the organizational model selectively to specific subject areas rather than the entire organization. This demonstrates the model's flexibility, showing that it can be effectively adapted to varying organizational contexts and applied at both school and subject-specific levels. Overall, TEPLAN enhances teachers' capacity to navigate the complexity of TEPL, supporting deliberate and context-sensitive innovations.

3.4. Theoretical validation

3.4.1. Relevant actants

The theoretical validation confirmed the presence of all actants from the TEPLAN model in recent literature. Across 22 reviewed articles, all actants were referenced (see Table A2), with individual occurrences ranging from three to twenty mentions. The least frequently cited actants were *Board* and *Grouping* (three references each), while *School culture* (20), *Professional development* (19), and *Innovation characteristics* and *Teacher* (18 each) appeared most often.

Overall, nearly all actants are referenced more frequently in recent studies, with the exception of *Teacher & curriculum standards/policy*, *Time and space of learning*, *Teacher*, and *Student*. *ICT policy planning & infrastructure* shows only a marginal decrease, likely due to the technology-oriented focus of earlier TEL studies. For *Time and space of learning*, however, a clear shift in emphasis is visible: earlier research primarily addressed the availability of ICT in classrooms (and occasionally at home) during school hours, whereas more recent studies emphasize how students use ICT to support personal goals, manage flexible learning time, and engage in online learning. No new actants were identified in the recent literature.

3.4.2. Model development

As shown in the frequency table (Table A2 in Appendix 1), current research continues to provide a fragmented understanding of TEPL. On average, 9,70 actants were included in the studies from the literature exploration, whereas the studies in the theoretical validation phase incorporated an average of 13,95 actants, representing approximately 58% of the actants included in TEPLAN. Nevertheless, most studies still address isolated components of the model, focusing on individual relationships rather than the system as a whole. For instance, several studies focus on how specific conditions, such as support and professional development, affect teachers' ICT use (Howard & Thompson, 2021), while others explore particular alignments between levels or phases of innovation, such as micro–meso coherence (Loor & DiMartino, 2023; Pettersson, 2021; Soza-Diaz, Fontalvo-Gómez, et al., 2022) or the sequencing of change processes (Prenger et al., 2022). Although these studies provide valuable insights into local mechanisms, they do not address the overall configuration of interdependencies that shape TEPL.

A few more recent studies move toward broader mapping of relationships. For example, Kanstantinidou and Scherer (2022) quantify the co-occurrence of actants across publications, yet their analysis remains limited to the frequency of mentions rather than the nature or strength of relationships. Similarly, Sony and Karingada (2024) include

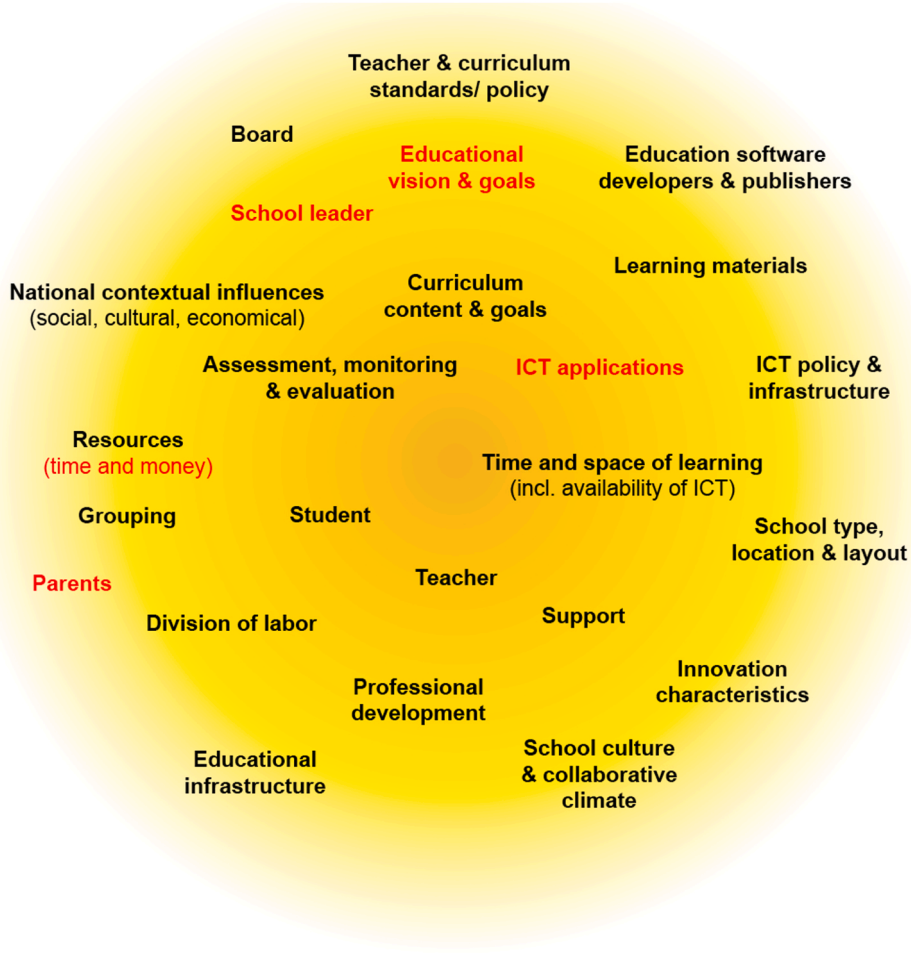


Fig. 6. Final version of TEPLAN including changes made during the empirical validation in red.

16 of the 24 actants identified in our model but conceptualize their interrelations as linear causal chains derived from expert opinions rather than as dynamic and reciprocal influences. Taken together, these approaches confirm that the field still lacks a comprehensive, relational understanding of TEPL. In contrast, the present study adopts a holistic, network-based perspective that conceptualizes the interplay among actants as mutually constitutive, thereby advancing theoretical insight into the organizational dynamics of TEPL.

4. Discussion

This study identified relevant aspects for the organization of TEPL, and integrated them into TEPLAN, an ANT-based mid-range theoretical model. TEPLAN addresses a gap in existing literature by introducing a novel network-based perspective that connects human and non-human actants across all levels and prioritizes the dynamic interrelations between actants over static, hierarchical structures. As a mid-range theoretical model, TEPLAN bridges the gap between abstract theoretical concepts, including centrality measures, and school practice by explaining the relational dynamics between human and non-human actants. TEPLAN explains how specific network configurations, characterized by the mutual translation of pedagogical goals and organizational conditions, shape the organizational dynamics and resilience of digital transformation.

The empirical validation revealed consistent patterns in how actants interact across schools. In early adoption stages, the network layout reveals a fragmented, top-down structure where influence is concentrated in formal gatekeepers, primarily teachers and leaders, who linearly translate goals to pedagogical practice. In contrast, mature TEPL practices are characterized by a higher network density and structural cohesion, facilitating a continuous flow of influence that moves beyond isolated clusters. In these mature configurations, students move from the periphery to a central position, gaining agency to actively shape the digital learning environment. This transition toward mutual translation and greater interdependence stabilizes the network, creating a resilient organizational configuration that is better anchored in actual pedagogical interactions rather than rigid, leader-centric visions.

This study offers several methodological and conceptual strengths. Its iterative, multi-phase design ensured both theoretical depth and empirical grounding. Furthermore, the study's close collaboration with practitioners strengthened its ecological validity and practical relevance. TEPLAN enables teacher teams to holistically approach their organizational dynamics by mapping current actants and their interrelations. By identifying “relational friction”, or misalignments between specific actants, teams can move beyond a fragmented view to diagnose which specific relations require strengthening. TEPLAN is not a prescriptive design tool, but a diagnostic-explanatory model that supports context-sensitive organizational translation and evaluates organizational readiness for digital transformation.

Despite its static visual form, TEPLAN illustrates the value of a network-based perspective by revealing how meaning and agency emerge through dynamic interactions among actants, including non-human ones such as ICT tools or school infrastructure, that independently shape educational practice. It aligns with recent work emphasizing the integration of organizational, pedagogical, and technological factors in learning environments (Tondeur et al., 2024). This reframes

TEPL implementation from a linear progression to an ongoing negotiation among interconnected actants. Drawing on Czarniawska's (2017) notion of organizing as continuous, socially constructed interaction, the model supports schools in visualizing desired and realized developments and navigating the evolving configurations of educational innovation.

This study faced several limitations. First, the methodological scope of the validation phases may include certain forms of bias. The expert validation, while valuable, reflected the perspectives of a specific group of experts, and the empirical validation involved schools that voluntarily participated, which could have resulted in participation bias. Also the data relied primarily on self-reported information from interviews, which may have been affected by social desirability bias. Second, the literature exploration primarily addressed ICT innovations due to limited TEPL-specific research at the time, though it provided a solid foundation for subsequent validation phases. Third, although the sample is not statistically representative, the inclusion of both mature TEPL practices and schools in the early stages of adoption ensured sufficient variation to achieve data saturation for model validation. The empirical findings should therefore be regarded as transferable rather than generalizable and remain specific to the Dutch educational context. This context is characterized by high school autonomy and a free market for educational content. While national learning goals are fixed, the absence of a mandatory national curriculum or standardized leadership requirements allows for diverse organizational dynamics. In such a decentralized landscape, external actants can exert more influence, which TEPLAN is uniquely positioned to map. These contextual conditions have influenced the relational patterns identified in our findings. While these factors define current contextual boundaries, they offer a robust foundation for future comparative research. Testing TEPLAN across more centralized policy landscapes or different institutional environments will further assess its cross-national transferability and refine its conceptual foundations beyond the Dutch scope.

5. Conclusion and recommendations

The central research question guiding this study was: *What does an organizational model for technology-enhanced personalized learning (TEPL) encompass in the context of K12 education?* This study successfully developed and validated TEPLAN, a robust and adaptable mid-range theoretical organizational model for TEPL, offering a network-based approach to understanding and implementing TEPL across diverse educational contexts.

Future research should focus on mapping and analyzing interrelations between actants using an ANT perspective to enhance understanding of the complex dynamics within organizational models for TEPL. Validation across diverse educational contexts, considering cultural and systemic variations, is necessary to broaden the model's applicability. Additionally, advancements in AI, such as adaptive learning algorithms, could enhance TEPL by enabling more personalized and efficient learning pathways, warranting further exploration. Practical research in schools could uncover organizational constellations of TEPL, supporting the development of practical scenarios. Longitudinal research can provide insights into how TEPLAN supports the coherence, effectiveness, and long-term sustainability of TEPL-related innovations and organizational transformations. Finally, the model's flexibility suggests potential for application beyond TEPL, making it a valuable tool for navigating educational innovation in an evolving digital landscape.

CRediT authorship contribution statement

Kirsten Erica de Ries: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anne-Marieke van Loon:** Funding acquisition, Data collection, Formal analysis, Writing reviews. **Irma van der Neut:** Data collection, Formal analysis, Writing reviews. **Mariola Gremmen:** Formal analysis, Writing reviews. **Marijke Kral:** Supervision, Writing – review & editing, **Marieke van der Schaaf:** Supervision, Writing – review & editing.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethical approval

This research was conducted in accordance with the Declaration of Helsinki. The study protocol, participant information materials, and informed consent procedures were formally reviewed and approved by the Ethical Advisory Committee of the HAN University of Applied Sciences. More information on the HAN informed consent procedure can be found at this link.

Participant recruitment and consent

A two-fold purposive recruitment strategy was employed. First, 35 innovative K12 schools were identified through professional networks and media analysis and categorized into four thematic clusters based on their innovative practices. Schools from each cluster were approached sequentially until a diverse representation of six schools was achieved. Second, nine schools were selected in coordination with school boards and through intake interviews as part of a national research program (OWP PO). Participation was entirely voluntary and contingent on school board approval and staff commitment.

Prior to data collection, all participants (school leaders, teachers, and students) received formal information letters detailing the research aims, procedures, and their right to withdraw at any stage without penalty. Formal informed consent was obtained from all participants before the commencement of interviews and classroom observations.

Data protection and management

To safeguard participant privacy and ensure compliance with GDPR requirements, all data remained hosted within the secure institutional environment of the HAN University of Applied Sciences. All data analyses were conducted internally. Prior to analysis, all participating schools and individual respondents were fully anonymized to prevent institutional or individual identification. Data management followed institutional policies, ensuring secure storage on encrypted servers with access strictly restricted to the primary research team.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 4.o in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kirsten Erica de Ries reports financial support was provided by Netherlands Initiative for Educational Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1. literature exploration and theoretical validation

This appendix outlines the literature selection strategy, methodological details of the data selection process, and the body of literature used for the development of TEPLAN, including a structured summary table of actant frequencies from the literature exploration and theoretical validation.

Data selection process for the literature exploration

For selecting the data from a TEL perspective five meta-analyses that depict organizational models of TEL are selected: Vanderlinde and van Braak (2010), Kozma (2003), Tearle (2004), Hew and Brush (2007), and Lim (2007). Based on the snowballing method, all articles that are referred to in these meta-analyses are included in the review. From a PL perspective, several articles were included, as the search, based on the terms 'differentiated learning' and 'personalized learning,' yielded a limited number of relevant sources.

Data selection process for the theoretical validation

The data selection procedure for this literature validation is systematic in nature. Sources used are ERIC/PsychInfo and Web of science, with search terms combining *technology*, *factors*, *school*, and *educational change*. Alternative terms are *digital* and *personalized* (technology), *organizational* and *model* (factors), and *educational innovation*, *transformation*, and *organization* (educational change). Selection criteria focus on European, American, Australian, or similar K12 education systems. Since ERIC and PsychInfo lack a K12 filter, general educational research is used instead. Articles are included from 2016 onward for ERIC and PsychInfo, and from 2013 onward for Web of Science, ensuring relevance and recency.

As presented in Fig. 2 the search yielded 2071 records, which were reduced to 1325 after removing 746 duplicates. Following the exclusion of irrelevant studies based on titles, 93 records remained. Exclusion criteria are described in Fig. 2. Studies were included if they addressed organizational aspects, curriculum reform, digital transformation, innovation adoption, or systemic factors influencing the educational transformation process.

In the selection process, 93 abstracts are reviewed, 49 are excluded for various reasons. Studies were included if they discussed factors influencing educational change, presented a model or framework for analyzing educational change, addressed processes of change with barriers and success factors, focused on PL and/or digital transformation, or with a system perspective on (TE)PL.

In the eligibility phase, 44 articles are reviewed, 22 are excluded. Studies included meet quality standards, are empirical (describing at least one case) or theoretical (reviewing aspects on at least two levels, including meso-level), with aspects drawn from multiple articles, focus on educational change or digital transformation, describing critical factors in this process. Consequently, 22 articles were included in the literature analysis.

Literature references on which TEPLAN is based

The organizational model is based on all the articles listed below, which were included in the literature exploration (indicated with an 'e' for exploration) or the theoretical validation (indicated with a 'v' for validation).

Summary table literature exploration and validation

The summary table (Table A1) provides an overview of the actants, including their labels and abbreviations as used in the visual representations of the Actant Network Maps (Figs. 4 and 5). It serves as a reference for the theoretical grounding of the actants incorporated in TEPLAN and consists of two sections. The first section lists all actants with their corresponding descriptions. The second section summarizes the literature exploration and theoretical validation, linking each actant to the studies in which it appears. Numerical codes in the columns of Section 2 correspond to the articles included in the literature exploration and validation; each number matches the reference list above (indicated by "e" or "v" for exploration or validation, respectively). Because studies 9, 10, and 11 were conducted by the same research group and include identical sets of actants, they are merged into a single column in Table A1, Section 2.

Table A1
Summary table – Section 1: Actant descriptions and abbreviations

Actant	Label	Abbreviation
Curriculum & Teacher standards	National and regional frameworks schools must adhere to, including curriculum goals, attainment targets, teacher qualification standards, and requirements regarding instructional time. They guide teaching practice and provide benchmarks for accountability.	Standards
Board	The governing body legally accountable for school quality, results, and strategic decision-making. Responsibilities include educational policy, staffing, financial management, and housing policy. Tasks are often delegated to school leaders but oversight remains with the board.	Board
Education software developers + publishers	External providers of digital learning tools, teaching methods, and content. They co-shape learning environments by developing and distributing educational materials and ICT applications that align with curriculum and policy requirements.	Publishers
Educational infrastructure	The broader system of collaborating organizations that support schools, including teacher education institutes, research and advisory centers, ICT service providers, and school support services. This infrastructure facilitates ICT use, innovation, and teacher professionalization.	Edu infra

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Table A1 (*continued*)

Actant	Label	Abbreviation
National influences (social, cultural, econ)	The societal context shaping education, including economic conditions, cultural norms, and social systems. These factors influence educational policies, resources, and expectations placed on schools.	Context
Parents	Parents are partners in supporting their child's learning process. Their involvement ranges from providing home support to engaging in collaboration with the school.	Parents
Educational vision and goals	The school's pedagogical and organizational vision that frames how teaching and learning are structured. Expressed in school-wide goals, plans, and development strategies.	Vision
School leader	Leaders initiate, guide, and sustain innovation and improvement processes. Leadership capacity often resides in distributed teams rather than a single individual, ensuring continuity and embedding of change.	Leader
School type, location & layout	The institutional setting of a school, including whether it is urban, rural, or community-based, and its physical layout (e.g., classrooms, learning spaces, silence rooms, digital environments).	School
Support (ict, pedagogy, innovation)	Structures and services that provide teachers and students with the necessary guidance and assistance to implement and sustain innovation. This includes pedagogical coaching, mentoring, instructional support, professional learning communities, as well as technical and administrative assistance that enable effective use of ICT within broader educational development.	Support
Ict policy & infrastructure	The planning, management, and provision of ICT facilities, including hardware, software, and reliable internet access, aligned with school goals for personalized learning.	ICT policy
Division of labor	Task and function differentiation among school staff. This includes varying responsibilities for teachers, assistants, coordinators, and specialists, depending on expertise and innovation needs.	Division
Professional development	Ongoing learning opportunities for teachers and leaders to build competencies needed for ICT integration, innovative pedagogies, and organizational change.	ProfDev
School culture/collaborative climate	Shared assumptions, values, and norms among school members. A collaborative culture is key for collective ownership of innovation and sustainable improvement.	Culture
Innovation characteristics	Features of how schools design and embed innovation, including teacher participation in decision-making, sense of ownership, shared vision, and strategies for implementation.	Innovation
Grouping	The way students are organized in groups, ranging from homogeneous to heterogeneous groupings, reflecting pedagogical choices and personalization strategies.	Grouping
Resources (time & money)	The financial and temporal resources schools can allocate to staff, innovation, ICT, and organizational development.	Resources
Assessment, monitoring & evaluation	Assessment refers to the deliberate collection and interpretation of information about individuals' performance within a specific domain, with the purpose of making informed decisions concerning those individuals. In the context of monitoring and evaluation, this process corresponds to the final two phases of the PDCA cycle: analyzing the outcomes of educational improvement and innovation and drawing conclusions based on these results.	Assessment
Learning materials	All resources used for learning, such as textbooks, methods, digital tools, assignments, and even people (teachers, peers, experts).	Materials
Curriculum Content & Goals	Concrete learning objectives, activities, and teaching methods that operationalize the intended curriculum in classrooms. Learning activities and formats that support the student's learning process. This includes the form in which learning takes place, such as direct instruction, self-study, experimentation, inquiry, or collaboration, often supported by physical or digital resources.	Curriculum
ICT applications	Digital tools for communication, presentation, task-based learning, and regulation (e.g., applications that support teacher orchestration or student self-regulation).	ICT apps
Time & space of learning	Where and when learning takes place, spanning physical classrooms, digital environments, and flexible schedules that extend beyond traditional school hours.	Time/space
Teacher	Teachers act as instructors, facilitators, or co-learners, depending on context. Their beliefs, attitudes, and ICT competencies directly shape classroom practice.	Teacher
Student	Students may have a passive role or act as active agents owning their learning process. Emphasis lies on autonomy, self-regulation, and collaboration.	Student

Table A1
Summary table – Section 2: Actant occurrence across literature exploration and literature validation sources

Abbreviation	Article number theoretical exploration (e1-e25)																						
	1	2	3	4	5	6	7	8	9	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Standards		x			x		x	x			x	x						x			x	x	x
Board					x																	x	
Publishers					x						x	x											
Edu infra											x	x			x						x		
Context					x		x				x	x						x		x		x	
Parents	x							x				x						x					
Vision				x	x						x												
Leader		x		x	x		x	x		x	x			x	x	x		x		x	x	x	x
School		x	x					x		x	x	x			x	x				x	x		
Support	x	x			x		x	x	x	x	x			x				x		x		x	x
ICT policy	x	x	x	x	x		x	x	x	x	x	x				x		x			x	x	
Division			x				x					x			x								
ProfDev	x	x	x	x	x		x	x	x	x	x			x	x	x		x		x	x	x	x
Culture			x				x	x	x	x	x	x	x	x	x	x				x	x	x	x
Innovation								x		x	x					x				x	x	x	x
Grouping											x												
Resources		x			x		x	x	x	x					x	x				x			
Assessment	x		x		x	x			x	x	x	x	x		x		x		x				
Materials			x												x								
Curriculum			x			x			x		x	x	x		x		x			x			
ICT apps	x		x		x	x	x			x	x			x	x				x			x	
Time/space	x	x	x				x	x	x	x	x	x	x	x	x		x	x		x	x		

(*continued on next page*)

Table A1 (*continued*)

Abbreviation	Article number theoretical exploration (e1-e25)																						
	1	2	3	4	5	6	7	8	9	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Teacher	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x		x		x	x	x	
Student	x		x		x	x	x				x	x	x	x	x	x	x	x					

Abbreviation	Article number theoretical validation (v1-v22)																			
	1	2	3	4	5	6	7	8	9	12	13	14	15	16	17	18	19	20	21	22
Standards					x	x		x									x			
Board					x		x											x		
Publishers					x						x							x	x	
Edu infra		x	x	x	x	x	x	x		x			x	x	x	x	x	x		x
Context					x	x			x			x					x	x	x	x
Parents				x	x		x							x			x	x	x	x
Vision			x	x			x	x				x	x			x	x	x	x	x
Leader		x		x	x	x	x			x	x	x	x			x	x	x	x	x
School		x	x	x				x			x	x	x	x		x	x	x	x	x
Support		x	x		x	x	x		x	x	x	x		x	x	x	x	x	x	x
ICT policy			x	x	x		x		x		x	x		x	x	x	x		x	
Division			x	x	x			x				x	x			x	x		x	
ProfDev	x	x	x		x	x	x	x	x	x		x	x		x	x	x	x	x	x
Culture	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
Innovation	x	x		x	x	x	x	x	x	x		x	x	x	x	x	x		x	x
Grouping							x						x					x		
Resources	x	x	x	x	x	x	x	x	x		x	x		x	x	x	x		x	x
Assessment		x	x	x	x		x	x	x		x						x	x	x	x
Materials						x	x	x				x	x			x			x	
Curriculum		x	x	x	x	x	x	x			x	x	x					x	x	
ICT apps			x	x	x		x		x	x	x	x	x	x	x	x		x	x	
Time/space			x	x	x		x	x	x		x			x	x	x		x	x	
Teacher		x	x	x	x	x	x		x		x	x	x	x	x		x	x	x	x
Student				x	x		x	x	x				x	x			x	x	x	x

Table A2
Frequency table of literature exploration and theoretical validation

Actant	Literature exploration		Theoretical validation	
	Number of articles that mention actant	Percentage of articles that mention actant	Percentage of articles that mention actant	Number of articles that mention actant
Curriculum & Teacher standards	10	43,48%	22,73%	5
Board	2	8,70%	13,64%	3
Education software developers & publishers	3	13,04%	22,73%	5
Educational infrastructure	4	17,39%	77,27%	17
National influences	7	30,43%	45,45%	10
Parents	4	17,39%	40,91%	9
Educational vision and goals	3	13,04%	54,55%	12
School leader	15	65,22%	72,73%	16
School type, location & layout	10	43,48%	63,64%	14
Support (ict, pedagogy, innovation)	13	56,52%	81,82%	18
Ict policy planning & infrastructure	15	65,22%	63,64%	14
Division of labor	4	17,39%	45,45%	10
Professional development	18	78,26%	86,36%	19
School culture/collaborative climate	15	65,22%	90,91%	20
Innovation characteristics	8	34,78%	81,82%	18
Grouping	1	4,35%	13,64%	3
Resources	9	39,13%	77,27%	17
Assessment	12	52,17%	63,64%	14
Learning materials	2	8,70%	40,91%	9
Curriculum Content & Goals	9	39,13%	63,64%	14
ICT applications	11	47,83%	72,73%	16
Time and space of learning	16	69,57%	63,64%	14
Teacher	19	82,61%	81,82%	18
Student	13	56,52%	54,55%	12
Average number of articles that mention an actant	9,29	40,40%	58,14%	12,79
Average number of actants mentioned per article	9,70	40,40%	58,14%	13,95

Appendix 2. expert validation

This appendix provides a detailed description of the experts involved and the validation activities performed. It includes the experts' professional expertise and short CVs, a description of the meeting activities, and an explanation of the feedback framework and consensus procedures applied. The concluding section details the experts' role in the validation process, focusing on how expert decision-making directly shaped the transition from a descriptive collection of factors to a explanatory model. By documenting the functional role of experts in refining the conceptual framework and validating the mechanism schema, this appendix provides a transparent audit trail of the model's development.

The experts engaged in the expert validation, based on their expertise, are:

- *Technology*: Prof. Dr. M. Specht, professor in the field of learning technology;
  - o Later replaced by: Prof. Dr. Ir. K. Kreijns – professor in the field of cognitive behavioral models and the use, sharing, and deployment of digital learning materials by teachers;
- *Organizational Change and leadership*: Prof. Dr. J. Imants – professor in the field of educational leadership, educational innovation, and change processes;
- *Technology integration*: Dr. F. Prinsen – senior researcher and professor of Digital Didactics with expertise in technological networks and organizational networks;
- *Governance and policy*: Dr. F. de Vijlder – professor of Good Governance and Innovation Dynamics in Social Organizations with expertise in governance context, good governance, and governance practices;
- *Assessment:* Dr. T. van Schilt-Mol, associate professor of Educational Assessment and Innovation with expertise in formative and summative assessment, assessment for learning, and the alignment of assessment with curriculum innovation and personalized learning.

Short CV's of experts

Prof. Dr. M. Specht – Professor of Learning Technologies (Open University). His expertise is in technology-enhanced learning, learning analytics, and the design of innovative digital learning environments. He contributed to the expert validation by reviewing the technological soundness and feasibility of TEPLAN. (Later in the process replaced by Prof. Dr. Ir. K. Kreijns).

Prof. Dr. Ir. K. Kreijns – Professor of Educational Technology (Open University). Specializes in cognitive-behavioral models, social aspects of learning with ICT, and the adoption and sharing of digital learning materials by teachers. In the expert validation, he contributed insights on teacher practices, technology adoption, and networked collaboration.

Prof. Dr. J. Imants – Professor of Educational Leadership and Innovation (Radboud University). His expertise includes organizational change, professional learning communities, and leadership for educational innovation. He provided guidance on the organizational and leadership dimensions of TEPLAN.

Dr. F. Prinsen – Senior researcher and Professor of Digital Didactics (Open University/later University of Applied Sciences Rotterdam). Specializes in technology integration in teaching and learning, as well as organizational and technological networks. She contributed to the validation with expertise on the interplay between digital didactics, teacher practices, and organizational embedding.

Dr. F. de Vijlder – Professor of Good Governance and Innovation Dynamics in Social Organizations (HAN University of Applied Sciences). His expertise includes governance, accountability, and innovation in complex organizational networks. He contributed to TEPLAN validation by reflecting on governance practices and policy contexts.

Dr. T. van Schilt-Mol – Associate Professor of Educational Assessment and Innovation (HAN University of Applied Sciences). Her expertise lies in assessment for learning, formative assessment, and the role of assessment in educational innovation. She contributed to the expert validation by ensuring that the assessment dimension was well integrated in TEPLAN.

Expert validation meetings and activities

The expert validation consisted of three structured meetings held over a period of seven months. Each meeting combined a presentation of the evolving factors or model with structured feedback rounds in which experts contributed from their specific domain knowledge (e.g., technology, organizational change and leadership, governance and policy, assessment).

The first meeting was primarily focused on validating and enriching the literature base that formed the preliminary foundation of the model. Experts contributed to the literature used, identified potential gaps, and reinforced the initial relevance and implications of the findings for practice. Experts were asked to elaborate on assigned factors, missing factors, their description and their interrelations, and to prepare short written contributions from their field of expertise (e.g., on assessment, professional development, ict use, leadership, policy).

The second meeting centered on substantiating these identified aspects by deepening factor descriptions and exploring their interrelations through scenario-building. Experts discussed the comprehensiveness and critically reflected on the boundaries of the model, discussing elements such as curriculum flexibility and logistics. A pivotal decision during this phase was the agreement to omit fixed relational lines and exclude hierarchical levels (micro/meso/macro) from the visual representation of the model. From an ANT-perspective, the experts reasoned that fixed structures or “nested” hierarchies would oversimplify the fluid and context-dependent relational dynamics of translation. By maintaining this generalized symmetry, the experts ensured that the model could accurately reflect the complex interactions between human and non-human actants without being constrained by traditional organizational layers. The third and final meeting (March 2016) aimed at conceptualization and interpretation of the organizational model as a functional whole. During this session, the panel formally concluded that Actor-Network Theory (ANT) provided the most robust explanatory lens for TEPLAN, transforming it into a formal mechanism schema for understanding the process of translation in schools. Furthermore, the experts played a decisive role in the operationalization of the model for empirical validation. They co-determined the specific network measures, such as centrality and bridging, that would be used to map school-based practice. They established the criteria for interpreting these metrics, ensuring they could effectively reveal instances of organizational alignment or friction.

Feedback framework

Feedback was gathered using a structured framework combining (a) written input prepared in advance, (b) group discussion guided by the project leader, and (c) explicit prompts on accuracy, comprehensiveness, and relevance of the factors and their interrelations. The model documents (Excel file with descriptions as well as a visual representation in Visio) served as a shared reference, with factors described in terms of definition, associated actors, actions, and scenarios. Experts were invited to enrich these with additions from their own research and practice.

Agreement procedure

Consensus was not sought for mere descriptive convergence but was focused on achieving a coherent conceptual framework. Consensus was reached through iterative discussion and synthesis. Diverging views were documented and then revisited in subsequent rounds until common ground was achieved. When disagreement persisted, it was addressed by integrating multiple perspectives into broader factor descriptions rather than forcing convergence. The project team facilitated this process by summarizing feedback after each round, sharing revised versions of the model with all participants, and explicitly checking agreement on contested points at the beginning of the next meeting. This consensus-based approach was chosen over formal inter-rater statistics, in line with the qualitative, model-development focus of the study.

Expert role in decision-making and theoretical refinement

The expert validation was not merely a check of individual factors but functioned as a critical process of middle-range theorizing. Throughout the iterative meetings, the experts made several fundamental decisions that directly shaped the transition from a descriptive synthesis to an explanatory system:

- Refinement of the conceptual framework: experts curated the literature base, identifying gaps and contributing key theoretical sources. This ensured that the model's categories were not just a ‘reorganization of factors' but a robust conceptual framework grounded in both theory and organizational reality.
- Conceptual labeling and positioning: experts collaborated on the precise labeling and placement of concepts within the model. This process shifted the focus from static definitions toward relational dynamics, emphasizing how actants interact within the school organization.
- Decision on visual and hierarchical logic: a pivotal decision was made to omit fixed relational lines and exclude hierarchical levels (micro/meso/macro) from the visual representation.
  - o *ANT Rationale:* This decision follows the ANT principle of generalized symmetry, acknowledging that the relational dynamics of translation are fluid and context-dependent rather than pre-determined by traditional organizational layers.
- Establishing the explanatory lens: the panel formally concluded that ANT provided the most appropriate theoretical perspective to move TEPLAN toward a mechanism-based middle-range theory. This lens allows the model to explain the “how” of digital transformation rather than just the “what."
- Operationalizing practice through network measures: experts co-determined the methodology for mapping school-based practice. They selected relevant network measures (e.g., centrality, density, and bridging) and established the criteria for interpreting these measures as indicators of organizational alignment or friction.

Appendix 3. empirical validation in practice

This appendix provides a detailed description of the schools involved, the interview and observation formats used in the empirical validation, and several anonymized school-based Actant Network Maps, complemented by a summary table linking actants to empirical sources. Together, these materials form the empirical basis for the scenarios presented in the Results section.

Sample description of the schools involved

The sample of innovative schools is purposively constructed to reflect a wide spectrum of organizational and pedagogical innovations. Initially, 35 candidate schools across the Netherlands were identified through publications, professional networks, and media coverage, and grouped into four thematic clusters: (1) advanced ICT integration, (2) flexible organization and timetabling, (3) personalized learning pathways, and (4) student engagement and agency. From each cluster, schools were approached sequentially; if a school declined, another from the same cluster was invited. Ultimately, six schools agreed to participate, providing sufficient variation to reach data saturation at the level of recurring aspects and their interrelations.

Profiles of the participating innovative schools

- A (Roermond) – Represents the *personalized learning pathways* cluster. Students follow self-directed learning trajectories without traditional classes, timetables, or subjects, supported by coaches who guide rather than instruct. The model emphasizes autonomy, intrinsic motivation, and responsibility.
- R (Almere) – Belongs to the *student engagement and agency* cluster. This school is characterized by flexible structures, strong attention to children's interests, and a project-based approach in which students have significant influence over their own learning.
- M (Dordrecht) – Represents the *advanced ICT integration* cluster. The school integrates one-to-one iPad use and adaptive software into daily learning, offering personalized learning routes and continuous feedback through digital platforms.
- D (Amersfoort) – Falls into the *flexible organization and timetabling* cluster. The school experiments with flexible scheduling, learning studios instead of traditional classrooms, and a focus on cross-curricular projects supported by ICT.

- W (Rosmalen) – Represents both *student engagement* and *flexible organization.* Students work in multi-age units rather than age-based classes, with emphasis on autonomy, collaboration, and individualized learning rhythms.
- T (Stevensbeek) – Belongs to the *advanced ICT integration and personalized pathways* cluster. The school implements blended and digital learning strategies, flexible curricula, and increased opportunities for students to tailor their learning programs to personal goals.

The second sample consists of nine schools from the Arnhem–Nijmegen region that participate in the NRO-funded Research Workplace *Personalized Learning with ICT in Primary Education (OWP PO)*. Schools are selected in consultation with school boards, based on intake interviews and predefined project criteria. Although they share a regional context, they vary in size, student population, and educational focus, ensuring sufficient variation and data saturation.

Profiles of the participating regular schools

- B (Haps) – Small village school (~200 pupils) with a close-knit community. Works on mixed-age classrooms where ICT supports differentiation and inclusive teaching.
- T (Oeffelt) – Medium-sized school (~250 pupils) serving a semi-rural population. Focuses on flexible ICT use to adapt instruction to different learning tempos.
- K (Nijmegen) – Urban school (~300 pupils) with a diverse student population, strongly engaged in formative assessment and ICT-based feedback tools.
- L (Wamel) – Medium school (~250 pupils) in a small town, exploring ICT to enable project-based learning and flexible grouping.
- V (Groesbeek) – Large school (~400 pupils) with varied student needs, using ICT primarily to support inclusion and special educational needs.
- U (Nijmegen) – Innovative city school (~350 pupils), known for collaborative and cross-curricular learning, experimenting with ICT to enable team-teaching approaches.
- M (Oosterbeek) – Medium-sized school (~280 pupils) with a relatively affluent catchment area, embedding ICT use in both classroom practice and school-wide organization.
- P (Arnhem) – Larger urban school (~400+ pupils), emphasizing mathematics and analytical skills with ICT-based environments, aiming at self-regulation.
- A (Zutphen) – Small-to-medium school (~230 pupils) with mixed socio-economic backgrounds, redesigning curriculum with ICT to increase student ownership.

Overall characteristics

The participating schools are all located within the Arnhem–Nijmegen region, covering both urban and semi-rural contexts. Their size ranges from approximately 200 to over 400 pupils, representing both small community schools and larger urban institutions. The student populations are diverse, spanning affluent suburban catchment areas as well as highly mixed urban contexts with varied socio-economic backgrounds. Across this diversity, all schools share a focus on differentiation, student agency, and the integration of ICT in instruction and assessment, while simultaneously embedding personalized learning in their school-wide organizational development. Together, these nine schools provide a balanced representation of the regional educational landscape, while ensuring sufficient diversity to observe recurring patterns across cases and reach data saturation in the validation of TEPLAN.

Observation and interview procedure and formats applied

Observations were conducted both at the classroom and the individual learner level. In each participating school, three students (low-, average-, and high-achieving) were systematically followed during lessons. Observers recorded their activities, interactions with teachers and peers, and the use of ICT at 5-min intervals. Short learner prompts ("What are you doing now?"/"What are you thinking now?") were included to capture student perspectives in real time. These observations were complemented with whole-class notes focusing on differentiation, grouping, teacher strategies, and the organizational embedding of ICT.

Table A3
Observation schedule

Aspect	Guiding questions	Notes
Learner agency	Who decides what, how, when, with whom, and at what pace students learn? What role does ICT play?	
Differentiation	What forms of differentiation are visible (content, level, timing, grouping, instruction, feedback, interests)? How does ICT support these?	
Vision and goals	What are the school's articulated aims for TEPL? How are they visible in practice?	
Learning objectives & activities	How are objectives, materials, and activities organized and aligned with TEPL?	
ICT applications & infrastructure	Which ICT tools and infrastructure are used, and how?	
Assessment, Monitoring & feedback	How is progress tracked and feedback provided?	
Time & space of learning	How flexible is the timetable and where does learning take place?	
Students	Attitudes, competences, and behavior observed	
Teachers	Attitudes, competences, and behavior observed	
Parents, leaders, boards	Role of parents, school leaders, and boards in supporting TEPL	
Resources	Time, funding, PD, and support allocated to TEPL	
Organization & culture	Grouping structures, school culture, national policy influences	

Semi-structured interview guide

Interviews were conducted with school leaders, internal supervisors, and teachers directly involved in the innovation. They followed a semi-structured protocol aligned with the TEPLAN framework, addressing school vision, organizational conditions, and the manifestation and interrelation of relevant aspects. In addition, interviews explicitly explored outcomes at three levels: concrete products (e.g., ICT-based arrangements), personal outcomes (e.g., teacher competences), and organizational outcomes (e.g., structural embedding in school development).Interviews with school leaders, internal supervisors, and teachers focus on:

1. School vision and ambitions: How does the school define and pursue TEPL?
2. Implementation of TEPL aspects: Which organizational, pedagogical, and technological aspects are most relevant?
3. Manifestation in practice: How do these aspects appear in daily practice?
4. Interrelations between aspects: How do actants (students, teachers, ICT tools, leadership, resources) influence each other?
5. Differentiation and learner agency: How is ICT used to support differentiation and student self-regulation?
6. Facilitators and barriers: What enables or constrains the implementation of TEPL?
7. Future perspective: What changes are desired to further TEPL?

Interviews are recorded and transcribed; data are coded with reference to the TEPLAN framework. Observation notes are aligned with the same framework to capture interrelations.

Table A4
School report format

Section	Content
General information	School (anonymized), region, size/structure, participants (roles), date of data collection
Positioning on learner agency	Table: who decides what/how/when/with whom/where/pace (student, teacher, ICT); short narrative
Forms of differentiation	Table: content, level, timing, grouping, instruction, feedback, interests; ICT tools; narrative
Organization of TEPL with ICT	Description of key actants (vision, goals, materials, activities, ICT, assessment, students, teachers, parents, leaders, boards, resources, grouping, culture, policy) and their interrelations
Illustrative quotes & observations	Selected anonymized quotes; classroom observations that illustrate practices
Actant map	Visual network showing actants and interrelations, based on interview data and refined with participants

Tabel A5
Empirical validation summary table

Abbreviation	Mature TEPL practice						Schools in Early Adoption stage (AE)										
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9		
Standards	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Board	x	x		x	x	x	x	x	x	x	x	x	x	x	x	14	93%
Publishers	x		x	x	x	x		x	x	x	x	x	x	x	x	13	87%
Edu infra	x		x	x		x	x	x	x	x	x		x	x	x	12	80%
Context	x	x	x	x	x	x			x	x	x	x	x			11	73%
Parents	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Vision	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Leader	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
School	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Support	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
ICT policy	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Division	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
ProfDev	x	x	x	x	x	x	x	x		x	x	x	x	x	x	14	93%
Culure	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Innovation	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Grouping	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Resources	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Assessment	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Materials	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Curriculum	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
ICT apps	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Time/space	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Teacher	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
Student	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	100%
	24	22	23	24	23	24	22	23	23	24	24	23	24	23	23		
	100%	92%	96%	100%	96%	100%	92%	96%	96%	100%	100%	96%	100%	96%	96%		
						23,33									23,22		
						97%									97%		

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