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Socio-ecological enactment process (SEEP) model for understanding digital technology integration

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Institute of Education, Faculty of Social Sciences, University of Tartu, Estonia

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II Raave, D. K., Roldan Roa, E., Pedaste, M., & Saks, K. (2022). Teachers' classroom digital technology integration practices. In S. Iyer et al. (Eds.), *Proceedings of the 30th international conference on computers in education* (pp. 730–735). Asia-Pacific Society for Computers in Education.

III Raave, D. K., Saks, K., Pedaste, M., & Roldan Roa, E. (2024). How and why teachers use technology: Distinct integration practices in K-12 education. *Education Sciences, 14*(12), Article 1301. https://doi.org/10.3390/educsci14121301

IV Raave, D. K., Pedaste, M., Saks, K., & Roldan Roa, E. (n.d.). Beyond Binary Adoption: A Dual-Pathway Model of How Digital Readiness and Attitudes Shape Teachers' Technology Practices [Manuscript submitted for publication].

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Article IV: composing the theoretical framework, formulating the research questions, co-conducting the data collection, conducting the data analysis, and writing the article as the main author in cooperation with the co-authors.

LIST OF RELATED PUBLICATIONS

Raave, D. K., Saks, K., Pedaste, M., Heintalu, K., Laanemets, L., Remmelg, M., Ilosaar, A., & Veskus, K. (2022). *DigiEfekti põhiuuringu tulemuste raport – digivahendite,-õppevara ja -sisu kasutamine [Report of the DigiEfekt project – use of digital technology]*. University of Tartu. https://doi.org/10.23673/re-417

Pedaste, M., Raave, D. K., & Baucal, A. (2023). *Digitaalsete õppematerjalide kasutamise efekt õpilaste õpitulemustele [The effect of using digital learning materials on student learning outcomes]*. University of Tartu. https://doi.org/10.23673/re-418

LIST OF ABBREVIATIONS

AI	–	Artificial Intelligence
CFA	–	Confirmatory Factor Analysis
DigCompEdu	–	Digital Competence Framework for Educators
DT	–	Digital Technology
DTI	–	Digital Technology Integration
EdTech	–	Educational Technology
EST	–	Ecological Systems Theory
GEM	–	Global Education Monitoring
ICT	–	Information and Communication Technology
LPA	–	Latent Profile Analysis
M	–	Mean
MLR	–	Multinomial Logistic Regression
PPCT	–	Process-Person-Context-Time
PR&A	–	Pedagogical Reasoning and Action
SAMR	–	Substitution, Augmentation, Modification, Redefinition
SD	–	Standard Deviation
SETI	–	Socio-Ecological Technology Integration
SEEP	–	Socio-Ecological Enactment Process
TAM	–	Technology Acceptance Model
TPACK	–	Technological Pedagogical Content Knowledge

1. INTRODUCTION

1.1. Research Problem

The research problem motivating this dissertation is simultaneously practical and theoretical. In practice, a recurring concern in the international literature is that improvements in the provision of digital technology (DT) (e.g., infrastructure, training, policy) have not, on their own, led to the classroom practices policy-makers and researchers had hoped for. Indeed, substantial international and comparative work has documented that teachers working under comparable conditions adopt markedly different practices, and that there is often a notable disparity between resource provision and eventual meaningful integration (e.g., Aubrey-Smith, 2020; Gabriel et al., 2022; Pozo et al., 2024; UNESCO, 2023). Theoretically, the field still lacks a comprehensive model to explain this variation. Existing frameworks have made considerable progress in mapping the conditions (e.g., skills, attitudes, infrastructure, policy) that surround digital technology integration (DTI) and in describing what teachers do with technology, but they have less to say about the why, about the situated pedagogical reasoning through which teachers convert affordances into action (Forkosh-Baruch, Phillips, & Smits, 2021). This dissertation argues that bridging the practical and theoretical sides of this problem requires foregrounding what this dissertation terms the primacy of pedagogical reasoning: the stance that teachers' situated professional judgment, meaning their capacity to interpret a classroom moment and determine whether, when, and how a digital tool can serve a pedagogical purpose, is the proximal mechanism through which DTI is realised, rather than provision or disposition alone.

In the remainder of this chapter, section 1.1.1 situates the research problem in the contemporary global landscape of educational digitalisation, where a push toward hyper-personalisation sits alongside an increasingly visible pushback. Section 1.1.2 then argues that what distinguishes meaningful DTI from shallow DTI is the primacy of teachers' pedagogical reasoning, introducing the Aristotelian concept of phronesis as a philosophical anchor for that claim. Section 1.1.3 closes by distinguishing conditions from process and arguing that the field's explanatory gap lies not in mapping the former but in theorising the latter.

1.1.1. Global Push for Meaningful Digital Technology Integration in Education

Digital technology (DT) has profoundly reshaped education, altering how knowledge is delivered, accessed, and absorbed. Zou et al. (2025) synthesise trends and innovations in digital learning, emphasising how technologies such as artificial intelligence (AI), virtual reality, and online platforms are transforming pedagogical landscapes and enhancing personalisation, engagement, and accessibility. The effectiveness of personalised learning through DT is further supported by

Zheng et al. (2022), whose meta-analysis shows positive effect sizes on achievement. Samaniego López et al. (2025) demonstrate that DT, especially assistive and adaptive DT, can reduce barriers and promote equity for learners with diverse needs. In underserved or remote contexts, Hanifah, Arnyana, and Margunayasa (2025) show that tech-focused policies, when aligned with infrastructure and training, significantly expand access to basic education.

The prominence of digital education intensified in the 21st century, particularly during the COVID-19 pandemic, which accelerated technology adoption across all educational levels. The European Commission (2020) and OECD (2023a) both report that the pandemic marked a turning point, prompting rapid digitisation and revealing gaps in infrastructure, teacher preparedness, and equitable access. However, this expansion has also led to critical reflection. Burden et al. (2019) argue that technology's pedagogical value is often overstated, warning against its use as a superficial enhancement rather than a transformative tool. The UNESCO Global Education Monitoring (GEM) Report (2023) similarly cautions that digital education must be aligned with human-centred values and inclusive policy frameworks to avoid exacerbating inequalities.

In response, some systems have begun scaling back their reliance on digital technologies in favour of more analogue approaches. UNESCO GEM Report (2023) notes that 79 education systems, including Finland and several parts of the United States, have introduced policies restricting smartphone use in schools. Reinforcing this trend, some countries have introduced even more comprehensive measures. France was one of the first countries to adopt a national school smartphone ban, prohibiting device use in primary and lower secondary schools since 2018, with exceptions only when explicitly authorised by the school administration for educational purposes (Ministère de l'Éducation nationale, 2018). Similarly, the Netherlands has adopted a strict "no, unless" policy, banning mobile devices in classrooms, including for educational use, unless explicitly justified for pedagogical reasons for a specific learning activity that cannot be effectively conducted otherwise (Rijksoverheid, 2024). Sweden has launched a national initiative to reduce screen time and promote printed textbooks, particularly emphasising analogue learning in early education (Regeringskansliet, 2024). In addition to the governmental efforts in some systems, Pozo et al. (2024) report a post-pandemic decline in digital resource use among teachers, and Reyes-Rojas and Sánchez (2025) find that many educators are reevaluating the pedagogical value of technology, leading to reduced DTI in daily practice.

Indeed, despite substantial investment in devices, training, and policy (Gabriel et al., 2022), the depth and pedagogical value of DTI remain uneven. Aubrey-Smith (2020) notes that many teachers use technology to replicate traditional practices rather than innovate, while Pozo et al. (2024) find that such replication limits the transformative potential of DT. This challenges the assumption that resources alone ensure meaningful integration. As Gottschalk and Weise (2023) argue, pedagogical intentionality is essential, as the impact of technology on learning is shaped not by its mere presence but by the pedagogical reasoning behind its integration. Forsström et al. (2025) further argue that the effectiveness of DT unfolds over time and is contingent on strategic implementation aligned with instructional goals. For instance, student outcomes improve when teachers align DT with instructional goals (Amemasor et al., 2025), and its effectiveness depends significantly on how thoughtfully it is embedded into lesson design (Sung, Chang, & Liu, 2016) and on purposefully selecting it to support specific learning processes (Wu, 2023). This requires teachers to make pedagogically informed decisions (Abildinova et al., 2024), embed technology within coherent teaching practices (Gabriel et al., 2022), and critically assess when it can extend or transform learning opportunities (Forkosh-Baruch, Phillips, & Smits, 2021). Without this, DT risks becoming a costly substitute for analogue methods with limited learning gains.

Teachers are uniquely positioned to make these judgments because, as Burden et al. (2019) argue, they possess deep, context-specific knowledge of their students and curricula, enabling them to discern when a DT serves as a pedagogical asset. Likewise, Karaseva, Siibak, and Pruulmann-Vengerfeldt (2015) found that Estonian teachers often evaluate DT based on their alignment with classroom dynamics and learning goals, rather than on technological novelty alone. In their meta-analysis, Valverde-Berrocoso, Acevedo-Borrega, and Cerezo-Pizarro (2022) stress that teacher agency and digital competence are critical for leveraging DT's potential in the classroom. Complementing these findings, the UNESCO GEM Report (2023) asserts that responsible, pedagogically aligned DTI is essential to improving educational quality, inclusion, and equity.

Accordingly, international frameworks such as the European Commission's Digital Education Action Plan (2021–2027) (European Commission, 2020) and UNESCO's ICT Competency Framework for Teachers (UNESCO, 2018) emphasise not just access to technology, but its meaningful use, deploying DT to deepen understanding, personalise learning, and broaden participation, rather than simply digitising traditional tasks. Supporting DTI in education, therefore, requires a clear understanding of how teachers can translate DT into pedagogically meaningful practices. Consequently, UNESCO (2022) calls for professional development that equips teachers not only with technical proficiency but also with pedagogical strategies to ensure that DT enhances learning rather than distracts from it. This global context establishes the foundation for this dissertation. As education systems worldwide face increasing pressure to either justify or reconsider their investments in DT (UNESCO, 2023), the question of how teachers can enact meaningful and thus impactful pedagogy through DT becomes central to advancing DTI in education.

In summary, the simultaneous push toward hyper-personalisation and the pushback of restrictive screen-time policies reveal that pedagogical value is never an inherent property of technology itself. It is a situated outcome contingent on a teacher's pedagogical reasoning and the strategic alignment of digital affordances with instructional goals. The research problem must therefore shift from a preoccupation with conditions to the dynamic, moment-to-moment processes through which technology is actually woven into classroom practice.

1.1.2. Primacy of Pedagogical Reasoning

To understand this intentionality, research has shifted attention to teachers' pedagogical reasoning and action (PR&A) in DTI (e.g., Forkosh-Baruch, Phillips, & Smits, 2021; Niess & Gillow-Wiles, 2017; Prestridge, 2017). PR&A is shaped not only by broader teaching paradigms but also by moment-to-moment decisions reflecting classroom realities, lesson aims, and individual student needs (Karaseva, Siibak, & Pruulmann-Vengerfeldt, 2015). Dron (2023) emphasised that teachers' reasoning unfolds in response to changing classroom conditions and curricular demands, underscoring its processual nature. It involves an ongoing interpretive process in which teachers diagnose the learning situation, select or adapt strategies, and determine how, or whether, DT can support the intended learning outcomes (Shulman, 1987). Research has also shown that teacher agency evolves over time, often triggered by new tools or pedagogical challenges, leading to shifts in orientation (Prestridge, 2017). This temporal and ecological dimension of agency, the view that teachers achieve agency through engagement with cultural and structural conditions rather than possessing it as a stable trait (Biesta & Tedder, 2007; Leijen et al., 2020), informs the account of pedagogical reasoning developed here.

Moreover, framing pedagogical reasoning this way connects DTI to a much older idea: Aristotle's concept of phronesis, or practical wisdom, referring to the situated capacity to discern the right action in particular, value-laden circumstances that cannot be settled by rule alone (Kinsella & Pitman, 2012). Recent educational technology scholarship has begun to recover this concept to describe what teachers actually do when they integrate digital tools well: not the application of generic best practice, but a context-sensitive judgment that weighs learner cues, curricular goals, institutional constraints, and the affordances of the tool at hand (Bardone & Bauters, 2017). Seen through this lens, DTI is not merely a technical or even a cognitive accomplishment; it is an ethical-practical one, in which the teacher exercises situated wisdom about whether, when, and how a digital tool can serve a pedagogical purpose in this moment for these students. This framing matters for what follows, because it locates the meaning of DTI in teachers' situated judgment rather than merely in the properties of the tool or the conditions of the setting.

Although PR&A is increasingly acknowledged as central to teachers' decision-making, Forkosh-Baruch et al. (2021) noted that it is often conceptualised narrowly as an individual cognitive process rather than as a dynamic, relational process shaped by personal dispositions, instructional goals, classroom dynamics, and institutional conditions. Morrison-Love & Patrick (2025) similarly critiqued this limited framing, arguing that it fails to capture the embedded and adaptive nature of pedagogical reasoning in digital contexts.

In response, a complementary line of research reframes DTI as fundamentally situated and contingent. Dron (2021) described it as a real-time assembly of tools, tasks, roles, and norms enacted through teachers' goal-anchored judgments. Forkosh-Baruch et al. (2021) supported this view by emphasising the need for adaptive formative assessment tools that align with teachers' interpretive practices. This reframing aligns with Fawns (2022), who critiques the "technology-led vs pedagogy-led" binarity as overly simplistic. Instead, DTI is increasingly understood as the dynamic orchestration of people, tools, and contexts (Dillenbourg, 2013), a process that is irreducibly entangled (Fawns, 2022) or sociomaterial (Burnett & Merchant, 2020) and situated (Dron, 2022).

1.1.3. From Contextual Conditions to Dynamic Enactment

To begin understanding this situated and entangled DTI, researchers have looked for an approach to map the multiple, overlapping contexts in which practice occurs. Bronfenbrenner's Ecological Systems Theory (EST) has provided this critical foundation, offering a language for how nested layers, from the immediate Microsystem to broader exosystemic and macrosystemic layers, shape human development (Bronfenbrenner, 1979), including educational phenomena (Tong & An, 2024). Building directly on this foundation, the Socio-Ecological Technology Integration (SETI) model (Crompton et al., 2024) applied Bronfenbrenner's ecological lens specifically to DTI. SETI's primary contribution has been to systematically map the various contextual factors (individual, institutional, and policy-related) that create the conditions for, and shape, DTI in schools.

However, a map of contextual factors (as provided by SETI) does not, by itself, explain how DTI is enacted. The absence of integrative models that explain how PR&A is shaped in technology-rich contexts limits both research and practice (Forkosh-Baruch, Phillips, & Smits, 2021). This gap between mapping conditions and understanding the enactment, understood as the situated negotiation of meaning and tools, is the central problem of this dissertation. This focus on process is precisely the limitation that Bronfenbrenner's own later work, operationalised as the Process-Person-Context-Time (PPCT) model, explicitly addresses (Bronfenbrenner, 1995). PPCT moves beyond a static inventory of influences by positioning recurring, dynamic, and reciprocal interactions, i.e., proximal processes, at the very centre of change. Translated to DTI, this provides the critical mechanism: the key determinant of meaningful integration is not simply what conditions, i.e., resources or policies, are present (the Context), but the quality of the Process, specifically, how teachers and students interact with, adapt, and appropriate technology to achieve pedagogical goals in their specific classroom moment-to-moment (Parsons et al., 2018).

To address this gap, we must first clearly distinguish between conditions and process. Conditions refer to the static factors of the educational environment, such as the availability of infrastructure, policy mandates, or a teacher's baseline digital skills (Lachner, Backfisch, & Franke, 2024). However, drawing on Bronfenbrenner's PPCT framework and recent neo-ecological extensions (Bronfenbrenner & Morris, 2006; Navarro & Tudge, 2022), conditions do not automatically produce outcomes; they are merely the stage. The process, functioning as proximal processes, is the actual engine of development and change (Bronfenbrenner & Morris, 2006). In the educational context, these can be seen enacted through dynamic, moment-to-moment teaching, in which educators constantly interpret, negotiate, and pedagogically adapt their tools to fit the classroom's contextual contingencies (Forkosh-Baruch, Phillips, & Smits, 2021; Parsons et al., 2018), with previous research consistently indicating that meaningful integration, rather than mere presence of technology, drives learning (e.g., Inan & Lowther, 2010; Tondeur et al., 2017; UNESCO, 2023).

This theoretical and methodological shift from conditions to process has not yet been fully realised in the field. Existing models, including SETI, have made important progress in capturing contextual and personal influences on DTI, and several recent contributions have begun to gesture toward enactment, reasoning, and temporality (e.g., Fawns, 2022; Forkosh-Baruch, Phillips, & Smits, 2021). What the field still lacks, however, is a comprehensive ecological-temporal mechanism that specifies how DTI actually unfolds: how proximal processes mediate between conditions and enacted practice, and how this mediation accumulates over time. In other words, the limitation is not that process-level thinking is entirely absent from the literature, but that it has not yet been integrated into a model whose components and relations are explicit enough to be operationalised, tested, and refined. By continuing to focus primarily on what conditions support DTI rather than how DTI unfolds in practice, existing research has inadvertently reproduced what Bronfenbrenner (1986, p. 288) warned against: "context without development", a comprehensive mapping of influences without examining the mechanisms by which change actually occurs.

Consequently, there is a pressing need to advance both theory and empirical research toward models that centre the dynamic, situated processes, which Bronfenbrenner terms proximal processes (Bronfenbrenner & Morris, 2006), through which teacher characteristics and institutional supports are reciprocally mediated into enacted DTI (Tong & An, 2024). In short, we lack a clear account of how teachers' internal dispositions and external conditions interact bidirectionally and over time to shape DTI.

1.2. Research Aim & Questions

This dissertation addresses the gap identified above by proposing and empirically grounding the Socio-Ecological Enactment Process (SEEP) model. The aim is twofold: (i) to conceptualise SEEP, extending SETI by foregrounding dynamic, situated Process and adding a Time lens; and (ii) to provide indicative empirical evidence from a digitally mature system (Estonia) that supports SEEP's explanatory potential for understanding how and why DTI unfolds in real classrooms.

To address the overarching aim of this dissertation, to conceptualise a time-considerate, process-level model of DTI (i.e., the SEEP model) and offer indicative empirical support from a digitally mature context, specifying testable propositions and concrete indicators of proximal processes to make the model actionable and falsifiable, the research is guided by three interconnected questions that integrate both conceptual and empirical inquiry:

1. RQ1: How can DTI be conceptualised as a situated process of pedagogical enactment, and what model emerges from this conceptualisation?

   This question leads to the dissertation's primary theoretical contribution: the development of the SEEP model. It identifies a critical limitation in existing research, the explanatory ceiling of models that treat DTI as a set of fixed conditions (such as infrastructure, skills, or attitudes), which fail to account for much of the situational variation observed in practice.

2. RQ2: What distinct profiles and practices of DTI emerge among teachers working under comparable conditions, and what do these patterns reveal about the situated nature of enactment?

   This question (addressed in Articles I, II, and III) provides the empirical grounding for the model. By investigating the Estonian context, where conditions like infrastructure and training are largely standardised, this question reveals the inherent heterogeneity of practice. The identification of distinct profiles demonstrates that even when distal conditions are equal, the actual enactment remains highly varied. This variation provides insight that DTI is not an automated output of resources but a situated choice driven by teacher judgment.

3. RQ3: To what extent do individual factors predict these teachers' technology-integration profiles?

   Building on the profiles identified in RQ2, this question tests the predictive limits of individual factors (addressed in Article IV). While teacher traits are often viewed as enabling conditions for technology use, this question examines their predictive power for teachers' practices. By identifying a ceiling where positive attitudes and good skills do not always translate into high-level DT integration, the question highlights a critical theoretical gap.

It is therefore crucial to note that the doctoral work this dissertation presents followed an abductive, iterative path: early empirical work (distinct profiles, within-teacher variability, teacher-level factors channel but do not determine effects) revealed the need for a process-centred account. However, before presenting and integrating those findings, the dissertation places the conceptualisation up front so that readers have the common vocabulary and mechanism (i.e., the SEEP model) needed to interpret the empirical patterns coherently. In short, while the theory was sharpened after initial analyses, it is presented before the empirical chapters to frame them, ensure conceptual clarity, and make the subsequent evidence cumulatively interpretable.

These three questions form a cumulative argument. RQ1 delivers the conceptual vocabulary, working definitions and propositions grounded in a critical synthesis of DTI models, Bronfenbrenner's socio-ecological theory, and scholarship on PR&A and orchestration. RQ2 provides descriptive empirical grounding by identifying distinct DTI patterns at the lesson level (hierarchical clustering, Article II) and the teacher level (Latent Profile Analysis, Article III), triangulated with qualitative insights from Article I. RQ3 tests the explanatory boundary of conventional predictors through multinomial regression (Article IV), showing that individual factors channel but do not determine practice. Together, they help build a case for a process-level account.

1.3. Research Contribution

This dissertation contributes to the study of DTI in three connected ways. Section 1.3.1 articulates the theoretical contribution (the SEEP model itself), Section 1.3.2 outlines the empirical contribution (indicative support from the Estonian case for the claims SEEP makes about enactment), and Section 1.3.3 describes the practical contribution (implications for how DTI should be supported in classrooms, schools, and policy).

1.3.1. Theoretical Contribution

The core theoretical contribution of this dissertation is the SEEP model, which explicitly adds Process as a mediating layer to account for the dynamic mechanisms through which these factors are translated into enacted practice. The Process captures the ongoing negotiation, adaptation, and situated decision-making that characterise real-world DTI (Parsons et al., 2018). This theoretical refinement responds to contemporary calls in EdTech research to move beyond binary debates of "technology-led vs pedagogy-led" approaches. Instead, SEEP recognises DTI as an inherently relational and situated phenomenon, which Fawns (2022) describes as the "entanglement" of people, tools, and contexts that cannot be reduced to simple cause-and-effect relationships.

Accordingly, SEEP is best understood as a model that aims both to explain (why does DTI vary as it does, even when conditions are held roughly constant?) and to help us understand (what is going on when a teacher, acting as the proximal mediator of the learning experience, interprets a classroom moment and adapts a digital tool to it?) DTI. It is not, in its current form, a prescriptive model: it does not specify what teachers ought to do, but rather offers a vocabulary and a structure for examining what they actually do and why.

1.3.2. Empirical Contribution

The dissertation supports the argument for SEEP through indicative empirical evidence drawn from Estonia, a digitally mature education system that provides an ideal context for examining processual factors. Estonia's advanced digital infrastructure (Põldoja, 2020), comprehensive teacher training programmes (Pedaste et al., 2019), and supportive policy environment (Gabriel et al., 2022) create conditions where structural barriers to DTI have been largely removed, allowing for clearer investigation of the process-level mechanisms that drive variation in practice.

Interlinked studies conducted within the DigiEfekt study, relying on classroom observations and teacher interviews to document pedagogical reasoning and in-the-moment adaptations, along with teacher surveys indexing digital readiness and attitudes, provide preliminary empirical support consistent with SEEP's claims. First, even with broadly uniform access and policy support, Estonian primary and lower secondary teachers enact purpose-sensitive patterns of use. This is seen at two levels: teachers cluster into six distinct pedagogical profiles, or average orientations (see Article III), yet the same teacher enacts different practices (e.g., motivational, cognitive) across different lessons, indicating that integration is a fluid, situated enactment rather than a fixed personal style (see Article II). Second, predictive analyses (see Article IV) show that individual factors guide practice rather than dictate it: digital attitudes are most closely associated with engagement-oriented uses, while digital readiness is positively associated with cognitively demanding profiles and negatively related to substitution-heavy patterns (see Article IV).

These patterns, read abductively, are consistent with a processual understanding and show that growing capacity enables, but does not guarantee, deeper pedagogical choices in DTI. Third, learner participation was observed to co-construct practice. Field notes from classroom observations documented moment-to-moment cues such as questions, stalls, and student-initiated workarounds that prompted teachers to interpret and adapt on the fly (Article I; Raave et al., 2022). In short, the empirical patterns analysed here show distinct practice profiles under similar provision, within-teacher variability, and individual factors that guide enactment. Together, these findings underscore SEEP's emphasis on proximal processes unfolding within the Microsystem, where learners' actions and signals actively shape the course of technology-mediated instruction. Taken together, these studies demonstrate that observed differences in DTI under enabling conditions are better explained by process than by provision, and they provide an initial empirical anchoring for SEEP's core propositions.

1.3.3. Practical Contribution

The convergence of theoretical refinement and empirical findings has direct implications for practice in three key areas (further developed in Section 4.2).

First, for policy, rather than focusing solely on resource provision and training requirements, policy initiatives informed by SEEP would emphasise supporting the processual aspects of integration, creating conditions for sustained reflection, experimentation, and adaptation in DTI. This might include policies that provide time for collaborative planning, opportunities for peer observation and feedback, and support for iterative curriculum development.

Second, for school leadership, the model highlights the principal's role in translating policy into practice. School leaders are crucial in cultivating an institutional culture of trust and experimentation and in structuring timetables that protect the collaborative time needed for teachers to engage in the reflective cycles of enactment that SEEP describes.

Third, for professional development, the processual perspective reframes what effective teacher learning looks like: rather than discrete training events, it calls for sustained, practice-embedded support that develops teachers' capacity to reason with technology across shifting classroom demands.

1.4. Dissertation Overview

This dissertation is organised to build a cumulative argument addressing a central problem: despite mature policies, infrastructure and training, classroom DTI still varies markedly and often reproduces "paper-era" pedagogy. The field has mapped contexts well, but lacks a process-level account of how teachers' moment-to-moment PR&A turn conditions into enacted practice over time. The dissertation, therefore, shifts the focus to enactment.

To address this gap, the dissertation proposes and grounds the SEEP model, a PPCT-informed refinement of SETI that centres Process and embeds Time (micro/meso/macro) to explain how classroom DTI actually unfolds. The overarching aim of this dissertation is to propose and conceptualise SEEP, provide indicative empirical evidence from a digitally mature context (Estonia), and offer testable propositions and concrete indicators for tracing proximal processes.

In short, this dissertation argues for the necessity of processual perspectives for understanding DTI and proposes the SEEP model, demonstrating its theoretical coherence and empirical grounding. The dissertation comprises five chapters containing the following:

Chapter 1 situates the access–impact paradox and reframes DTI as a problem of enactment, not merely provision or predisposition. It identifies a research gap: existing models (e.g., SETI) map influences but do not explain the proximal processes by which internal dispositions and external conditions are translated into classroom practice over time. In response, the chapter states the dissertation aim: to propose and empirically ground the SEEP model, a PPCT-informed refinement that centres Process and embeds Time. The chapter also formulates three research questions: (RQ1) conceptualising technology-integration as enactment and deriving SEEP; (RQ2) identifying distinct practice profiles under comparable provision and interpreting what they reveal about enactment; and (RQ3) testing how individual factors account for those profiles, assessing whether dispositions channel rather than determine practice. The chapter also outlines the dissertation's theoretical, empirical, and practical contributions.

Chapter 2 establishes the theoretical foundations for the evolution from SETI to SEEP, grounding the refinement in Bronfenbrenner's bioecological theory (Bronfenbrenner & Morris, 2006) and contemporary EdTech theoretical, conceptual and empirical research. It details how the processual layer and Chronosystem address limitations in the existing SETI model. More specifically, it distinguishes the instructional Microsystem (activities, roles, relations, features) from the proximal processes that convert capacity into pedagogy, and it formalises micro-, meso-, and macro-time to explain moment-to-moment pivots, routine formation, and system-level shifts. This turns static context maps into a developmental account of DTI, yielding concrete propositions/indicators that later analyses can test.

Chapter 3 presents the empirical foundations from the DigiEfekt research study, positioning Estonia as a digitally mature critical case in which variation in DTI practices is more plausibly processual than structural. The chapter first details the author's core empirical analysis (forming the basis of Articles I-IV), which draws on 169 observed lessons, post-lesson interviews, and teacher surveys to analyse teacher-level practices, profiles, and their predictors. To build a complete, holistic model, the chapter then synthesises this core analysis with related project-level findings on student-side interactions and temporal patterns (e.g., Opiq platform traces). This synthetic approach is necessary to empirically ground all layers of the proposed SEEP model, particularly the student-facing elements of the Micro-system and the recurring meso-time patterns of the Chronosystem. Together, these analyses reveal significant variation in DTI practices and within-teacher fluidity, showing that comparable provision and predispositions do not uniformly determine enactment.

Chapter 4 provides explicit answer to the posed RQs and discusses the implications of SEEP across theoretical, research, and practice domains, demonstrating how it provides a more comprehensive account of meaningful DTI as the dissertation argues that it is within the dynamic, recursive, and context-sensitive processes, central to the SEEP model, where meaningful DTI truly occurs, as only so can pedagogical actions attain genuine meaning, ensuring they are situationally appropriate, responsive to emergent needs, and coherently aligned with intended learning outcomes. The chapter also acknowledges limitations (e.g., scope and generalisability, measurement of proximal processes) and delineates avenues for future work alongside practical implications.

Chapter 5 concludes by synthesising the thesis's theoretical and empirical contributions, limitations and a forward agenda. It outlines three priority directions: (1) trace process indicators (e.g., goal-framing, orchestration moves, responsiveness) in fine-grained studies; (2) use longitudinal/meso-time designs to examine how routines consolidate or drift; and (3) design training, professional development and policy that cultivate adaptive expertise so capacity reliably converts into meaningful DTI.

2. THEORETICAL FOUNDATION & ELABORATION: CONCEPTUALISATION OF SEEP

The integration of technology into teaching and learning has long been a central focus of educational research. However, the global disruption caused by the COVID-19 pandemic exposed the limitations of existing conceptual models (Crompton, Chigona, & Burke, 2023), and Gabriel et al. (2022) show that the failure to align digital affordances with instructional goals frequently undermines integration efforts. While frameworks such as TPACK, SAMR, and SETI have advanced the field in important ways, each has been critiqued for specific limitations, from TPACK's insufficient attention to contextual variables (Wohlfart & Wagner, 2023) to SAMR's rigid hierarchy that oversimplifes DTI, ignoring the actual processes of teaching and learning (Hamilton, Rosenberg, & Akcaoglu, 2016). In response, the SETI model (Crompton et al., 2024) adopted Bronfenbrenner's ecological lens to map the nested systems influencing DTI, offering the most comprehensive contextual account to date. Yet even SETI, as this chapter will argue, stops short of explaining the dynamic mechanisms through which those contextual influences are translated into enacted classroom practice.

The rest of this chapter unfolds in three sections. Section 2.1 surveys the analytical lenses through which DTI has been conceptualised over the past two decades, tracing a progressive widening from the individual teacher to the surrounding ecology. Section 2.2 then focuses on SETI to identify the specific gap that motivates this dissertation's refinement. Section 2.3 introduces the SEEP model itself, summarises its key refinements relative to SETI, elaborates on each component, and concludes by showing how the components interrelate as a single explanatory mechanism.

2.1. Conceptual Analysis of Digital Technology Integration Frameworks

To situate the SETI model that SEEP refines, this section surveys the landscape of DTI models that preceded it. The following examples are not exhaustive but illustrate the key trends.

Over the past decades, research has moved from individual teacher-focused, skill-based perspectives toward more pedagogically nuanced and systemically informed approaches (Alam et al., 2025). Some analytical lenses focus heavily on the individual user's psychological state, aiming to predict the intention to adopt a given technology. Models such as the Technology Acceptance Model (TAM) (Davis, 1989) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003) explain integration primarily through individual attitudes and beliefs, such as perceived usefulness and perceived ease of use. While TAM has been widely applied in educational contexts to investigate and predict teachers' willingness to adopt DT, it remains limited by its focus on intention rather than enactment, and by its neglect of contextual and pedagogical dynamics that shape actual classroom practice (Kimmons, Graham, & West, 2020; Scherer, Siddiq, & Tondeur, 2019). Although extensions of TAM, such as the UTAUT (Venkatesh et al., 2003), incorporate additional variables, such as social influence and facilitating conditions, they still primarily operate within an individual-level framework.

As the field recognised that the willingness to use technology does not equate to effective teaching with it, the analytical lens shifted to the professional knowledge required of educators. The Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006) highlights that effective DTI requires the simultaneous intersection of a teacher's knowledge of technology, pedagogy, and subject content. While highly influential, it primarily maps static domains of knowledge but has been noted to fail to explain the dynamic, real-time cognitive processes required to construct this knowledge on the fly during actual teaching (Lachner, Backfisch, & Franke, 2024).

To address the gap between what teachers know and what they actually do, some models shifted the lens toward technology usage. Frameworks like SAMR (Substitution, Augmentation, Modification, Redefinition) (Puentedura, 2006) and RAT (Replacement, Amplification, Transformation) (Hughes, Thomas, & Schruber, 2006) evaluate how technological affordances can alter the learning activity. Yet, models like SAMR are also heavily criticised for a rigid, hierarchical structure that oversimplifies DTI by dismissing the complex, multifaceted, and situated practice of teaching (Hamilton, Rosenberg & Akcaoglu, 2016). In reality, teachers often move between levels based on lesson aims and student needs, rather than following a fixed trajectory (Bicalho et al., 2023).

A more recent framework, the PICRAT model (Kimmons, Graham & West, 2020), attempts to refine this approach by evaluating both the student's behaviour with the technology (Passive, Interactive, Creative) and the technology's impact on teacher practice (Replacement, Amplification, Transformation). While PICRAT does shift the focus away from the technology itself and toward student learning behaviours, it is explicitly designed to evaluate specific, isolated classroom activities rather than a teacher's overall practice.

Recognising that teachers do not operate in a vacuum, researchers adopted ecological perspectives to map the external forces that constrain or enable integration. Models such as the Socio-Ecological Technology Integration (SETI) model (Crompton et al., 2024) and Zhao and Frank's Ecological Perspective (Zhao & Frank, 2003) apply a systems approach, arguing that integration is mediated by nested layers of context (Microsystem, Mesosystem, Exosystem, Macrosystem) ranging from school infrastructure and district policies to national culture and historical events. While these models successfully shift the burden of integration away from the individual teacher to the broader community and resource infrastructure, they remain structural maps, outlining the conditions for success but lacking the fine-grained cognitive and process details on how teachers mediate these external structures in the moment-to-moment flow of instruction.

In short, existing frameworks tend to treat individual capacities, instructional processes, and ecological contexts as analytically separate. Where holistic frameworks have been proposed, they have typically privileged one of these three elements over the others rather than holding them in dynamic relation. This justifies the necessity for a model that moves beyond mapping the conditions of integration to modelling the mechanisms that link them, placing the proximal processes (the dynamic, reciprocal interactions through which teaching is enacted) at the centre, while acknowledging that these processes are synergistically driven by the teacher's individual capacities and the nested ecological contexts over time. This dissertation, therefore, takes SETI as its primary conceptual point of departure, since Zhao and Frank's (2003) evolutionary framing is oriented toward predicting adoption rather than explaining situated enactment.

2.2. Advancing the Ecological Lens

To understand the theoretical necessity of the SEEP model, it is essential to first ground the discussion in the framework from which it departs. Outlining the specific modifications and refinements made to the SETI model is not a critique of its internal validity, but rather a necessary exercise in conceptual precision. By explicitly mapping the boundaries of SETI's intended scope, we can more clearly define the specific "site of enactment" that requires the new lenses of Process and Time. This comparison ensures that SEEP is understood as a cumulative evolution, one that preserves the robust systemic architecture of SETI while introducing the explanatory mechanisms needed to understand how teachers navigate those systems in real-time.

2.2.1. Overview of the SETI Model

The SETI model represents a paradigm shift from individual-focused perspectives to a holistic, systems-based approach. Its development was a direct result of empirical research conducted during the COVID-19 crisis, which revealed that teacher success was profoundly impacted by factors far beyond their personal control or pedagogical skill (Crompton et al., 2024). The model, adapted from an earlier mobile learning integration model, was updated to explicitly include new findings from the pandemic, such as the critical role of family and national infrastructure (Crompton et al., 2024).

The core idea behind SETI is that DTI is not merely an outcome of individual competence but rather a collective outcome of a complex socio-ecological system (Crompton et al., 2024). This reframing from a personal responsibility to a community-wide effort is what distinguishes SETI, as it provides a comprehensive lens to analyse how various components of the educational ecosystem interact and influence the educator's ability to integrate technology effectively.

In SETI, the educator is positioned at the centre, surrounded by the Microsystem (school, including technology support, access to technological tools, training and learning conditions such as face-to-face or online), the Mesosystem (links between Microsystems), the Exosystem (broader school system, including policies, funding for technology and technological support, culture around textbook and course adoptions), and the Macrosystem (national standard, cultural and social technological norms, and wider infrastructure such as internet connectivity). This mapping allows for a systematic identification of what factors influence integration and where they are situated in relation to the teacher.

SETI's strength lies in its ability to consolidate a broad range of influences into a single model. This makes it well-suited for policy-oriented diagnostics, as it enables researchers and practitioners to pinpoint which contextual layers might facilitate or constrain integration. In contexts with varying levels of infrastructure or professional development, SETI provides a structured way to identify priority areas for intervention. It also resonates with the increasing recognition in educational research that DTI cannot be reduced to individual teacher capacity alone but must be understood within its organisational and socio-cultural context.

2.2.2. Bridging SETI and the PPCT Framework

SETI provides a diagnostic map of contextual conditions, identifying and categorising the individual, institutional, and policy-level influences surrounding DTI. Its current form, however, remains largely static and structural: it tells us what matters but does not capture the situated decision-making, iterative adaptation, and reciprocal feedback loops through which teachers negotiate these influences in real-time. Without a processual lens, it cannot explain why teachers with comparable access, training, and policy support enact markedly different practices.

This conceptual orientation calls for an explicit refinement that moves from SETI's static mapping toward a dynamic explanation of the instructional process. Two complementary perspectives reinforce this direction: technology-mediated learning theory (Bower, 2019), which holds that DTI's educational value is always mediated by human intentions and interactions; and entangled pedagogy (Fawns, 2022), which argues that the value of DT emerges from ongoing, situated interactions between teachers, students, and resources. These interactions are contingent, adaptive, and embedded in broader socio-material arrangements (Fawns, 2022), meaning they cannot be fully understood by examining conditions in isolation.

Other recent attempts to bridge this gap have moved toward a process from a different starting point. The Teachers' Professional Competence for Technology Integration (TPTI) framework (Lachner, Backfisch, & Franke, 2024), for example, shifts the focus toward the active practice of teaching but defines integration primarily through an internal, cognitive lens, foregrounding the teacher's professional vision (noticing, reasoning, and acting on the basis of pre-existing knowledge scripts). TPTI also treats context mainly as an immediate situational boundary condition, such as classroom infrastructure or time constraints, used to predict teaching quality and student achievement. The model that this dissertation develops takes a different route: rather than working outward from the teacher's internal cognition, it works inward from the ecological systems that already organise SETI, adding the Process layer at the point where personal characteristics and contextual conditions meet.

Bronfenbrenner himself addressed the abovementioned gap of static mapping of environmental influences by shifting it to a dynamic explanation of how development actually happens through his later PPCT model (Bronfenbrenner, 1995), which offers four analytically distinct but interdependent elements (Merçon-Vargas et al., 2020):

1. Process – Proximal processes are the reciprocal and progressively complex interactions between an individual and their environment through which development occurs. In the case of EdTech, this shifts the analytical lens from the mere presence of resources, training, or policy support to the ongoing, situated processes by which teachers adapt, negotiate, and embed DT into their pedagogical routines over time.

2. Person – Individuals are active agents, not passive recipients of environmental influences. In Bronfenbrenner's model, this agency is shaped by three interrelated types of characteristics:
    1. Demand characteristics are immediately observable attributes of the individual that can influence how others respond to them and how they engage in interactions, acting as stimuli that invite or inhibit interaction (e.g., teaching experience, subject specialisation, school level).
    2. Resource characteristics: mental, emotional, and material resources influencing the capacity to engage in and benefit from proximal processes (e.g., digital competence, access to devices, prior experience).
    3. Force characteristics: dispositional traits influencing the direction, intensity, and persistence of engagement in developmental processes (e.g., motivation, self-efficacy, resilience).

   Moreover, these personal characteristics are not static; they evolve through interaction, meaning that who a person is both influences and is influenced by the quality and frequency of their ongoing proximal processes.

3. Context – The nested systems of EST (Bronfenbrenner, 1979) remain but are reframed as dynamic, interconnected settings with bidirectional influences:
    1. Microsystem: an immediate setting in which the person engages in face-to-face interactions with other people, objects, and symbols. It is the most proximal environment, encompassing activities, roles, and interpersonal relations experienced directly by the individual (e.g., the classroom environment, direct relationships with students, peers, and DT).
    2. Mesosystem: interrelations among two or more settings in which the person actively participates, essentially interconnections between Microsystems (e.g., alignment between digital practices at home and school expectations).

   3. Exosystem: settings in which the person does not actively participate but which nonetheless influence processes within the immediate setting (e.g., ICT policies, professional development programmes).
   4. Macrosystem: overarching patterns of culture, including the belief systems, values, laws, customs, and resources of the broader society (e.g., cultural norms, national curricula, societal attitudes toward technology).

4. Time – Chronosystem of temporal dimensions operating at multiple scales:
   1. Micro-time: the timing and sequencing of events and interactions within a single activity or short episode, occurring in real-time during specific activities or interactions (e.g., moment-to-moment classroom decision-making, such as whether to switch from a malfunctioning tool to an analogue backup).
   2. Meso-time: periodicity of these episodes across broader time intervals, such as days, weeks, or months. This refers to how often and in what rhythm certain types of interactions or activities recur, shaping development over medium timescales (e.g., recurring patterns of DT use over weeks or months, such as integrating a platform into every unit or using it primarily during assessments).
   3. Macro-time: evolving pattern of events, transitions, and sociohistorical conditions over the life course and across generations. This includes both individual life transitions (e.g., changing workplace or school) and larger sociohistorical shifts (e.g., national policy reforms, technological revolutions) (e.g., the COVID-19-induced pivot to remote teaching, the pressure of AI integration into curriculum design).

2.3. Introducing the SEEP Model

The preceding section established that PPCT offers the dynamic mechanism missing from SETI. The SEEP model proposed in this dissertation is an attempt to bring the two together: it extends SETI by foregrounding the situated, moment-to-moment activity through which teachers interpret their classroom ecology and orchestrate digital tools in relation to specific pedagogical goals, and by embedding this activity within an explicit temporal dimension that tracks how integration unfolds across micro-, meso-, and macro-timescales. The result is a model that does not replace SETI but rebuilds it on PPCT foundations: the ecological layers SETI identified are retained, but they are now organised around a central mediating mechanism (the Process layer) and situated within a temporal envelope (the Chronosystem) that together explain not only where influences on DTI reside, but how those influences are mobilised into practice and when that mobilisation consolidates, shifts, or fades.

The model's name, Socio-Ecological Enactment Process, reflects the two things it brings together: a theoretical lineage (the processual machinery inherited from

Bronfenbrenner's PPCT) and an empirical phenomenon (enactment, the situated realisation of DTI in classroom practice). Throughout this dissertation, the term "process" is used in the technical, PPCT-anchored sense to refer to the Process layer and to proximal processes; "enactment" is used to refer to the situated, observable practice that the Process layer is designed to explain.

Next, section 2.3.1 first summarises the four refinements that distinguish SEEP from SETI. Section 2.3.2 then elaborates the components of the model in detail, with particular attention to the Process layer and the Chronosystem as the two most substantial refinements. Last, section 2.3.3 shows how these components interrelate as a single mechanism of DTI.

2.3.1. Key Refinements

SEEP introduces four targeted refinements to SETI's ecological scaffolding, which together shift the model from a static map of conditions to a dynamic account of how integration is enacted and how it evolves over time.

First, centring Process as an explicit mediating layer. The most consequential refinement is the introduction of a Process layer, absent in SETI, that sits between the Person and the immediate instructional environment. This layer captures the adaptive, reciprocal orchestration through which teachers interpret a classroom moment, adapt their plans to it, and negotiate the use of digital tools with students in real-time. By placing this layer at the analytical core, SEEP answers calls in DTI research for more process-oriented theorisation (Dron, 2023; Wu, 2023) and moves the model from mapping the bidirectional factors influencing DTI to explaining the mechanism by which those factors are converted into practice.

Second, embedding Time as an explicit Chronosystem. SEEP adds a Chronosystem layer that renders the temporal dimension of DTI analytically tractable, distinguishing three interconnected timescales: the micro-time of moment-to-moment pedagogical decisions, the meso-time of recurring routines and consolidated practices, and the macro-time of societal, institutional, and policy shifts. The Chronosystem is positioned as the outermost layer, encompassing all others, because time is not confined to any single ecological level: e.g., classroom interactions (Microsystem), collegial relationships (Mesosystem), institutional structures (Exosystem), and societal conditions (Macrosystem) all unfold, consolidate, and periodically reconfigure over time. This positioning allows the model to connect in-the-moment orchestration to the gradual consolidation or reconfiguration of practice over weeks, terms, and years, and thereby to account for how DTI adapts to shifting tools, pedagogies, and policy environments while remaining educationally relevant.

Third, reconceptualising the Person as an active agent. Drawing on PPCT, SEEP refines the Person component to foreground teacher agency, understood as the interplay of three dimensions: Attributes (role markers such as subject, experience, and school level), Capacities (knowledge, skills, and resources, including digital competence and pedagogical repertoire), and Dispositions (value beliefs, motivational orientations, and pedagogical commitments). These traits are treated as dynamic and continually reshaped by interaction, feedback, and evolving local conditions (Biesta, Priestley, & Robinson, 2015), rather than as static background characteristics predicting integration outcomes.

Fourth, reconceptualising the nested Context layers. SEEP retains SETI's nested ecological systems (Microsystem, Mesosystem, Exosystem, Macrosystem) but redefines several of them to better reflect the interplay of factors identified in the literature. Most consequentially, the Microsystem is narrowed from the school level to the immediate instructional environment where direct pedagogical interactions actually occur, which allows SEEP to distinguish classroom-level enactment (Microsystem) from school-level institutional processes (Exosystem) and to account for variation between teachers working within the same school. Innovations that emerge in the classroom (Microsystem) can first travel laterally through the collegial relationships and shared professional spaces through the Mesosystem interconnections, as when a teacher observes a colleague's approach and adapts it for her own practice, and from there shape institutional routines and policies at the school level (Exosystem) or even inform national-level policy and societal expectations (Macrosystem), as well as the other way around.

Together with the refined Person and the newly introduced Process and Chronosystem layers, these reconceptualised Context layers complete the SEEP model. The full model thus comprises seven following components. At its core is the Person (Teacher) (Attributes, Capacities, Dispositions), surrounded by Process (Orchestration), in which practice is enacted through interpretation, adaptation and negotiation. The Microsystem (Instructional Environment) is the immediate teaching-learning setting, while the Mesosystem (Interconnections) reflects the connection between the Instructional Environment and other Microsystems. The Exosystem (Institutional Environment) encompasses schools, governance, professional organisations, and service providers, and the Macrosystem (Societal Conditions) covers wider influences such as culture, policies, infrastructure, and norms. The Chronosystem (Temporal Dynamics) is represented as three overlapping lobes rather than a single ring, reflecting the three qualitatively different timescales through which all other layers operate: micro-time (moment-to-moment classroom decisions), meso-time (recurring routines that consolidate over weeks and terms), and macro-time (long-term societal and policy shifts). The lobes overlap because the three timescales are not discrete phases but co-occurring dimensions of the same unfolding practice. Solid bidirectional arrows (left) represent the continuous flow of influence through adjacent layers. Each arrow pair sits at a layer boundary indicates that influence is mediated step by step as it travels inward or outward through the nested system. Dotted unidirectional arrows (right) represent episodic influences from the Exosystem and Macrosystem that reach the Process layer directly at particular moments, as for example, when an institutional decision or a societal disruption triggers an immediate adaptive response in classroom orchestration. Figure 1 presents the model in full. Each component is elaborated in 2.3.2.

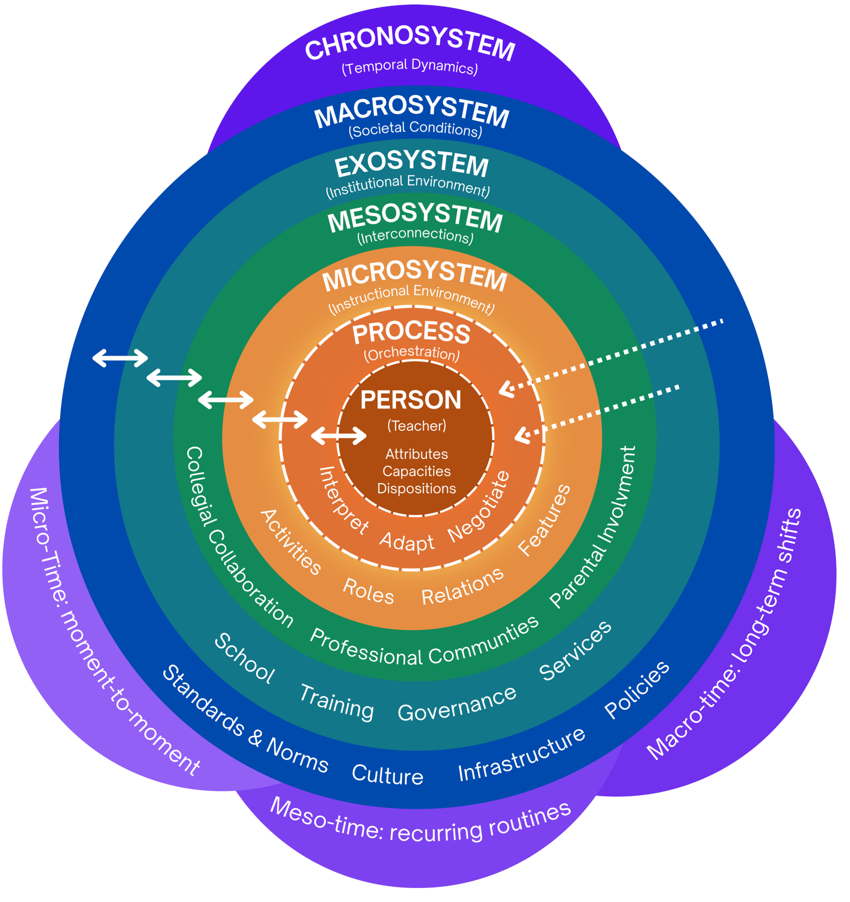

Figure 1. The Socio-Ecological Enactment Process (SEEP) model

2.3.2. SEEP Detailed Overview

This section elaborates on each SEEP component, working outward from Person through Process, Microsystem, Mesosystem, Exosystem, Macrosystem, and Chronosystem. The Process layer and Chronosystem, as the most substantial refinements, receive the most detailed treatment.

Person: Educator

At the centre of SEEP sits the Person, reconceptualised as an active agent whose practice emerges from the interplay of three dimensions: Attributes, Capacities, and Dispositions. This framing recognises that integration is shaped by educators' professional agency rather than being reducible to their background traits. In the SETI model, by contrast, the educator was reduced to being characterised primarily in terms of family culture and beliefs, instead of recognising the full spectrum of agentic characteristics. To address this, we draw on Bronfenbrenner's PPCT model (Bronfenbrenner & Morris, 2006), which distinguishes between three sets of personal characteristics (i.e., demand, resource, and force characteristics) that shape the form, frequency, and quality of proximal processes while also evolving through interaction over time. While conceptually precise, these original terms are not self-explanatory for readers unfamiliar with PPCT or the bioecological theory (Bronfenbrenner & Morris, 2006). To improve clarity and interpretability in SEEP, we rename them as Attributes, Capacities, and Dispositions, and refine each in the context of EdTech as follows.

First, Attributes (in PPCT referred to as "demand characteristics") are outwardly visible features of educators that frame how DTI is anticipated and initiated. These include role-related markers such as subject area, teaching experience, or school level, which often carry implicit expectations about what kinds of DT will be relevant. For example, a science teacher might be positioned to use simulations, while a language teacher might be expected to use digital dictionaries. Attributes provide an entry point into integration, shaping the initial orientation toward DT without fully determining practice.

Second, Capacities (in PPCT referred to as "resource characteristics") encompass the professional knowledge, skills, and resources that enable teachers to sustain meaningful engagement with technology. This includes, for example, digital competence, pedagogical repertoire, access to reliable infrastructure, and accumulated professional experience. Capacities form the toolkit educators draw on when deciding whether, when, and how to adapt technologies to serve pedagogical aims.

Third, Dispositions (in PPCT referred to as "force characteristics") refer to enduring orientations that shape the direction and persistence of DTI. These include 1) value orientations, e.g., a belief that technology should promote collaboration, equity, or inquiry, which influences tool selection and use; 2) motivational orientations, e.g., openness to experimentation, persistence in troubleshooting, or a tendency toward cautious adoption, and 3) pedagogical orientations, e.g., commitment to student-centred learning versus preference for teacher-directed instruction, which steers how DT are enacted.

Together, these three dimensions move beyond SETI's earlier reduction of the teacher to "family culture and beliefs". Bronfenbrenner's categories already accommodate beliefs under Dispositions (as a value stance guiding practice) and family culture across all three dimensions, depending on how it manifests, as an observable attribute (e.g., communication style), an internalised capacity (e.g., familiarity with pedagogical traditions), or a dispositional orientation (e.g., collaborative ethos). The relabelling thus broadens the representation of the Person so that family culture and beliefs become one influence among many rather than the sole defining features. The empirical rationale for this disaggregation is developed in Section 3.3.3.

Process: Orchestration

As outlined in 2.3.1, the Process layer sits between the Person and the Microsystem, mediating between teacher characteristics and contextual conditions. In Bronfenbrenner's PPCT model (1995), process is the engine of development: recurring, reciprocal interactions between individuals and their environments. SEEP extends this logic to DTI, emphasising how personal traits and contextual factors are mediated through situated interactions that shape practice. This addresses the limitations of static SETI-like models and aligns with PPCT's emphasis on developmental drivers rather than mere settings.

Following Dillenbourg (2013) and Fawns (2022), we use the term "orchestration" to name the dynamic, coordinated activity that constitutes this layer: the moment-to-moment pedagogical moves by which teachers interpret a classroom situation, adapt their plans to it, and negotiate the use of digital tools with students in real-time. In the context of DTI, the Process layer captures this orchestration as the adaptive, interactional mechanisms through which integration unfolds: the space where teacher agency, student engagement, and contextual affordances converge into observable practice. Concretely, this includes moment-to-moment pedagogical decisions, iterative adaptation of tools based on student feedback, negotiation between curricular goals and technological possibilities, the establishment of classroom norms for DTI, and longer cycles of reflection and refinement, such as redesigning or experimenting with new tool applications.

The orchestration is reciprocal; teachers shape tool use, but tools and their affordances also influence dynamics in the instructional environment. Indeed, technology can act as a participant in proximal processes. For example, when engaging with platforms like learning management systems or AI-driven tools, the interaction is not merely contextual; it is structured by the tool's affordances. For instance, an AI system that provides real-time student analytics does more than "exist" as a resource; it continually prompts the teacher to interpret, adapt, and negotiate the affordances on offer (Shi & Choi, 2024). In this sense, technology is not only a background condition but a dynamic co-driver of pedagogical reasoning. The Process layer thus captures not only what teachers do with technology, but how feedback loops among students, tools, and pedagogical intentions generate emergent, context-sensitive practices.

The orchestration that constitutes the Process layer becomes especially visible when comparing classrooms with a seemingly similar Microsystem. For example, a classroom may share similar activities (group problem-solving), roles (teacher as instructor, students as collaborators), relations (peer interaction, teacher-student instruction), and features (group seating, tablets). Yet the enacted practices diverge: in one class, the teacher engages in continuous, adaptive interactions, adjusting instructions moment by moment, moving between groups, probing reasoning, and directing students to use the tablets as tools for exploration. Students revise their work and use the tablets to dig deeper, which in turn sparks further discussion and refinement. In another classroom, the teacher introduces the task and withdraws; tablets become quick fact-check devices, group dialogue fades, and the activity stalls. Both classrooms share the same Microsystem, but the enacted practices differ profoundly. This contrast illustrates why the Process layer is indispensable: it explains how seemingly identical environments generate qualitatively different DTI depending on how interactions unfold.

Positioning the Process layer between the Educator and Microsystem highlights its mediating role. Educator traits do not directly shape classroom activity; their influence emerges through interpretation, adaptation, and negotiation. Similarly, Microsystem factors, such as curriculum, student needs, and infrastructure, gain meaning only through this orchestration. SEEP thus reframes DTI not as the sum of static traits and conditions, but as the outcome of dynamic, reciprocal interactions. This shift moves beyond descriptive mapping toward a more explanatory account of how integration is enacted, sustained, and differentiated in practice. The empirical rationale for positioning Process as the central mediating layer of SEEP is developed in Section 3.3.1, drawing on patterns of between- and within-teacher variation in the DigiEfekt data.

Although Process is positioned between Person and Microsystem in Figure 1, this does not mean that the outer ecological layers influence practice only through the Microsystem. Their influence operates through two pathways. First, the Exosystem and Macrosystem shape the conditions that define the Microsystem (e.g., available tools, curriculum mandates, timetable structures, assessment demands) which are then encountered and navigated through Process. This pathway is continuous: the outer layers set the stage on which orchestration plays out. Second, events from the outer layers can reach Process episodically and directly: a collegial exchange (Mesosystem) gives a teacher a new strategy she tries in her next lesson; a policy shift (Macrosystem) forces an immediate reconfiguration of practice. These punctuated influences do not bypass the Microsystem permanently but alter what Process has to work with at particular moments. In Figure 1, these two pathways are distinguished visually: solid bidirectional arrows represent the continuous mediated flow through adjacent layers, while dotted unidirectional arrows represent episodic influences from the Exosystem and Macrosystem that reach Process directly.

Microsystem: Instructional Environment

In SEEP, the Microsystem is defined as the immediate instructional environment, comprising activities, roles, relations, and features. It encompasses any setting where teaching and learning interactions take place, whether in physical classrooms, in virtual or hybrid formats, or in asynchronous environments such as discussion forums and learning platforms. While educators also participate in other Microsystems (such as school staff and peer groups), these do not serve as the primary arena in which DTI unfolds; institutional provisions (e.g., professional development programme structures, device and network policies) belong to the Exosystem, whereas what teachers do with those provisions in class is Microsystem enactment. This framing extends Bronfenbrenner's bioecological definition of the Microsystem (Bronfenbrenner & Morris, 2006), the immediate setting where the individual directly participates, characterised by activities, social roles, interpersonal relations, and physical or symbolic features, by narrowing it from the school level (as in SETI) to the immediate teaching-learning environment, the rationale for which is detailed at the end of this subsection. Within this Microsystem, four key interconnected dimensions shape the enactment of DTI:

1. Activities – what is actually done in the setting, meaning the patterned practices of teaching and learning that invite, sustain, or inhibit complex engagement with technology. Examples include collaborative group projects, inquiry-based problem solving, assessment tasks, and tool-specific practices such as coding or simulation. Activities gain developmental significance when they persist over time, scaffold progressively complex engagement, and become central to how teachers and students experience learning. For instance, a one-off use of a digital quiz tool may have limited impact, but sustained use as part of formative feedback cycles can reshape practice.

2. Roles – expectations attached to people in that setting, dependent on socio-cultural expectations and activity structures. Roles are fluid and situational, not fixed; they shift as these factors change. Teachers may act as instructional leaders, facilitators, co-learners, or orchestrators of digital collaboration. Students, in turn, may take on roles such as peer tutor, collaborator, designer, or content producer. These role configurations influence authority, responsibility, and participation in technology-rich environments. For example, a flipped classroom model repositions students as active knowledge constructors, while teachers shift toward facilitation and feedback.

3. Relations – the interpersonal, e.g. teacher-student, student-student, dynamics and the actual enactment of the roles in practice, which gain pedagogical significance when they exhibit reciprocity, mutual positive affect, and increasing complexity (Bronfenbrenner, 1995; Bronfenbrenner & Morris, 2006). Under these conditions, relations move beyond surface-level exchanges to foster trust, responsiveness, and deeper interaction. DT can further shape these dynamics, for example, by amplifying student voice in online forums, enabling peer feedback through shared platforms, or fostering collaboration.

4. Features – encompassing both material and symbolic aspects. Material features encompass the infrastructural and physical environment in which learning takes place. In traditional classrooms, this includes devices, connectivity, and room layout, while in virtual classrooms, it extends to hardware (e.g., cameras, headsets) and the digital interface that structures interaction. Symbolic features capture the cultural and normative meanings attached to DTI within the learning space. These include, for example, curricular priorities, disciplinary traditions, and the value assigned to DTI in a given subject. For example, coding may be treated as a legitimate practice in mathematics for computational thinking, but marginalised in literature, even with the same tools available. Strong symbolic legitimation can elevate the role of even limited resources, whereas symbolic devaluation can marginalise DTI despite ample infrastructure. Crucially, these

features are not passive backdrops; they possess affordances (what they enable) and constraints (what they restrict) that the teacher's PR&A must actively interpret and negotiate. For example, a platform's design (a feature) can afford collaboration but constrain individualised assessment, directly shaping the enactment.

These four dimensions do not operate independently. Activities determine which roles become possible; relations renegotiate roles in turn (a student who is quiet face-to-face may emerge as a leader in online forums); and features shape both what activities can be enacted and how relations unfold (reliable connectivity enables sustained collaborative work; cultural emphasis on individual assessment limits group learning). Activities, roles, relations, and features can also reinforce one another over time, as when a successful peer-feedback cycle leads teachers to design more student-driven activities.

Framing the Microsystem at the instructional environment level rather than the school level (as in SETI) is what gives the layer the granularity needed to explain why two teachers in the same school, with the same training and infrastructure, can enact radically different integration practices: such divergences cannot be explained by school level descriptors alone, but emerge through classroom-level activities, role configurations, relationships, and symbolic meanings.

Mesosystem: Interconnections

The Mesosystem in SEEP reflects the connections between the immediate instructional environment and other contexts in which educators actively participate, such as collegial collaboration, parental engagement, and professional communities. Within these interconnected settings, cultural and structural conditions, including shared values, beliefs, and professional discourses, act as enablers, resources, or constraints that shape how educators evaluate situations and make pedagogical decisions (Leijen, et al., 2020). By engaging with these conditions, educators can alter their structuring relationship to their contexts of action (Biesta & Tedder, 2007). It is through this dynamic, temporally embedded engagement that teachers achieve agency, enabling them to navigate and actively reshape practice within the instructional environment (Biesta & Tedder, 2007; Leijen et al., 2020). In Bronfenbrenner's bioecological theory (Bronfenbrenner, 1979; Bronfenbrenner & Morris, 2006), the Mesosystem is defined as the interconnections between two or more Microsystems in which the Person actively participates.

In SEEP, this principle is retained but reframed around the educator as the focal Person: the Mesosystem captures the bidirectional interconnections linking the teaching-learning environment where direct pedagogical interactions occur with other settings the teacher also inhabits, such as the family-school interface, interactions with colleagues, and professional development communities.

These connections are consequential because they shape how practice evolves. For instance, professional collaboration with colleagues may provide inspiration or shared resources that influence DT use; parental engagement can reinforce or conflict with classroom practices; and professional development experiences link directly to experimentation in the classroom. Importantly, these interconnections are not one-way: experiences also flow back into the school and community, shaping institutional priorities and professional networks. Specifying the *Mesosystem* as the web of relationships between the educator's multiple *Microsystems* highlights that integration is not only shaped by what happens within the learning space but also by how the learning space is linked to, supported by, and in tension with other contexts in which the educator is embedded.

Exosystem: Institutional Environment

The Exosystem in SEEP refers to institutional processes that indirectly condition DTI, including leadership decisions, resource allocation, and professional development provision. It is closest to the educator at the school, where leadership decisions, timetabling, staffing, budgeting, and ICT management shape everyday possibilities for integration, and extend outward to encompass connected institutions such as municipal governance, professional development providers, and service partners (e.g., EdTech companies).

Drawing on Bronfenbrenner's bioecological model (Bronfenbrenner & Morris, 2006), the Exosystem encompasses settings that do not directly involve the person but nonetheless shape their immediate environment. While teachers and students inhabit the school physically, many of the institutional processes in a school remain outside their direct control, yet they strongly condition the possibilities for DTI in the instructional environment. For instance, decisions about teacher workload allocation, such as limited hours for collaborative planning, may profoundly shape how technology is used in the instructional environment, even if neither teachers nor students had input in those decisions.

Whereas SETI treated the Exosystem mainly as a set of static descriptors (e.g., policies, training, support), SEEP reconceptualises it as a dynamic arena of institutional processes through which resources are organised, distributed, and sustained over time. Its scope is broadened to include not only material resources but also non-material capacities such as time and opportunities for collaboration for peer learning.

It is also important to distinguish exosystemic influences from symbolic features of the Microsystem. Symbolic features describe how norms and priorities are interpreted and enacted by participants within the immediate instructional environment (e.g., the value assigned to a coding platform in mathematics versus literature). Exosystemic features, by contrast, are institutional and infrastructural conditions set outside the instructional environment (e.g., device procurement, technical support).

Thus, the Exosystem in SEEP consists of the structures that educators and students inhabit physically but cannot fully influence. Their impact is indirect: it creates enabling or constraining conditions for practice, which are then enacted in the Microsystem and mediated through processual mechanisms of teaching and learning.

Macrosystem: Societal Conditions

In Bronfenbrenner's bioecological theory (Bronfenbrenner & Morris, 2006), the Macrosystem encompasses the cultural and institutional conditions that indirectly shape all other systems. It constitutes the broad cultural, religious, and institutional conditions that indirectly shape all lower-order systems (Bronfenbrenner, 1995; Bronfenbrenner & Morris, 2006). Specifically, it consists of the shared belief systems, resources and hazards, lifestyles, opportunity structures, and macro-institutions that set the broadest parameters for development within a given culture or subculture (Bronfenbrenner, 1995). These influences are distal but powerful: they do not act directly on day-to-day interactions, but filter down through exo-systemic, mesosystemic, and microsystemic processes to shape what kinds of activities, roles, and relationships are possible (Bronfenbrenner, 1979; Bronfenbrenner & Morris, 2006). For example, a national belief in digital education, coupled with policy investment in digital equity, may translate into school-level device programmes and classroom-level practices of DTI.

In SEEP, the *Macrosystem* retains this distal-but-powerful function and is reorganised into four functional categories that make Bronfenbrenner's original elements more directly legible in the context of digital education: standards and norms, culture, infrastructure, and policies. Belief systems are expressed through culture, understood as the shared orientations and expectations around technology, and through standards and norms, where these orientations are formalised in curricula, digital competence frameworks, and assessment systems. Resources are reframed as infrastructure, covering broadband provision, devices, platforms, and their uneven distribution. Macroinstitutions are reflected in policies, which include governance structures, national strategies, funding priorities, and regulatory frameworks that shape how technology is integrated into schools.

Standards and Norms reflect shared belief systems and expectations. Examples include national curriculum standards that embed digital competencies or professional frameworks such as DigCompEdu, which shape expectations of teacher practice.

Culture captures the wider societal values, traditions, and lifestyles that influence how technology is perceived and legitimised. For instance, Estonia's strong cultural orientation toward digitalisation positions technology as a natural part of civic and educational life. By contrast, societies with more cautious or sceptical attitudes toward digitalisation may place greater emphasis on risk and restriction.

Infrastructure represents the resources and hazards available at the societal level. This includes national broadband coverage, device accessibility, and the digital divide between urban and rural regions. Strong infrastructure enables integration, while uneven provision or inequities act as hazards that constrain it.

Policies capture the influence of macroinstitutions and governance structures. These include government programs, funding schemes, and regulatory frameworks that set conditions for integration. For example, decisions about national digital strategies or centralised learning management systems shape instructional environment practices even though teachers and students do not directly participate in those decisions.

Chronosystem: Temporal Influences

The Chronosystem in SEEP makes explicit the role of time in DTI across three interconnected scales: micro-time (moment-to-moment sequences), meso-time (recurring routines), and macro-time (long-term societal or historical shifts). DTI is thus understood as a temporal process, adapting and evolving across scales. The Chronosystem is positioned as the absolute outermost layer in the SEEP model because the temporal dimension encompasses and influences all other nested systems (Bronfenbrenner & Morris, 2006). It effectively extends the entire ecological environment into a new dimension by capturing the change and consistency over time that occurs within both the developing person and all surrounding environmental layers. While the SETI model acknowledged that its development was influenced by real-world events such as the COVID-19 pandemic (Crompton et al., 2023), it did not define how the dimension of Time itself shapes DTI. Drawing from Bronfenbrenner's bioecological theory (Bronfenbrenner & Morris, 2006), the Chronosystem captures the temporal dimension of development, recognising that the timing, sequencing, and duration of events play a crucial role in shaping processes and outcomes.

This temporal layer is divided into three interconnected time scales:

1. Micro-time refers to the immediate, moment-to-moment continuity or discontinuity within a specific activity or interaction. For example, a teacher's decision to redirect students to analogue resources when a DT malfunctions, or the rhythm of student engagement in a collaborative platform during one lesson.
2. Meso-time focuses on the consistency and recurrence of activities over extended intervals, such as days and weeks. For example, a teacher's recurring routine of reflecting on lesson analytics every Friday to adjust the following week's instruction.
3. Macro-time encompasses broader, long-term societal changes and historical events over an individual's lifespan and across generations, such as systemic educational reforms, technological revolutions (e.g., the rise of AI in education), and disruptive global events such as the pandemic that reshape the meaning and possibilities of DTI.

In this way, the Chronosystem highlights that DTI is inherently temporal. Practices emerge, adapt, and sometimes fade in response to both micro-level instructional environment dynamics and macro-level societal transformations. Including this layer ensures that SEEP reflects how DTI is enacted at a given point, but also how it evolves over time, adapts to changing conditions, and sustains or loses relevance in shifting educational landscapes. The empirical rationale for adding the Chronosystem as an explicit temporal dimension of SEEP is developed in Section 3.3.2, drawing on evidence at the micro-, meso-, and macro-time scales.

2.3.3. Conceptual Significance of SEEP

The components of SEEP set out above are not a list of parallel factors. They are designed to work together as a single explanatory mechanism, and the significance of the model lies precisely in how its components interrelate.

At the centre of the mechanism is the Person (i.e., Teacher), understood not as a bundle of static traits but as an active agent whose Attributes, Capacities, and Dispositions are brought into play through situated judgment. These Person-level resources do not, on their own, determine what happens in a classroom. They become consequential only when they are mobilised through the Process layer, the orchestration by which teachers interpret the immediate instructional environment, adapt their plans to it, and negotiate the use of digital tools with students in real-time. The Process layer is thus the mediating mechanism of the model: it is where the personal resources of the Person meet the structural conditions of the Microsystem and are converted into observable practice.

The Microsystem, in turn, is not a passive setting on which the Process layer acts. Its activities, roles, relations, and features constitute the material and relational arena that the teacher orchestrates, and its affordances and constraints shape what the Process layer can plausibly do in any given moment. The relationship between the Microsystem and the Process layer is therefore reciprocal: the Microsystem supplies the elements to be orchestrated, and the Process layer determines how those elements are mobilised and transformed in practice. Two teachers facing identical Microsystems can enact very different DTI, and the same teacher can enact different DTI across consecutive lessons, because the Process layer is the site where that variation is generated.

The outer ecological layers (Mesosystem, Exosystem, and Macrosystem) influence the mechanism through indirect pathways. Rather than acting directly on the Process layer, they shape the Microsystem and the Person, thereby defining the specific resources and constraints that the Process layer must navigate during enactment. The Mesosystem links the focal instructional environment to the other settings the teacher inhabits (staff room, professional learning community, family-school interface), and these interconnections feed back into the teacher's capacities and into the resources available in the Microsystem. Similarily, the Exosystem and Macrosystem set the institutional and societal conditions within which schools and teachers operate, shaping what is available, permitted, valued, or expected. These distal layers matter not because they determine practice directly, but because they shape the terrain for the Process layer.

Running through the whole mechanism is the Chronosystem, which renders the temporal dimension of DTI analytically tractable. Every interaction within the Process layer unfolds at micro-time; every routine that consolidates or loosens across weeks and terms unfolds at meso-time; every shift in the broader ecology of tools, pedagogies, and policies unfolds at macro-time. The Chronosystem is not a separate process happening alongside the others, but the dimension within which all the other layers operate, and it is what allows the model to account for how DTI evolves rather than merely how it presents at a single moment.

SEEP is a model in which personal resources (Person) are mobilised through situated orchestration (Process) within a specific instructional arena (Microsystem), under conditions shaped by broader ecological layers (Mesosystem, Exosystem, Macrosystem), and across multiple timescales (Chronosystem). Each component is necessary, but none is sufficient on its own. The Process layer is what binds them together into a mechanism: it is the site at which the Person's resources, the Microsystem's affordances, the outer layers' conditioning influences, and the Chronosystem's temporal influences meet and are converted into the practice that an observer sees in a classroom.

These refinements move SEEP from a static map of influences toward a developmental and explanatory account of how DTI unfolds in real-world settings. Importantly, SEEP was not derived deductively from PPCT alone, nor inductively from the Estonian empirical material in isolation, but abductively, through a sustained dialogue between the conceptual machinery of PPCT and the patterns of variation observed in classrooms where structural conditions for DTI were already in place. The model is the result of that dialogue: a conceptual structure shaped to make sense of empirical patterns that condition-based frameworks could not satisfactorily explain. The theoretical implications of these contributions are further elaborated in Section 4.2.1.

3. EMPIRICAL FOUNDATION: SUPPORT FOR SEEP FROM THE ESTONIAN CONTEXT

The preceding chapter conceptualised the SEEP model. It refines existing ecological models by incorporating two crucial, previously missing layers: a dynamic Process layer to explain how DTI is enacted, and a Chronosystem to explain when this enactment evolves over time. This addresses the key research gap where models mapped static influences but failed to explain the mechanisms of practice. SEEP thus provides a richer, process-level account of DTI.

However, to advance beyond conceptual refinement, the model must be examined in light of indicative empirical evidence. The Estonian DigiEfekt study provides a unique opportunity for such an examination. Estonia's education system offers near-universal access to digital infrastructure, comprehensive teacher training, and supportive policy frameworks, minimising structural barriers that often confound analyses of DTI. Within this high-connectivity context, substantial variation in classroom practice persists, making it an ideal testbed for investigating the process-level mechanism and temporal dynamics proposed in SEEP.

This chapter presents the empirical foundation for the SEEP refinement, recapitulating the methodology and key findings from the DigiEfekt study. Section 3.1 details the methodology; Section 3.2 reports the empirical findings on DTI practices, profiles, and their predictors; and Section 3.3 develops the empirical rationale linking these findings to each SEEP refinement.

3.1. Methodology: DigiEfekt Study in the Context of the Dissertation

This section presents the methodology of the DigiEfekt study as it relates to this dissertation, moving from context to procedure. Section 3.1.1 states the rationale for the study and positions Estonia as a critical case for examining process-level factors in DTI. Section 3.1.2 clarifies the author's own contribution to the DigiEfekt project and delimits the dissertation's analytical scope, distinguishing primary analytic material from corroborating evidence and descriptive context. Section 3.1.3 describes the postdigital Estonian context in which the data were collected. Section 3.1.4 details the sampling strategy and the characteristics of the teacher sample, and Section 3.1.5 summarises the ethical considerations that governed data collection. Sections 3.1.6 and 3.1.7 then describe the data collection instruments and the analytical procedures, respectively, with particular attention to how the structured observation protocols and semi-structured interview guides were designed for triangulation and to how the multinomial logistic regression in Article IV treated self-efficacy as a concept-driven weight rather than a covariate.

3.1.1. Rationale

The DigiEfekt study (May 2020–April 2023, see Figure 2), led by the University of Tartu and funded by the Estonian Ministry of Education and Research (project code DIGIVARA5), was a national research and development initiative aimed at generating an evidence base for enhancing teachers' meaningful integration of DT in general education. The study responded to a pressing need to move beyond infrastructure-focused metrics of digitalisation toward understanding *how* and *why* DT are used in instructional practice and how such uses relate to both cognitive and non-cognitive student outcomes. These aims were explicitly aligned with national education policy priorities, ensuring that the study's outputs could inform both school-level professional development and system-wide strategy. More specifically, the study was designed with four interlinked aims:

1. Framework development – to conceptualise different ways of using digital learning materials based on classroom observations (grades 3, 6, 9 in Estonian language, mathematics, and natural sciences), post-lesson interviews with teachers, and interaction log data from the Opiq e-textbook platform.
2. Quantitative description – to determine the prevalence of different usage types using both observation-based coding and Opiq log data.
3. Database construction – to integrate multiple data sources, including teacher and student questionnaires, student assessments, national registry data, and school- and class-level indicators, enabling multi-level analysis.
4. Predictive modelling – to develop and validate models forecasting the effects of different digital integration patterns on student outcomes, distinguishing predictors at individual and classroom levels.

Estonia's digitally mature education system, featuring near-universal connectivity, robust national platforms, and sustained teacher development investment, minimises the infrastructural barriers common in other contexts, making observed variation in DTI more plausibly processual than structural. The Estonian context is detailed in Section 3.1.3.

3.1.2. Author's Contribution and Dissertation Scope

While this dissertation is situated within the broader framework of the DigiEfekt research project, it is essential to delineate the specific datasets, analytical choices, and methodological contributions that constitute this independent work. The full DigiEfekt study collected a wide range of data, including extensive student learning outcomes in science, mathematics, and socio-emotional skills (see more Pedaste, 2023). Of the study's four interlinked aims, this dissertation focuses specifically on the first two (conceptualising DTI practices and identifying their teacher-level predictors) and is therefore scoped to the data sources that explain teacher enactment: classroom observations, post-lesson teacher interviews, and teacher surveys.

Within this scope, data sources are classified into three analytic categories: primary analytic material, corroborating evidence, and descriptive context as mapped in Table 1, which links each research question to its article(s), data sources, analytic status, and the SEEP element it grounds. The empirical findings associated with each row of this table are reported in Section 3.2, and their implications for each element of the SEEP model are developed in Section 3.3 and interpreted in the discussion in Section 4.1.

A clear distinction must also be made regarding the provenance of the research instruments. While the survey instruments used to assess digital readiness, self-efficacy, and attitudes were part of the DigiEfekt project's validated toolkit, the instruments designed to capture the dynamic, situated nature of classroom practice were developed by the dissertation author. This includes the design of both the structured classroom observation protocols and the semi-structured post-lesson interview guides. These two instruments were developed to operate in methodological synergy: the structured protocols provided the standardisation and inter-rater reliability required for a multi-researcher team to consistently record visible classroom interactions, while the semi-structured interviews complemented these observations by eliciting the underlying pedagogical rationales.

This dual approach enabled triangulation of teacher enactment, capturing both the visible orchestration of technology and the pedagogical reasoning behind specific instructional pivots. The analytical focus, the abductive development of the SEEP model, and the resulting process-oriented insights are the distinct intellectual contributions of the author, independent of the project's broader descriptive goals.

Table 1. Mapping of Research Questions, Articles, Data Sources, and SEEP Elements

RQ	Article / Source	Data Sources	Analytic Approach	Analytic Status	SEEP Element Grounded
RQ1 Conceptualisation of DTI and development of SEEP	Critical synthesis (Chapter 2; no associated empirical article)	Theoretical and conceptual literature on DTI, ecological systems theory, PPCT, orchestration, and entangled pedagogy	Critical synthesis and abductive theory-building	Conceptual	The SEEP model as a whole (all seven components)
RQ2 Distinct profiles and practices of DTI under comparable conditions	Article I (Raave et al., 2022)	169 classroom observations and post-lesson teacher interviews	Qualitative analysis of field notes and illustrative cases	Primary	Process layer (in-the-moment negotiation, adaptive pivots); Microsystem (heterogeneous learner ecologies within shared instructional settings)
	Article II	Lesson-level coding of classroom observations and post-lesson interviews	Hierarchical clustering (Ward’s method, Euclidean distance)	Primary	Process layer (within-teacher variation across consecutive lessons, indicating that the same teacher enacts different DTI in different moments)
	Article III	Lesson- and interview-level data aggregated to the teacher level	Latent Profile Analysis (six-profile solution)	Primary	Process layer (between-teacher variation under broadly comparable conditions, indicating that provision and disposition do not determine practice)

RQ	Article / Source	Data Sources	Analytic Approach	Analytic Status	SEEP Element Grounded
RQ3 Individual factors as predictors of integration profiles	Article IV	Teacher surveys: digital readiness, digital attitudes, self-efficacy	Multinomial logistic regression weighted by self-efficacy	Primary	Refined Person layer (differential prediction of profiles by readiness vs attitudes motivates the Capacities / Dispositions distinction; residual variation after personal predictors motivates the necessity of the Process layer)
—	Opanasenko, Pedaste & Siiman (2022, 2023)	Opiq e-textbook platform-trace logs (student interaction data)	Sequence analysis of recurring temporal patterns	Corrobo-rating	Chronosystem at meso-time (recurring rhythms of digital engagement across the school year, interpreted as downstream proxies of teachers' orchestration decisions)
—	DigiEfekt project context data (Pedaste, 2022; Pedaste, Raave & Baucal, 2023)	Sample composition; school level infrastructure and policy data; broader project findings on the institutional setting	Descriptive only	Descriptive context	Establishes the postdigital empirical setting (Estonia) within which the rest of the analysis takes place; not used as analytical material

3.1.3. Context

Estonia has been considered a leading example of DTI in education (see Mehisto & Kitsing, 2022). Since the mid-1990s, the country has pursued a comprehensive and sustained strategy that includes robust school infrastructure, systematic teacher training, and the development of educational software (Põldoja, 2020). Key national initiatives, such as Tiger Leap, Digital Turn, and the e-Schoolbag (Põldoja, 2020), and more recently AI-Leap (EMER, 2025), have played a central role in embedding DT into everyday teaching and learning.

With nationwide broadband, widespread one-to-one device access, and digital infrastructure integrated into public services (Põldoja, 2020), Estonia has already overcome many of the logistical and infrastructural barriers that continue to challenge other systems (Pedaste & Bardone, 2023) and is ranked with the highest digital readiness compared to other EU countries (Beblavý et al., 2019). Moreover, its teacher professional standards embed digital competence as a core teaching requirement, emphasising not just tool use but pedagogically meaningful integration (Mukan et al., 2019). At the same time, the Estonian curriculum grants substantial teacher autonomy (see Pedaste & Bardone, 2023). Taken together with a high-performing educational system (Estonia leads Europe and sits in the global top tier on recent PISA tests; see OECD, 2023b), these features make Estonia a compelling context for exploring the practice-level dynamics of DTI.

This characterisation of Estonia as a digitally mature system can be productively read through the lens of postdigital education, which frames the digital and the non-digital as no longer meaningfully separable in everyday educational practice (Fawns, 2018). In a postdigital setting, technology has receded into the background as invisible infrastructure rather than a novel addition that demands separate justification (Jandrić & Knox, 2021), and the explanatory variable for what happens in classrooms shifts away from access and toward teacher agency, pedagogical reasoning, and situated judgment. Estonia, with its near-universal infrastructure and decades of normalised digital practice, exemplifies this condition. It is precisely in such a context that the question "Why does DTI still vary so much when access does not?" becomes most acute, and where a process-oriented model like SEEP has the most explanatory role to play. The postdigital framing therefore, reinforces, rather than supplements, the rationale for studying DTI at the level of teacher orchestration: when technology is no longer the variable that distinguishes one classroom from another, what remains is the situated activity through which teachers integrate it.

A contextual note is warranted regarding the COVID-19 situation in Estonia during the data-collection period. Although the acute phase of the pandemic had passed, intermittent disruptions still occurred: individual classes or, at times, entire schools moved to short periods of home-based learning and hybrid arrangements were occasionally used to include students isolating at home. Moreover, prior emergency remote teaching had already accelerated teachers' and students' familiarity with digital platforms and routines. These conditions likely elevated baseline levels of digital use and shaped pragmatic choices about tools and formats, making observed practices partly contingent on residual pandemic-era arrangements.

3.1.4. Sampling

The DigiEfekt research study employed a purposeful sampling strategy to ensure maximum variation across schools and teacher participants while retaining comparability across key parameters. Unlike random or representative sampling, this approach was chosen because the aim was to identify and compare patterns of DTI rather than to estimate prevalence in the population. The selection was based on three key criteria:

1. Academic Performance – measured using results from national examinations and standardised academic tests.
2. Digital Competence – for teachers, this was assessed via self-evaluations; for students, both self-assessment and results from a digital competence test (including practical tasks) were used.
3. School Satisfaction – measured through a national survey administered to teachers, students, and parents.

Each criterion was dichotomised into high and low categories, producing eight typological combinations (e.g., high-high-low). Schools were ranked within each category for typicality, and invitations were extended sequentially until quotas were met. This approach aimed not to produce a statistically representative sample of all Estonian schools, but to capture a diverse range of contexts in which DTI occurs. This process resulted in 14 participating schools distributed across different regions and varying considerably in size, ranging from 126 to 995 students and from 17 to 94 teachers. The observed classes included approximately 959 students across 62 classes, spanning the end grades of each primary and lower secondary school level in Estonia (3rd, 6th and 9th grades).

Within these schools, the focal teacher sample comprised 93 educators, with 79 teachers from 13 schools forming the final analytical sample based on their integration of DT into lessons. The sample teachers were distributed across grade levels, with 24% teaching 3rd grade, 38% teaching 6th grade, 24% teaching 9th grade, and the remaining 14% teaching both 6th and 9th grades. In line with the Estonian system, 3rd-grade teachers typically taught Estonian language, mathematics, and natural sciences, while 6th and 9th-grade teachers specialised in a single subject. Subject representation among 6th and 9th-grade teachers included Estonian language (28%), mathematics (44%), and natural sciences (28%). Additional information on the sampling procedure and the sample overview can be seen in Pedaste, Raave & Baucal (2023).

The sample was predominantly female (84 teachers, 90%) (matching the national average on the data collection school year 2021/22, Haridussilm, n.d.), with an average age of 48.2 years (SD = 9.1) (close to the demographics average of 49 years, see OECD, 2025). Teachers reported an average of 20.2 years of teaching experience (SD = 9.9) (close to the demographics average of 22.7 years of experience, see Taimalu et al., 2019), with the majority completing their qualifications in the 1990s and early 2000s. Educational attainment was high: 75%

held a Master's degree, 20% a Bachelor's degree, and small proportions held secondary or doctoral-level qualifications. Most teachers (67%) had acquired teacher education in a traditional integrated format, while others had sequential, fast-track, or non-pedagogical routes; about 3% reported lacking full subject or pedagogical qualifications (based on Haridussilm, n.d., the national average on the data collection school year 2021/22 was 18%). Further details on the teacher sample can be seen in Pedaste (2022).

3.1.5. Ethical Considerations

The study received formal approval from the University of Tartu Research Ethics Committee under protocol codes 327/T-8 (19.10.2020) and 347/M-23 (16.06.2021), ensuring that all research activities adhered to national and institutional ethical guidelines for educational research.

Participation by schools, teachers, and students was entirely voluntary. All participants (and parents/guardians in the case of minors) were fully informed of the study's aims and procedures prior to data collection and provided written consent. No incentives were offered, and participants were reminded that they could decline or withdraw at any stage without any negative consequences. Moreover, written informed consent was obtained from all adult participants, with parental or guardian consent and student assent required for minors.

Observations were scheduled in coordination with teachers to minimise disruption, taking place in situ during regular classroom activities. Researchers emphasised that their role was purely observational and non-evaluative, while surveys were arranged in consultation with school staff to further reduce disturbance.

To ensure confidentiality and anonymity, all data were pseudonymized prior to analysis. Data handling followed strict security protocols as all materials were stored on access-controlled servers with access limited to authorised team members, and full compliance with General Data Protection Regulation regulations was maintained. Fully anonymised datasets were deposited in the DataDoi repository to ensure long-term open access.

3.1.6. Data Collection

The data used in this dissertation, collected within the DigiEfekt study, integrated multiple complementary sources. Specifically, it combined classroom observations of 169 lessons, post-lesson teacher interviews, and teacher surveys on self-efficacy, digital readiness, and attitudes, together with student surveys on digital competence and digital trace data from the Opiq e-textbook platform. In addition, school background data was collected on student composition, as well as available resources and infrastructural barriers, providing an important contextual layer. The data was collected during the school year 2021/22 as part of the DigiEfekt study. See Figure 2 for a comprehensive overview of the DigiEfekt study design and data collection. Next, we describe how and what data were collected only for the original publications forming the basis of this dissertation.

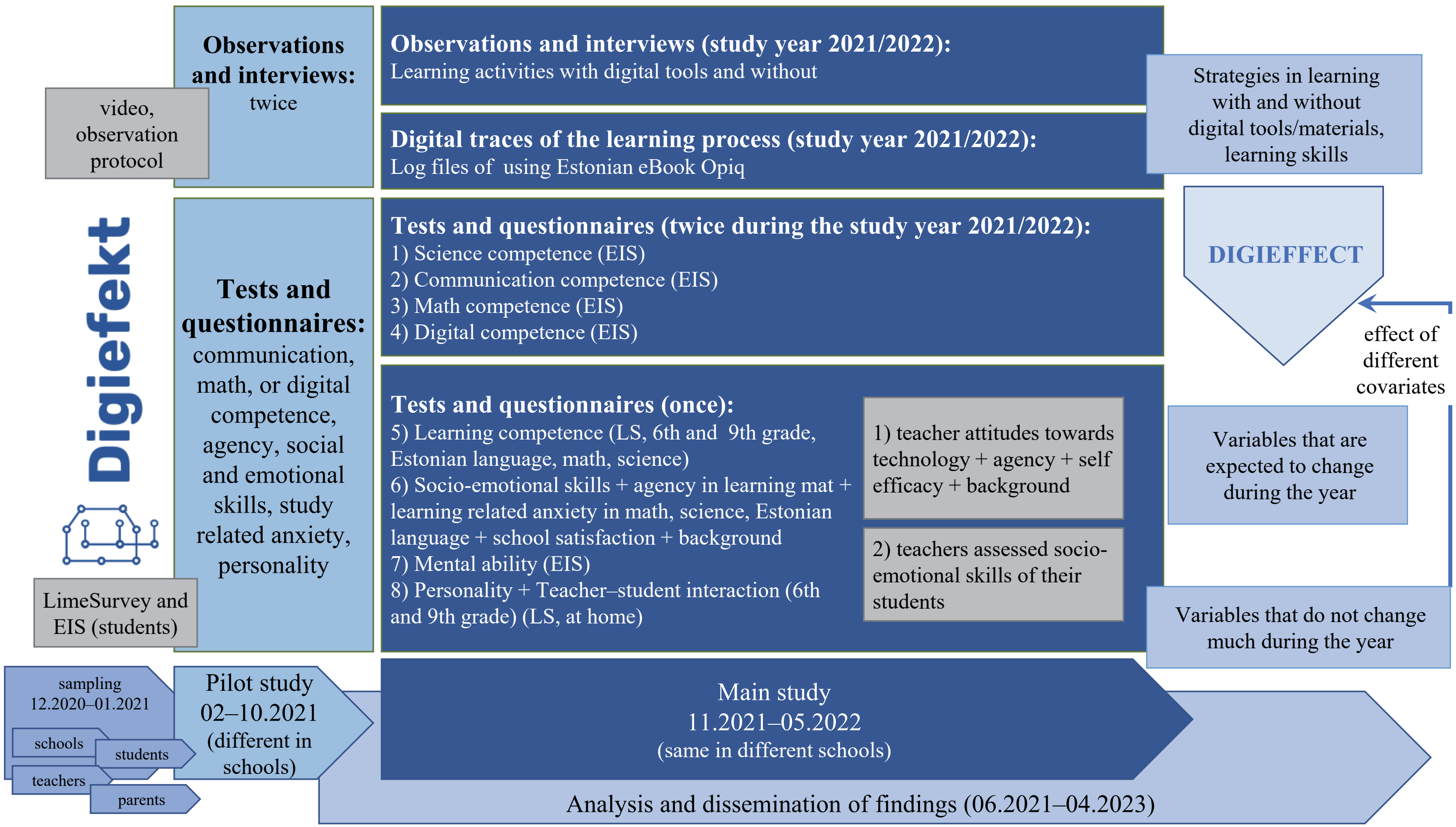

Figure 2. The DigiEfekt Study Design.

Classroom Observations

A total of 169 lessons were observed, of which 138 lessons (82%) involved DTI. Observations were conducted across all three focal grades (3, 6, and 9) and subject areas (Estonian language, mathematics, and natural sciences). To ensure authenticity, observations were scheduled randomly within the available timetables of participating schools, coordinated directly with teachers and school leaders. This approach minimised the risk of demonstration bias and ensured that lessons were reflected in situ, in everyday teaching practice, rather than in staged or specially prepared sessions.

The observation team consisted of seven trained researchers who completed a one-month calibration and training phase co-led by the dissertation author prior to data collection. Training familiarised the team with the observation protocol and coding framework, involved practice sessions analysing multiple lesson recordings to identify and code uses of DT, and included iterative feedback discussions to resolve ambiguities in coding decisions. Inter-rater reliability was established at Fleiss' $\kappa = .79$, indicating substantial agreement across observers.

During classroom observations, researchers systematically documented the sequence of lesson activities using a structured protocol, recording detailed notes on activities, task types, and interaction patterns. For every instance of DT use, observers noted the specific tool employed, how it was used in the context of the lesson (i.e., in what type of activity, e.g., such as content presentation, interactive practice, assessment, or collaboration), and the instructional task in which it was embedded.

All field notes were recorded on a structured observation sheet designed to capture both categorical codes and rich qualitative descriptions. The SAMR model (Puentedura, 2006) was used as the lens for categorising *how* technology was integrated, distinguishing four levels: Substitution, Augmentation, Modification, and Redefinition. At the Substitution level, DT functions as a direct replacement for non-DT with no functional change (e.g., projecting a text instead of writing it on the board). Augmentation similarly involves substitution but with functional improvements, such as automated feedback or digital annotation. Modification enables a significant redesign of tasks, for instance, allowing real-time collaborative writing. Finally, Redefinition refers to the creation of entirely new tasks that would not be possible without DT, such as facilitating hybrid learning across locations.

Teacher Interviews

Teacher interviews were conducted immediately after each observed lesson, which included DTI. This timing was intentional to capture the teacher's proximal pedagogical reasoning, as the thought processes and decision-making factors were still fresh in their minds, thereby reducing recall bias. A semi-structured interview protocol was used to ensure consistency across researchers while allowing flexibility to probe deeper into individual cases. The protocol included open-ended questions about the objectives of DTI within lesson aims, inquiries into tool selection and the alternatives considered, and reflections on how DT supported the intended learning goals.

The Technology-Enhanced Learning framework developed by Kirkwood and Price (2013) guided the thematic structure and subsequent coding of interview responses. Within this framework, teachers' reasons for using technology were grouped into three categories. Operational Improvement refers to using technology to streamline processes, improve efficiency, or facilitate lesson management. Quantitative Change captured practices aimed at increasing the amount or speed of student practice, expanding access to resources, or enhancing engagement opportunities without fundamentally altering the nature of the learning task. Finally, Qualitative Change described instances where technology enabled new forms of learning, deeper cognitive engagement, or complex problem-solving that would be difficult or impossible to achieve otherwise.

Each interview lasted approximately 10–15 minutes and was conducted in the teacher's classroom or another quiet space, such as the teachers' lounge, to ensure comfort and minimise interruptions. Researchers documented the conversation directly in the structured interview protocol as it took place, noting key statements verbatim, representative excerpts, and illustrative examples provided by the teacher.

During the interview, researchers engaged in member checking by paraphrasing or summarising the teacher's responses in real time and, when uncertain, explicitly asking the teacher to confirm whether the interpretation was accurate. This immediate clarification ensured that any ambiguities were resolved on the spot and that the researcher's notes accurately reflected the teacher's intended meaning. This process strengthened the credibility and trustworthiness of the qualitative data by grounding the coding categories in participants' own validated perspectives.

Teacher Surveys

Three validated self-report instruments were administered to all participating teachers to capture individual-level predictors of DTI. These instruments were selected to reflect self-efficacy, digital readiness, and digital attitudes and to provide quantitative variables for subsequent statistical modelling. Teachers completed the questionnaires digitally at their own convenience within a specified response window, ensuring flexibility and minimising disruption to teaching schedules.

1. Self-Efficacy
    - Instrument: Short form of the Teacher Sense of Efficacy Scale (Tschannen-Moran & Woolfolk Hoy, 2001).
    - Focus: Two subscales (Instructional Strategies and Student Engagement) chosen for their direct relevance to teachers' ability to design and deliver effective DTI.

- Example items:
  - How much can you do to motivate students who show low interest in schoolwork? *(Instructional Strategy)*
  - To what extent can you provide an alternative explanation or example when students are confused? *(Student Engagement)*
- Scale: 7-point Likert-scale (1 = Very little, 7 = A lot).
- Scoring: Mean scores were calculated separately for each subscale; higher scores indicated greater perceived self-efficacy.
- Validation: See consolidated CFA discussion below; full results in Article IV.

2. Digital Readiness
- Instrument: Developed from the DigCompEdu framework (Redecker, 2017).
- Focus: Assessed both perceived problems and perceived opportunities related to DT use in teaching.
- Example items:
  - [There is a] lack of digital equipment (e.g. desktops, laptops, tablets, mobile phones, projectors, TVs). *(Problems, reverse coded)*
  - I have the necessary technical and pedagogical skills to use digital devices in teaching. *(Opportunities)*
- Scale: 4-point Likert-scale (1 = Strongly disagree, 4 = Strongly agree).
- Scoring: Two subscales (problems and opportunities) were combined into a single higher-order construct to reflect overall readiness.
- Validation: See consolidated CFA discussion below; full results in Article IV.

3. Digital Attitudes
- Instrument: Adapted from the Theory of Planned Behaviour (Ajzen, 1991) to the context of DTI in teaching.
- Focus: Three components: Attitudes toward behaviour (beliefs about the value of digital integration), Perceived behavioural control (beliefs about one's capacity to use DT effectively), and Behavioural intention (willingness to integrate technology in future practice).
- Example items:
  - I get confused when I have to use a lot of different digital environments to teach. *(Attitudes Related to Behaviour, reverse coded)*
  - I have no issues with using different digital devices. *(Perceived Control)*
  - If I can give feedback to students orally in class or in a digital environment, I prefer the digital environment. *(Behavioural Intention)*
- Scale: 5-point Likert-scale (1 = Strongly disagree, 5 = Strongly agree).

- Scoring: Subscale scores computed separately; higher values indicate more positive attitudes, greater perceived control, or stronger intentions.
- Validation: See consolidated CFA discussion below; full results in Article IV.

Across the three instruments, CFA results were mixed. Self-efficacy showed strong incremental fit (CFI = .989, TLI = .984) but elevated RMSEA (.099); digital readiness showed adequate fit on incremental indices (CFI = .913, TLI = .899) but high RMSEA (.133); and digital attitudes showed similar incremental fit (CFI = .916, TLI = .874) with RMSEA of .180. All three models were retained on theoretical grounds, but findings derived from these instruments are interpreted with awareness of these measurement limitations, particularly for digital attitudes, where model fit was weakest.

Furthermore, teachers completed a demographics questionnaire containing items on age, gender, teaching experience (in years), workload, subjects taught, grade levels taught and educational qualifications (see Figure 2). This information was collected to provide a richer contextual understanding of the teacher sample, enabling the interpretation of observed practices and survey responses in light of participants' professional backgrounds.

3.1.7. Data Analysis

The analytic procedures in the DigiEfekt study combined qualitative and quantitative methods to generate a multi-layered empirical base for refining the SETI model into the SEEP model.

Data Coding and Reliability

Observation and interview data on the use of DT were coded deductively. Observational data were coded according to the SAMR model (Substitution, Augmentation, Modification, and Redefinition). Follow-up interview utterances describing teachers' rationales for DTI were coded using the Technology-Enhanced Learning framework (Operational Improvement, Quantitative Change, and Qualitative Change) (Kirkwood & Price, 2013).

The reliability of the coding was checked in two stages. During the training phase, inter-rater reliability was calculated using Fleiss' Kappa, which yielded a coefficient of .79, indicating substantial agreement. For the final dataset, reliability was assessed on 60 lessons coded independently by two different pairs of coders. Cohen's Kappa was .91 for the observation data (SAMR) and .79 for the interview data (TEL), both reflecting strong consistency.

Descriptive Statistics

In general, descriptive statistics were calculated either in SPSS 28.0 or in JASP version 0.18.3, depending on the dataset. For all datasets, however, standard descriptive measures, including means, standard deviations, and range, were produced to provide an overview of variation. For the observation and interview data (see Article III), additional steps were necessary because the number of coded instances differed across teachers. To ensure comparability, raw counts of SAMR levels and Technology-Enhanced Learning reasons were converted into proportions. Furthermore, because these variables were later used in Latent Profile Analysis (LPA), which assumes by default distributional properties of the input data, their distributional properties were assessed using the Shapiro-Wilk test. None of the DTI variables followed a normal distribution ($p < .001$ for all), and this non-normality was accounted for in LPA by applying robust estimation.

Cluster Analysis

The analysis of DTI practices at the lesson level was conducted using hierarchical clustering (see Article II). The data consisted of coded observations of classroom practices and interview segments linked to individual lessons, producing numerous concrete and observable instances of DTI. Hierarchical clustering was implemented in SPSS (v.28) using Ward's method with Euclidean distance, after standardising variables to ensure comparability. The number of clusters and their initial centroids were determined by inspecting the dendrogram and then refined using k-means clustering. This approach was selected because it is exploratory and data-driven, grouping lessons based on similarity without requiring prior assumptions about the number of clusters. It is particularly suited for identifying recurring practice patterns across lessons, which can be understood as descriptive groupings of observed behaviours rather than latent constructs. Robustness was checked through split-half validation, re-running the clustering on random halves of the data, and through ANOVA with η^2 values to identify which variables most strongly discriminated between clusters.

In the initial lesson level clustering, reasons were initially separated into teacher-focused and student-focused purposes (e.g., practical support for the teacher vs. practical support for students) (see Article II). This separation increased the granularity of the analysis and helped to detect subtle differences between lessons. However, a reanalysis presented in the later report aggregated these categories, showing that the clusters remained substantively similar even when teacher- and student-focused purposes were combined (see Raave et al., 2022), suggesting that such distinctions did not meaningfully affect the overall clustering and profile solutions. On this basis, the aggregated form was retained in later analyses, as it avoided redundancy, simplified interpretation, and reflected the fact that both perspectives represent the same underlying pedagogical orientations (practicality, engagement, and learning).

In contrast, the analysis of DTI profiles at the teacher level employed LPA (see Article III). For this analysis, coded lesson and interview data were aggregated per teacher using averages and proportions. This approach normalised for differences in the number of lessons per teacher, ensured comparability across indicators derived from both data sources, and captured teachers' relative tendencies in DTI across multiple lessons. In doing so, it provided a basis for LPA to identify profiles that reflect orientations within the sample rather than single-lesson variation. Unlike practices, which are directly observable, teacher profiles represent underlying patterns that cut across lessons. LPA was conducted in Mplus (v.7.4) using the robust maximum likelihood estimator to account for non-normal distributions. Models with increasing numbers of profiles were compared sequentially, and solutions were evaluated using multiple fit indices (AIC, BIC, SABIC), likelihood-ratio tests (VLMR, LMR, BLRT), and entropy. The final profile model was selected for its statistically significant likelihood-ratio test, high entropy values, and interpretability in light of theoretical frameworks of DTI. Teacher cluster membership probabilities were also calculated, allowing for the assessment of how consistently individual teachers aligned with their assigned profiles. Robustness was further checked by excluding rare practices (i.e., modification and redefinition), which otherwise destabilised the models, and by confirming the distinctiveness of profiles through post-hoc ANOVAs.

Variables with very low frequency, such as modification and redefinition, were treated differently across the two analyses (Articles II and III). In the hierarchical clustering, these variables were retained during computation because the distance-based algorithm is robust to their low occurrence; however, they contributed minimally to group differentiation and were therefore excluded from the interpretation of cluster solutions. In the LPA, by contrast, such rare variables acted as statistical outliers that destabilised the mixture models and hindered convergence. To ensure model stability and interpretability, they were excluded from the estimation of teacher-level profiles. This distinction reflects the different methodological logics of the two approaches: hierarchical clustering tolerates low-frequency indicators without distortion (Manning, Raghavan, & Schütze, 2008), whereas LPA requires sufficient variance in each indicator to estimate reliable latent subgroups (Williams & Kibowski, 2016).

Predictive Analysis

In Article IV, to examine how teacher characteristics influenced their classroom DTI practices, a Multinomial Logistic Regression (MLR) model was employed. Because the outcome variable was categorical, the MLR framework was suitable for predicting membership across six empirically derived DTI profiles. The analysis was weighted by teachers' self-efficacy scores. Rather than including self-efficacy as a covariate, it was applied as a concept-driven weight in line with Bandura's Social Cognitive Theory (Bandura, 2001), which positions self-efficacy as the proximal psychological engine that enables readiness and attitudes to be translated into enacted practices. This weighting procedure meant that each teacher's record contributed to the model in proportion to their self-efficacy score, thereby foregrounding the practices of teachers for whom self-efficacy was not a limiting factor. In this way, the model produced weighted summaries that reflected the theorised amplifying role of efficacy, allowing a sharper examination of how digital readiness and attitudes predicted profile membership when teachers were already confident and predisposed to act.

The MLR model was based on survey data from teachers. The independent variables were digital readiness and digital attitudes, while the dependent variable was membership in one of six distinct DTI profiles previously identified through LPA. The analysis was conducted in JASP version 0.18.3 using maximum likelihood estimation. The reference category was defined as the group of teachers whose practices were the least diverse and who reported the lowest overall levels of digital readiness and attitudes. This group was chosen because it provided a stable baseline against which other, more varied integration patterns could be meaningfully contrasted. The model generated estimated coefficients (β) representing the log-odds of belonging to each profile relative to the reference group. Coefficients were evaluated at $p < .05$, and odds ratios were calculated through exponentiation of the coefficients.

3.2. Empirical Findings on DTI

This section reports the empirical findings from the DigiEfekt study that inform the SEEP model. Section 3.2.1 describes the characteristics of the teacher and student samples. Section 3.2.2 then reports the prevalence and forms of DTI observed in classrooms (the what and how of integration), while Section 3.2.3 presents the reasons teachers articulated for their DTI decisions (the why). Section 3.2.4 reports the six teacher-level practice profiles identified through latent profile analysis, and Section 3.2.5 presents the predictive analyses that link individual teacher characteristics (readiness, attitudes, self-efficacy) to those profiles. The empirical rationale these findings provide for each SEEP refinement is then developed in Section 3.3.

3.2.1. Characteristics of the Sample

Teachers

As shown in Article IV, teachers' reported self-efficacy was strong, with an overall mean of 5.20 (SD = .82) on a 7-point scale, indicating high confidence in their ability to plan and deliver instruction and engage students. Teachers also reported generally higher levels of digital readiness (M = 2.90, SD = .53 on a 1–4 scale) (Article IV). Moreover, teachers expressed generally positive digital attitudes (M = 3.93, SD = .63 on a 1–6 scale) (see Article IV).

Students

Pedaste, Raave & Baucal (2023) report that students' digital competence showed relatively high levels of between-class variation compared to other competencies (see Pedaste, Raave & Baucal, 2023). Intraclass Correlation Coefficients (ICCs) ranged from 21.2% to 52.8% across the dimensions, with class-level dispersion values ranging from 210.272 (programming digital content) to 772.616 (behavioural attitudes). This indicates that a substantial portion of the variance in digital competence was attributable to the class or teacher, rather than solely to individual student differences.

3.2.2. Prevalence & Forms of Digital Technology Integration: "What" & "How"

General Overview

As shown in Article I, across the observed 169 lessons, 82% actively incorporated DT, in which we identified 269 distinct learning activities leveraging DT. The tools implemented were primarily categorised as content-focused resources (63%), complementing the use of process-supporting tools. Content resources prominently included online and interactive learning materials (33%), such as LiveWorksheets and GeoGebra, along with online quizzes and games like Kahoot and Quizizz (12%), and video platforms (10%). Process-supporting tools, utilised 37% of the time, included essential applications such as presentation software and note-taking tools.

Regarding how technology was integrated, the predominant way was substitution (67% of the observed activities). The most prevalent specific substitution use, constituting 54% of identified activities, was displaying learning content (e.g., using presentation software such as PowerPoint). Other substitution uses (13% of the activities) included consolidating content and tools in a single environment (e.g., using a platform like Google Classroom). Augmentation was observed in 26% of the activities, including the use of technology for automatic control and feedback, which represented 21% of the uses, and interaction through technology, such as with Answergarden (5%). Modification (e.g., simulations) accounted for 2% of uses, and redefinition accounted for 5% of uses by facilitating hybrid learning.

Distinction per Grade and Subject

As shown in Raave et al. (2022), DT was used most frequently in the 6th grades (83%) of observed lessons, followed closely by the 9th grades (80%) and the lowest rate of integration was found in the 3rd grades (76%). When looking at the way of use (SAMR levels), Substitution occurred almost equally across all grade levels (Raave et al., 2022). However, augmentation and modification were observed more frequently in the 6th grade. Conversely, the highest level of transformative use, redefinition, was most common in the 3rd grades, while it was entirely absent in the 9th grades (Raave et al., 2022).

Among the subjects (Estonian language, mathematics, and natural sciences), use was highest in natural sciences (89%). The rate was slightly lower in Estonian language lessons (77%) and lowest in mathematics lessons (75%). Per SAMR, substitution was most prevalent in natural sciences and least common in mathematics, while augmentation was employed more often in mathematics lessons than in other subjects. Modification was seen most often in natural sciences, but was not observed in Estonian language lessons; redefinition, likely incidentally, was used most frequently in Estonian language classes.

3.2.3. Reasons for Digital Technology Integration: "Why"

General Overview

As shown in Article III, the underlying motivations (why technology was used), differentiating between operational, quantitative (engagement), and qualitative (cognitive) goals, showed that operational improvement, meaning streamlining tasks for convenience and efficiency, was the most common objective overall (45%). Qualitative improvement, or enhanced learning, focusing on cognitive skill development and deeper understanding, followed by 32% and quantitative improvement, or enhanced engagement, aiming for motivational and emotional improvement, accounted for 23% of reasons.

Within operational improvement, the most prevalent sub-goals were facilitating access to learning activities, content, and materials (19% of reasons), and leveraging the availability of ready-made learning content and resources (14% of realsons) (Raave et al., 2022). For instance, teachers noted that DT provided a convenient and accessible way to perform routine tasks, such as looking up word forms using online dictionaries or accessing materials for group reading (Article III). The pre-existence of usable materials, such as a Quizizz or Kahoot! quizzes, was also cited as an operational benefit because a quiz could be reused multiple times, thereby simplifying planning and assessment (Article III). Furthermore, 12% of the rationale was dedicated to enhancing monitoring and enabling automatic feedback on learning processes (Raave et al., 2022).

For qualitative change aimed at improving comprehension and further supporting cognitive skills, common reasons included practising and consolidating learned material (14% of reasons), and activating prior knowledge to foster deeper understanding (13% of reasons) or simply acquisition of new knowledge or skills (3% of reasons) (Raave et al., 2022). In some instances, utilising DT for merely displaying exercises (a substitution level use) was noted to support qualitative changes by enabling personalised learning paths and independent study, allowing students to engage with content at their own pace and revisit materials, thereby fulfilling individual needs (Article III).

More advanced uses, such as DTI for simulations or augmented reality experiences (modification and redefinition levels), were specifically intended to achieve qualitative change by enabling experimentation in simulated environments to provide better understanding and hands-on exploration of concepts that would otherwise be difficult to replicate physically (Article III). Tools like Answergarden were used to foster reflection by prompting students to engage with each other's responses and stimulate deeper thinking, while also supporting participation and motivation; in this way, they served both learning (qualitative change) and engagement (quantitative change) objectives simultaneously (Article III).

The third category, enhanced engagement, focused on motivational and emotional impacts (a quantitative change). Generating interest and maintaining student attention was the most cited sub-reason within this category (15% of reasons), driven by the understanding that simply using exciting media, such as a video projection, was something students enjoyed (Article I). Other aims included fostering positive emotions and establishing a safe learning environment (4% of reasons), and diversifying learning activities (4% of reasons) to sustain student interest (Article I).

Distinction per Grade and Subject

Raave et al. (2022) further show that operational improvement remained relatively constant across the 3rd, 6th, and 9th grades. However, the 6th grade exhibited the highest frequency of use intended for both qualitative change (enhanced learning) and quantitative change (enhanced engagement). Moreover, the 3rd grade utilised DT for qualitative change somewhat less frequently than the 6th grade, but employed it for quantitative change at a frequency similar to the 9th grade. Conversely, the 9th grade showed the lowest frequency of DT use intended for qualitative change.

Natural sciences lessons demonstrated the highest frequency of DT use for both operational improvement and qualitative change. Using DT for quantitative change was similar in natural science and mathematics lessons. Estonian language lessons used DT least frequently across all three key categories.

3.2.4. Digital Technology Integration

Lesson Level Distinction of Practices

The lesson level clustering (Article II) revealed four distinct practice types (Introducing, Motivating, Facilitating, and Deepening) primarily distinguished by their pedagogical purposes, with Quantitative Change (Enhanced Engagement) contributing the strongest distinction among variables ($\eta^2 = .603$), followed by Qualitative Change (Enhanced Learning) ($\eta^2 = .467$), and Augmentation use ($\eta^2 = .419$). This analysis demonstrated the diversity of DTI within classrooms and underscored that practices vary by the pedagogical intentions guiding each lesson. The identified practices were as follows:

1. Introducing (50%) practices represented the most frequently observed cluster. In this type, teachers integrated DT less often than the overall lesson average, relying primarily on Substitution. A defining characteristic was the lack of a strong pedagogical objective for DT use. When present, the purpose most

often related to Operational Improvement. This type suggests early-stage or trial uses of DT, and was identified across varied subject areas.

2. Deepening (24%) represents the most varied use of DT among observed lessons. Practices in this cluster frequently employed both Substitution and Augmentation, with the central and most prominent objective being Qualitative Change (Enhanced Learning). Lessons characterised by deepening practices emphasised using DT affordances to support in-depth learning, comprehension, and cognitive engagement. These practices were most often observed in mathematics lessons.
3. Motivating (20%) practice integrated DT more frequently than the overall lesson average, with the dominant mode of use being Substitution. The most prevalent purpose was Quantitative Change (Enhanced Engagement), while Operational Improvement and Qualitative Change appeared at levels close to the overall average. This type emphasises the use of DT for stimulating interest and participation, and it was particularly common in natural sciences lessons.
4. Facilitating (6%) practices resembled the Motivating type in using DT more frequently than the average lesson, again predominantly through Substitution. However, their objectives were more diverse. These lessons most often focused on Operational Improvement alongside Qualitative Change (Enhanced Learning). This type is characterised by balancing streamlining processes with deeper learning aims, and was observed across multiple subject areas.

Teacher Level Distinction of Profiles

Teacher-level LPA (Article III) moved beyond single lessons to identify broader pedagogical orientations by aggregating lesson and interview data per teacher. The resulting six profiles should be interpreted not as fixed categories but as average orientations, sort of a teacher's "centre of gravity" tendency.

This analysis identified six distinct profiles, each characterised by unique patterns of how technology was used (Substitution and Augmentation) and why it was used (Operational Improvement, Quantitative Change, and Qualitative Change). Uses of Modification and Redefinition were excluded from the model because of their rarity (mean occurrences of 2% and 2.4%, respectively), which threatened model stability. The most powerful variables distinguishing the six profiles were the pedagogical purposes of integration, specifically Qualitative Change ($\eta^2 = .922$), Operational Improvement ($\eta^2 = .877$), and Quantitative Change ($\eta^2 = .770$). The identified profiles were as follows:

1. Motivating Facilitators (28%). The largest profile, where teachers rely mainly on substitutional technology use, with only occasional augmentation. Their practice emphasises Operational Improvement and Quantitative Change (enhanced engagement), focusing on keeping students involved and motivated.

2. Depth Facilitators (23%). This profile combines substitution with some augmentation, using DT to foster Qualitative Change (enhanced learning) and, secondarily, Operational Improvement.
3. Efficiency Engineers (18%). These teachers rely almost exclusively on substitution, focusing overwhelmingly on Operational Improvements. They use DT primarily to increase efficiency (e.g., automation, monitoring, feedback) rather than to enhance engagement or learning. This group served as the reference category in subsequent regression analysis.
4. Engaging Innovators (10%). This group employs a mix of substitution and augmentation to achieve both Quantitative Change (engagement) and Qualitative Change (learning).
5. Depth Divers (10%). Like Depth Facilitators, Depth Divers integrate both substitution and augmentation with a strong emphasis on Qualitative Change. They differ by making heavier use of augmentation to foster higher-order thinking and inquiry-based learning.
6. Motivating Traditionalists (10%). This group resembles Motivating Facilitators in using substitutional technology to encourage quantitative change (student engagement). However, they invest little in Operational Improvements, maintaining more traditional instructional structures.

3.2.5. Predictors of Teacher Practices

In Article IV, an MLR model, weighted by teacher self-efficacy, was used to determine how individual characteristics predict membership in these six profiles. In the MLR, the Efficiency Engineers profile was used as the reference category. This choice was made because Efficiency Engineers represented the most stable and least diverse integration pattern, characterised almost exclusively by substitution for operational purposes. Using this group as the baseline provided both statistical stability and a conceptually meaningful contrast, allowing the analysis to highlight the predictors of moving beyond efficiency-focused use toward engagement- and learning-oriented practices.

MLR demonstrated differentiated pathways. Digital attitudes, particularly motivation and affective dispositions, were the strongest predictors of practices oriented toward motivational goals (e.g., Motivating Facilitators, Motivating Traditionalists). By contrast, digital readiness was more closely linked to cognitively demanding practices (e.g., Depth Facilitators, Depth Divers). The only negative effect observed was for readiness predicting membership in Motivating Facilitators, suggesting that teachers with higher readiness were less likely to remain in profiles characterised by limited, substitution-heavy practices.

More specifically, for the Motivating Facilitators profile, digital attitudes significantly increased the likelihood of membership ($OR = 2.300$, $p = .012$), while digital readiness was a strong negative predictor ($OR = .135$, $p < .001$), indicating that higher readiness reduced the probability of belonging to this substitution-oriented group. For the Depth Facilitators profile, both digital attitudes (OR = 4.007, $p < .001$) and readiness (OR = 2.487, $p = .013$) were significant positive predictors, highlighting the combined role of dispositions in enabling this deeper integration approach.

In contrast, the Engaging Innovators profile was most strongly predicted by digital readiness (OR = 11.332, $p = .004$), representing the single most powerful predictor effect in the model. Digital attitudes were not significant for this group (OR = .820, $p = .697$). Similarly, readiness also significantly predicted membership in the Depth Divers profile (OR = 5.311, $p = .017$), underscoring its role in explaining participation in depth-oriented practices. Finally, for the Motivating Traditionalists profile, digital attitudes were the only significant predictor (OR = 2.228, $p = .026$).

Moreover, it is relevant to point out that the profiles were also examined against teacher demographics and background characteristics (such as age, gender, teaching experience, or level of formal education), and none of the six teacher practice profiles showed any systematic associations. This indicates that variation in DTI was not determined by demographic or background factors, but by teacher dispositions.

3.3. Empirical Rationale for SEEP

The empirical material presented in Section 3.2 supports the SEEP model through five traceable links between DigiEfekt findings and each element of the model's refinement (see Table 2 for an overview). SEEP emphasises that integration is continually negotiated by teachers as they interpret and balance multiple, sometimes competing, demands. The evidence from the DigiEfekt study, presented in the Articles and related reports, reinforces this repositioning by demonstrating that (1) teachers with similar capacities enact diverse practices, (2) competing motivational, operational, and cognitive aims generate distinct pathways of integration, (3) student behaviours and dispositions introduce further unpredictability, and (4) both processual adaptations and temporal influences shape how integration unfolds.

Five findings ground these links. First, six distinct practice profiles among teachers with broadly comparable conditions (Articles I, III) motivate the Process layer. Second, within-teacher variation across lesson-level practice clusters (Article II) grounds the Process layer as the site of situational enactment. Third, the dual-pathway prediction by readiness and attitudes (Article IV) motivates the disaggregation of the Person layer. Fourth, temporal patterns at micro-, meso-, and macro-scales motivate the Chronosystem. Fifth, these findings support SEEP as an integrated mechanism in which each element is necessary, and none is sufficient. Table 2 maps each finding to its source and reasoning.

Table 2. Abductive Argument Chain from DigiEfekt Findings to SEEP Refinements

Empirical Findings	Source	SEEP Layer	Reasoning
Between-teacher variation: six distinct practice profiles among teachers with broadly comparable readiness, attitudes, and access	Articles I and III	Process layer as the mediating mechanism	If provision and disposition alone were sufficient, similar teachers would enact similar practices. The observed divergence requires a mediating mechanism between conditions and practice, which SEEP names as the Process layer.
Within-teacher variation: the same teacher belongs to different lesson-level practice clusters across consecutive lessons	Article II	Process layer as the site of situational enactment	If DTI were a fixed personal style, a teacher would enact similar practices across lessons. Within-teacher variation instead shows that enactment is situationally negotiated, supporting the characterisation of the Process layer as the site of moment-to-moment orchestration rather than as the direct and stable output of teacher traits.
Dual-Pathway prediction: digital readiness and attitudes predict DTI profiles through distinct, sometimes opposing routes; substantial variation remains after personal predictors are modelled	Article IV	Refined Person layer: disaggregation into Attributes, Capacities, and Dispositions	If personal characteristics operated as a single “digital-mindedness” construct, readiness and attitudes would predict in parallel. The differential and sometimes opposing prediction instead shows that Capacities (i.e., readiness) and Dispositions (i.e., attitudes) do structurally different work, motivating the three-way disaggregation of the Person layer.
Temporal patterns across three scales: in-the-moment adaptations in field notes (micro); recurring usage rhythms in platform logs (meso); post-pandemic digital fatigue and policy shifts (macro)	Articles I, III; Opanasenko, Pedaste & Siiman (2022, 2023); interview data	Chronosystem as an explicit temporal dimension with three scales	If DTI were analytically reducible to a single time scale, findings at different scales would converge on the same account. The convergence of evidence at distinct scales instead shows that DTI unfolds simultaneously at micro-, meso-, and macro-time, motivating the Chronosystem as a structural layer rather than a contextual afterthought.
Combined evidence from all four patterns taken together	All four articles plus corroborating DigiEfekt materials	SEEP as a whole: an integrated explanatory mechanism	No single one of the four patterns is sufficient on its own. The Process layer needs the Person layer to explain what gets mobilised; the Person layer needs the Process layer to explain how dispositions become practice; both need the Chronosystem to explain how practice consolidates or drifts over time. The combined evidence therefore supports SEEP not as a collection of independent refinements but as a single mechanism in which each element is necessary, and none is sufficient.

The remainder of this section develops the empirical rationale for SEEP in three parallel steps, one for each of the refinements introduced in Section 2.3. Section 3.3.1 shows how patterns of between- and within-teacher variation motivate the addition of the Process layer as the mediating mechanism through which conditions become practice. Section 3.3.2 presents the temporal evidence across micro-, meso-, and macro-time that motivates the inclusion of the Chronosystem. Section 3.3.3 then draws on the predictive analyses from Article IV to motivate the disaggregation of the Person layer into Attributes, Capacities, and Dispositions. The interpretive implications of each refinement are subsequently developed in the corresponding subsection of Section 4.1.

3.3.1. Empirical Rationale for Adding the Processual Layer

Dispositions and Divergent Practices

As established in Sections 3.1.1 and 3.1.3, Estonian teachers entered the classroom with broadly comparable capacity, i.e., low operational barriers, high self-efficacy and readiness, and generally positive attitudes. Against this uniform baseline, DTI practices diverged substantially. Teachers enacted six distinct profiles, ranging from Efficiency Engineers, who relied on substitution for operational streamlining, to Depth Divers and Engaging Innovators, who used augmentation for deeper learning. These profiles differentiated primarily by pedagogical purposes: operational improvement, motivational engagement, or cognitive deepening. The DigiEfekt findings show that DTI is not a straightforward reflection of capacity, but the connection between dispositions and enactment is asymmetrical. Digital readiness (teachers' sense of competence and opportunity to use DT) was consistently linked to cognitively demanding profiles, such as Depth Divers and Engaging Innovators. At the same time, higher readiness reduced the likelihood of belonging to motivationally narrow, substitution-heavy practices like Motivating Facilitators. This dual effect makes readiness the clearest indicator of a reallocation: the same capacity that enables deeper cognitive practices also steers teachers away from simpler motivational ones.

Digital attitudes, by contrast, aligned strongly with motivational and engagement-oriented profiles (Motivating Traditionalists, Motivating Facilitators) and also supported depth-focused ones (Depth Facilitators). However, they did not show the same negative association with other profiles. In other words, positive attitudes helped to channel practices toward engagement goals, but they did not displace or trade off with efficiency or cognitive depth in the same systematic way that readiness did. This pattern explains why the most visible trade-offs emerged around readiness rather than attitudes. Readiness captures teachers' technical-pedagogical capacity, which forces a choice: when that capacity is high, teachers can reach for cognitively deeper uses, and in doing so, they are less likely to settle for substitutional motivational routines. Attitudes, meanwhile, operate more as a motivational lens, encouraging engagement-oriented enactments but not excluding other possibilities.

The DigiEfekt study showed that teachers, despite broadly similar readiness, self-efficacy, and resources, enacted markedly different practice profiles. These profiles were defined primarily by pedagogical purposes and were not explained by demographics or background characteristics. Predictive analysis demonstrated that teacher dispositions were the strongest drivers of profile membership. In Estonia's digitally mature system, where infrastructural inequalities are minimal, variation in practice stems from the relational, processual practice of teaching: balancing efficiency, engagement, and depth against heterogeneous learner ecologies. Dispositions establish a shared baseline, but enactment is not linear. It emerges through situated negotiation and trade-offs, particularly around readiness, which enables cognitively demanding integration while reducing reliance on substitutional, motivation-only practices. Attitudes, in turn, orient teachers toward engagement goals but do not displace other purposes in the same way. This dynamic balancing is precisely what SEEP frames as enactment: teachers exercising agency to navigate competing pedagogical demands, rather than simply adopting DT.

Processual Dynamics Within Teachers

However, modelling at the between-teacher level explains only who is more likely to adopt certain practices on average. The LPA and MLR predicted profile membership based on stable dispositions, showing how readiness and attitudes differentiated teachers into six distinct practice types. But this approach relied on aggregating multiple lesson observations per teacher into a single average profile score, explicitly noted in the study as a step that may obscure important variations in DTI across different subjects, limiting our ability to capture the finer distinctions in how teachers adapt their practices for various classroom contexts. In other words, while the models capture between-teacher differences, they cannot explain how the same teacher adapts across lessons or groups and so the six profiles identified should be understood as pedagogical leanings rather than as fixed, deterministic categories as the very act of aggregation, although necessary for LPA, flattens practice into an average and risks obscuring what may be the most critical finding: the variation around that average.

This situational dynamism is not methodological noise to be ignored; it is direct empirical indication of the SEEP *Process* layer in action, and is further supported by lesson-level clustering, which identified four distinct practice types: Introducing, Motivating, Facilitating, and Deepening. These represent descriptive groupings of observed behaviours that varied within the same teacher across lessons. Subsequent analyses of cluster membership revealed that a single teacher could be associated with multiple lesson-level practices across different lessons, further underscoring the situational nature of enactment. This indicated that not all teachers fit neatly into their assigned profile, diverging from the expected pattern in ways that reflected contextual demands. It is precisely this fluidity that demonstrates DTI is not a fixed personal style but an enacted, negotiated practice.

Qualitative data further revealed that teachers' purposes for using DT shifted across lessons, moving flexibly between operational efficiencies, motivational engagement, and cognitive deepening depending on the student group, lesson goals, or even time constraints. Substitutional uses that sometimes served operational convenience in one lesson could, in another context, be repurposed for motivational attention-grabbing or even for supporting qualitative changes such as independent study or reflection.

These situationally driven shifts cannot be explained by stable dispositions alone. They exemplify SEEP's processual claim: dispositions provide the baseline capacity and orientation, but enactment unfolds dynamically through moment-to-moment sequencing, framing, and adjustment in the classroom. DTI must be understood as an enacted negotiation that is context-sensitive. In this way, the DigiEfekt findings show that variation in DTI is not only a matter of which profile a teacher generally belongs to, but also how the same teacher actively negotiates competing purposes across lessons in response to the immediate realities of their learner ecology.

Heterogeneous Learner Ecologies

Moreover, learner ecologies were heterogeneous. Schools varied widely in the proportion of students with a different mother tongue, special educational needs, or low socio-economic status, with dispersions nearly as large as the means. This meant that some schools had almost none of these students, while others had much higher proportions, creating distinctly different classroom ecologies that demanded tailored pedagogical responses. Beyond demographics, students' digital competence profiles were uneven. They were relatively strong in communication and online protection but significantly weaker in programming and technical operations. This imbalance indicated that while many students could use digital platforms to interact or navigate safely, they lacked the skills required for deeper, constructive engagement with technology. Student digital attitudes added further complexity: perceived control over technology was relatively high, but preference for digital solutions correlated negatively with socio-emotional outcomes such as persistence, self-control, empathy, and cooperation. Thus, the very inclination to choose digital options did not guarantee better learning and, in some cases, hindered non-cognitive development.

Crucially, students' digital competence was not only a matter of individual capacity but also strongly shaped by the class and teacher. Compared to other competencies, digital competence displayed unusually high between-class variation, with ICCs ranging from 21.2% to 52.8% across its dimensions. This means that a substantial share of the differences in student digital competence could be traced back to the classroom context and the teacher's approach. Hence, digital competence was co-constructed within classrooms. Faced with heterogeneous student profiles, uneven skills, contradictory attitudes, and class-level differences, teachers had to interpret how best to align DT with the learners in front of them.

Furthermore, student platform engagement patterns (discussed in 3.3.2 as meso-time evidence) suggest that teacher orchestration decisions shape not only in-class activities but also the temporal rhythm of students' digital engagement across the school year.

3.3.2. Empirical Rationale for Adding the Chronosystem

The DigiEfekt dataset contains multiple strands of evidence demonstrating that DTI is shaped not only by contextual conditions and educator dispositions, but also by temporal influences operating at different scales. These findings provide strong empirical justification for explicitly including a Chronosystem in the SEEP model.

Micro-time: Within-lesson Adaptations

Observation protocols and qualitative field notes contained multiple examples of teachers making in-the-moment changes to their planned DT use. These shifts were typically triggered by real-time cues such as changes in student engagement, spontaneous questions, technical issues, or emerging opportunities to deepen learning.

For instance, in one observed lesson, a teacher displaying an Opiq textbook page to the whole class noticed that several students were disengaged. The teacher quickly reorganised the activity, asking students to work in pairs on a collaborative task in Google Docs, with the platform projected at the front of the room. In another case, when a student asked a question about an unfamiliar concept in a science lesson, the teacher paused the planned slide sequence and launched an unplanned YouTube simulation to visually illustrate the phenomenon before resuming the original activity.

Technical issues also prompted adaptations: in one lesson, when several students could not log in to the digital platform, the teacher improvised by pairing them with logged-in peers and shifting to group problem-solving, ensuring the learning objective could still be met without delay. Conversely, in a history lesson, a spontaneous connection made by a student to a prior topic led the teacher to retrieve archival photographs from an online repository on the spot, integrating them into a whole-class discussion.

These examples from the qualitative dataset illustrate how integration patterns can change within a single teaching event, even when the same teacher, the same tool, and the same group of students are involved. In each case, the adaptation was a processual decision responding to momentary conditions, and it directly altered the type, scope, or depth of the learning activity.

Such minute-to-minute adjustments highlight the importance of situating the Process layer within the Chronosystem in SEEP. They demonstrate that the enacted practice is not solely the product of advanced planning or stable personal traits, but also emerges from real-time instructional decision-making that shapes the trajectory of learning in unpredictable but pedagogically significant ways.

Meso-time: Recurring Patterns Across the School Year

Beyond individual lessons, data revealed that DTI also follows recurring rhythms and routines over weeks and months. Student Opiq usage patterns further confirmed meso-time regularities. Log data showed recurring strategies such as fast drop, late drop, systematic use, and single-chapter engagement, each reflecting rhythms of digital engagement over the course of the school year (see Opanasenko, Pedaste & Siiman, 2022, 2023). Importantly, these patterns were not purely learner-driven: teachers determined when and how Opiq was used, whether as short-term revision, ongoing formative assessment, or project-based learning. Thus, the temporal structuring of student engagement can be understood as a downstream proxy of teachers' orchestration decisions.

Observational evidence from the DigiEfekt study triangulates this finding, suggesting that patterns of DT use in lessons varied according to the pedagogical aims of the session, such as revision, assessment, or the introduction of new content. For example, some lessons devoted to revising prior material relied on short, targeted digital activities, whereas lessons introducing new content often integrated more sustained, interactive use of digital resources. While the Opiq platform logs capture only student activity, it is plausible that these variations in lesson aims and associated in-class digital practices are reflected in the broader temporal patterns of student platform engagement. In contexts where teachers incorporated Opiq for ongoing formative assessment or cumulative projects, one might expect more systematic and steady platform use over time, whereas its use for discrete revision or assessment sessions could produce more episodic engagement patterns.

This convergence of platform log and observation data underscores that meso-time patterns in student Opiq activity are not purely learner-driven, but embedded in the processual layer of teacher decision-making. It also reinforces the rationale for the Chronosystem in SEEP: the temporal structuring of integration, whether continuous, cyclical, or episodic, is a function of how teachers regulate, pace, and embed DT over the academic year, and these patterns in turn shape student engagement trajectories.

Macro-time: Historical and Policy Contexts

Finally, DigiEfekt situates DTI within longer-term historical trajectories and systemic conditions. Estonia's decades-long digitalisation strategy, which has ensured universal access to infrastructure, stable platforms, and teacher training, forms the macro-time backdrop against which teachers negotiate DTI. Because infrastructural barriers are minimal, teachers' choices are less about overcoming access constraints and more about pedagogical purpose and adaptation.

Macro-time conditions also include sociohistorical shocks such as the COVID-19 pandemic, which forced the rapid adoption of hybrid and remote practices. Some of these innovations persisted beyond the pandemic, while others were deliberately abandoned due to digital fatigue. In teacher interviews, several teachers reported deliberately reducing their digital use in the post-pandemic period due to a sense of digital fatigue among both staff and students. After extended periods of remote learning, many students were perceived as preferring more hands-on, collaborative, and physically interactive activities. In response, some teachers shifted portions of their lessons back to offline formats, even though DT remained readily available. Teachers' post-pandemic adjustments illustrate how accumulated historical experience shapes current enactments. Looking forward, the recognition of artificial intelligence as an emerging educational tool, and the new teaching practices it enables (Shi & Choi, 2024), signals the next macro-time challenge requiring negotiation.

At the same time, certain pandemic-era innovations, particularly those enabling flexible participation and differentiated pacing, were retained. Practices at the redefinition level of SAMR, such as hybrid lesson structures and simultaneous in-person/remote participation, continued to be used beyond the pandemic. These were valued for their potential to support absent students, facilitate differentiated grouping, and provide multiple pathways for engagement.

Teachers also acknowledged the enabling macro-time context created by Estonia's sustained investment in digital infrastructure and competence-building. The widespread availability of stable platforms, school-provided devices, and national repositories such as Opiq and eKoolikott had made rapid adaptation during the pandemic possible and ensured that innovations developed during that period could be integrated into regular practice.

These findings demonstrate that DTI is inherently temporal as well as contextual. At the micro-level, teachers improvise and adjust in real-time; at the meso-level, they establish recurring practices and orchestrate rhythms of student engagement; and at the macro-level, they operate within sociohistorical trajectories shaped by national policy, global events, and technological change. Incorporating a Chronosystem layer into SEEP ensures that the model captures this multiscalar temporality of enactment. Without it, analyses risk overstating the determinism of dispositions or context while underestimating how digital integration unfolds as a dynamic, historically situated process.

3.3.3. Empirical Rationale for the Refined Person Layer

The third element of the empirical rationale for SEEP concerns the Person layer. Where 3.3.1 showed that the Process layer was needed because teachers with similar dispositions enacted divergent practices, and 3.3.2 showed that the Chronosystem was needed because DTI unfolds across multiple temporal scales, the Person refinement is motivated by findings of a different kind: the predictive analyses in Article IV revealed that individual teacher characteristics do not operate as a single underlying construct but as analytically distinct pathways that predict DTI profiles in structurally different ways. Three findings from those analyses motivate the disaggregation of the Person into Attributes, Capacities, and Dispositions.

Differential Prediction

Article IV modelled DTI profile membership as a function of two teacher-level predictors, digital readiness and digital attitudes, with self-efficacy applied as a concept-driven weight. The analysis revealed what the article terms a Dual-Pathway Model: readiness and attitudes did not pattern across the six profiles as correlated indicators of a general “digital-mindedness,” but predicted profile membership through distinct routes with characteristic convergence and divergence.

Engaging Innovators was predicted exclusively by digital readiness ($\beta = 2.43$, odds = 11.3), with no significant effect of attitudes. Motivating Traditionalists showed the inverse pattern, a significant attitude effect ($\beta = 1.13$) with no significant readiness effect. Depth Facilitators and Depth Divers were predicted by both readiness and attitudes, with attitudes having the strongest effect on Depth Facilitators across the entire model ($\beta = 1.39$, odds = 4.0). Most strikingly, digital readiness was a negative predictor of membership in the Motivating Facilitators profile ($\beta = -2.00$, odds = 0.135), the substitution-heavy motivation-focused group: as teachers’ readiness increased, the probability of membership in this profile decreased substantially.

These patterns motivate the first structural decision about the Person layer in SEEP: personal characteristics are disaggregated into Capacities (where the digital readiness conceptually belongs) and Dispositions (where digital attitudes belong), because they predict different DTI profiles in different ways and in some cases pull in opposite directions.

Self-Efficacy as Amplifier

A second analytical feature of Article IV speaks to a further structural decision. Self-efficacy was not entered as a covariate alongside readiness and attitudes; it was applied as a concept-driven weight, following both Bandura’s (2001) theoretical claim that efficacy is the proximal psychological mechanism through which other personal characteristics are translated into action and Gelman and Hill’s (2006) methodological guidance for variables that both influence participation and lie on the causal path. Under this scheme, each teacher’s record contributed to the model in proportion to their self-efficacy score, and the weighted summaries reflected the theorised amplifying role of efficacy rather than treating it as a parallel predictor.

This analytical choice motivates the second structural decision: within the Dispositions dimension, SEEP retains Bronfenbrenner’s distinction between content-supplying characteristics (value and pedagogical orientations) and force-supplying characteristics (efficacy, motivational intensity, persistence), modelling the two as distinct internal layers of a single dimension rather than collapsing them into one.

Residual Variation

Even with both pathways and self-efficacy weighted, the practices of teachers with comparable scores remained considerably varied (Article IV). This is corroborated by the finding that teachers rated their own goal-setting more positively than the supportiveness of their classroom and school environments (Pedaste, 2022), suggesting that strong intentions alone do not guarantee the practice they would otherwise afford. This motivates the third structural decision: the Person layer is necessary but not sufficient, standing in constitutive relation to the Process layer.

Taken together, these three findings demonstrate that personal characteristics contribute to DTI through structurally differentiated pathways rather than as a unified construct. Readiness and attitudes predict different profiles through different routes, sometimes converging and sometimes diverging; efficacy operates not as a predictor on the same plane but as a modulator of how other characteristics translate into action; and even with these dimensions correctly identified, considerable variation in enactment remains beyond what personal predictors alone can account for.

Incorporating a disaggregated Person layer into SEEP, with Attributes, Capacities, and Dispositions modelled as distinct dimensions and Dispositions internally layered to distinguish content from force, ensures that the model represents the structured way in which teacher characteristics contribute to practice without overclaiming their explanatory reach. The interpretive implications of this refinement are developed in 4.1

Table 3. Synthesis of Indicative Empirical Evidence for SEEP

Layer	Definition	Key Elements	Indicative Empirical Evidence from DigiEfekt	Supporting Source
Person	The teacher as an active agent with specific competencies and dispositions that shape technology integration.	Digital competencies, pedagogical repertoire, openness to change, student-centred orientation.	Teachers reported generally high self-efficacy, digital readiness, and positive digital attitudes. Yet, these capacities translated into divergent practices, demonstrating that dispositions shape but do not determine enactment.	Articles III and IV
Process	The routine, interactional, adaptive, and temporal mechanisms through which technology is enacted in classroom practice.	Moment-to-moment pedagogical decision-making, adaptation to student feedback, negotiation between curricular aims and tech affordances, classroom norms for tech use.	Despite similar capacities, teachers enacted distinct practices driven by balancing operational, motivational, and cognitive goals. Although in teacher profiling aggregation masked intra-teacher shifts, qualitative evidence showed adaptive re-purposing and real-time changes (e.g., switching tools, reframing substitution for engagement or learning). Moreover, lesson level clustering revealed that the same teacher could belong to different practice clusters across lessons, further underscoring that integration is not fixed but varies situationally in response to contextual demands.	Articles I, II and III
Micro-system	The immediate teaching-learning environment where processes occur.	Learning goals, curriculum, classroom culture, infrastructure, student needs, interaction dynamics, support, resources.	Systematic variation showed that natural sciences relied most heavily on DT for both operational improvement and qualitative change, while the Estonian language used it least. Student digital competence was highly co-constructed within classrooms, with unusually high between-class variation, indicating strong teacher influence.	Article II, Pedaste, Raave & Baucal, 2023

Layer	Definition	Key Elements	Indicative Empirical Evidence from DigiEfekt	Supporting Source
Meso-system	Bidirectional relationships linking the classroom with school, home, and community contexts.	Professional collaboration, parental involvement, local cultural expectations.	Estonia's digitally mature policy environment establishes a high societal and educational expectation for digital practice, reflected in the finding that DT was used in 82% of the observed lessons. At the same time, the data also revealed exceptions: for instance, one sample school deliberately chose not to use DT at all. This illustrates that, despite strong national policy support and cultural expectations, schools retained autonomy to position themselves differently, underscoring that integration is not only shaped by systemic enablers but also by local institutional stances.	Article III, Pedaste, Raave & Baucal, 2023
Exo-system	Indirect influences from school level structures and decisions.	Leadership priorities, policy implementation, resource allocation, professional development opportunities.	Schools differed widely in student composition, but reported minimal structural barriers. This meant practices reflected institutional support and autonomy, not resource gaps.	Pedaste, Raave & Baucal, 2023; Puusepp & Pedaste, 2022
Macro-system	The broader cultural, infrastructural, and policy context.	Standards and norms, cultural values, national infrastructure, education policy.	Estonia's digitally mature policy environment and teacher autonomy created conditions where infrastructural barriers were negligible, positioning DTI variation as the product of pedagogical negotiation rather than access.	Article III
Chrono-system	The temporal dimension influences all other systems.	Micro-time (lesson moments), meso-time (curricular cycles), macro-time (historical events, reforms).	Micro-time: Observation protocols and qualitative field notes captured evidence of in-the-moment changes to planned DT use, triggered by real-time cues (e.g., spontaneous student questions, changes in engagement, technical issues), reinforcing the need to capture instructional sequencing and adjustment Meso-time: Sequence analysis of Opiq log data revealed recurring patterns, which tended to repeat within cohorts and reflected curricular rhythms, such as exam preparation, making them downstream indicators of teachers' sequencing decisions. Macro-time: Teachers used DT to facilitate hybrid learning, a remnant from COVID-19, and reported avoiding DTI due to digital fatigue.	Article I; Opanasenko, Pedaste & Siiman (2022, 2023)

4. DISCUSSION

The preceding chapters established that DTI varies markedly even where infrastructure, training, and policy are broadly enabling, and proposed the SEEP model, centering Process and embedding Time to explain this variation. The DigiEfekt findings confirmed that divergence in practice is better accounted for by how teachers enact technology than by what conditions surround them. This chapter interprets those findings in light of the SEEP model and the wider literature, and develops the model's implications for theory, research, and practice. Section 4.1 works through the indicative empirical evidence for each of SEEP's three substantive refinements, first answering the three research questions directly and then discussing the evidence for Process, Chronosystem, and the refined Person layer as parallel interpretive moves. Section 4.2 develops the implications of SEEP across six domains: theory, research, pre-service teacher training, professional development, school-level practice, and policy. Section 4.3 closes by acknowledging the limitations of the empirical material and the contextual and analytical boundaries within which the dissertation's claims should be read.

4.1. Interpreting the Empirical Findings

Section 4.1 unfolds in four subsections. Section 4.1.1 directly answers the three research questions, drawing on the findings reported in Chapter 3. Sections 4.1.2, 4.1.3, and 4.1.4 then discuss the interpretive significance of the evidence for each of SEEP's three substantive refinements in turn: the Process layer, the Chronosystem, and the refined Person layer.

4.1.1. Answering the Research Questions

RQ1: How can DTI be conceptualised as a situated process of pedagogical enactment, and what model emerges from this conceptualisation?

The critical synthesis in Chapter 2 showed that existing DTI models effectively map contextual conditions but do not explain the dynamic mechanisms through which those conditions become classroom practice. This gap motivated the SEEP model's two core additions: an explicit *Process* layer (capturing interpretation, adaptation, and negotiation) and an explicit *Chronosystem* (tracking how enactment unfolds across micro-, meso-, and macro-time).

RQ2: To what extent do individual factors predict these teachers' technology-integration profiles?

Empirically, teachers clustered into six distinct practice profiles (see Article III) that reflected different pedagogical aims (operational improvement, motivational engagement, cognitive deepening). Crucially, the same teacher appeared with different lesson-level practice types across lessons (see Article II), indicating that DTI is fluid, situated, and purpose-sensitive rather than a stable personal style. This cross-lesson variability, observed within teachers and not only between them, indicates that DTI is actively negotiated in practice: teachers interpret goals and constraints, adapt tasks and tools, respond to student uptake, and revise subsequent moves, rather than simply enacting what infrastructure permits. Infrastructure and baseline competence set the stage but do not script the play: what happens in the classroom emerges from on-the-spot interpretation directed at concrete instructional purposes. This is consistent with characterisations of PR&A as enacted and situational (Shulman, 1987; Karaseva, Siibak, & Pruulmann-Vengerfeldt, 2015; Morrison-Love & Patrick, 2025).

RQ3: To what extent do individual factors predict these teachers' technology-integration profiles?

Predictive analyses indicated a goal-specific alignment between teacher attributes and enactment. Digital attitudes are most strongly aligned with motivation-oriented profiles that prioritise attention, participation, and affective uptake. By contrast, digital readiness best predicted cognitively demanding profiles (knowledge building, analytical work, multi-step problem solving) and is negatively associated with substitution-heavy, motivation-focused profiles (see Article IV). In practical terms, as capacity increases, teachers are more likely to select complex, student-centred designs (Pozo et al., 2024) and less likely to stop at simple digitisation, common amongst novice DTIs (Kimmons, Graham & West, 2020). This pattern is evidence of agency within process: teachers do not merely express attitudes; they choose higher-leverage uses when they have the competence to enact them.

At the same time, dispositions and capacities did not fully determine practice. Evident from observational field notes, the teacher pivoted aims across lessons, and enactments shifted with learner ecologies (e.g., student preparedness, resistance/uptake), task constraints (e.g., time, assessment demands), and situational frictions (e.g., technical hiccups, room layout). Indeed, previous research indicates that the specific context of enactment greatly influences the practices (Tondeur et al., 2017), as teachers must make decisions based on moment-to-moment interactions, which require spontaneous interpretation of the perceived surrounding conditions (Forkosh-Baruch, Phillips, & Smits, 2021), as DTI in reality involves the learner, the teacher, and countless other co-participants (Dron, 2022). These contingencies echo research on classroom orchestration (Dillenbourg, 2013) and instructional adaptations (Parsons et al., 2018), where plans and tools are resources to be adapted rather than determinants and underscore SEEP's claim that DTI is processually negotiated through interpretation, adaptation, reciprocity, and reflection, rather than linearly dictated by traits.

4.1.2. Evidence for Process: Negotiation & Co-Construction

The inclusion of a distinct Process layer is arguably the most significant conceptual refinement of SEEP from its predecessor. The empirical warrant for this refinement was developed in Section 3.3.1, where patterns of between- and within-teacher variation were shown to require a mediating mechanism to explain how available resources, skills, and supports are translated into specific pedagogical moves. This section interprets those findings in discussion, drawing out what they imply about the nature of enactment.

Evidence from previous research shows that teachers integrate DT through iterative reflection and adaptation (Niess & Gillow-Wiles, 2017). This reality compels a critical re-evaluation of descriptive, influence input-based models and demands a theoretical lens capable of capturing the dynamic negotiation that defines enactment. The fundamental assumption underlying this shift is that agentic intentions reside with humans, and not with technology (Bower, 2019). Teachers exercise agency by making choices, which requires interpretation and adaptation, meaning agency is inherently temporally embedded (Biesta, Priestley, & Robinson, 2015) and fostered by attending to the cultural and structural conditions that enable it (Emans et al., 2025), and positioning them as key agents of change (Brown, White, & Kelly, 2021).

Indeed, the empirical data from the DigiEfekt study sustains SEEP's premise that practice is truly shaped within the Process layer through PR&A. Crucially, this dynamic balancing involves tangible, agentic negotiations (Biesta & Tedder, 2007). The six distinct profiles identified (see Article III) are not static types but rather empirical snapshots of the Process layer in action, revealing how teachers interpret, negotiate, and adapt to their context. For instance, the Depth Divers and Engaging Innovators profiles reflect an interpretation of purpose focused on cognitive deepening. This was then negotiated with the teacher's Capacity (digital readiness), which the predictive analysis (see Article IV) found was the strongest predictor for these complex profiles. In contrast, the Motivating Traditionalists profile reflects an interpretation of purpose focused on engagement, which was predicted by the teacher's Disposition (digital attitudes).

The predictive analysis also found that high readiness negatively predicted membership in substitution-heavy, motivation-focused profiles (Motivating Facilitators). This provides clear evidence for agentic negotiation: as teachers' Capacity grows, they actively choose to move beyond simpler routines. This mapping demonstrates that DTI is an outcome of agentic choice, the process of translating Capacities and Dispositions into practice, not passive compliance. Consequently, the explanatory variable for classroom events shifts away from static conditions like access toward teacher agency, pedagogical reasoning, and situated judgment. The pre-planned design of a digital task only provides a structure; it is the teacher's orchestration, the responsive, on-the-fly guidance and moment-to-moment adaptations, that actually define how technology is enacted in practice (Dillenbourg, 2013; Fawns, 2018).

The Aristotelian concept of phronesis or practical wisdom, the capacity to discern the right action in particular circumstances that cannot be settled by rule alone (Kinsella & Pitman, 2012), describes exactly this kind of situated judgment. The Estonian teachers who moved between substitution-heavy and cognitively deeper integration, or who reconfigured a planned activity in response to student disengagement, were not applying a generic best practice. They were exercising phronetic judgment about what this technology, in this classroom, with these students, could serve pedagogically at this moment (Bardone & Bauters, 2017). SEEP's Process layer is the site at which phronesis operates which is why it cannot be reduced to the conditions that surround it.

Read at this level, the teacher in SEEP functions not merely as one mediator among others, but the proximal agent through whom the technological mediation of learning is itself mediated. Where digital tools mediate students' encounters with content, the teacher mediates whether, when, how, and to what end that mediation actually shapes learning, converting the latent affordances of Capacities and Context into the specific configuration of observable pedagogical practice. DTI is, therefore, likely exercised through the continuous interpretation and balancing of multiple demands, continuously monitoring and adjusting instruction (Parsons et al., 2018), mediated by the teacher's professional agency and situated pedagogical judgment (Biesta, Priestley, & Robinson, 2015).

This signals that readiness (Capacity) and attitudes (Disposition) establish the potential for DTI, but the specifics of the enactment are determined by the teachers' in situ choices, evidenced further by the finding that a single teacher could be associated with multiple lesson-level practice types (Introducing, Motivating, Facilitating, Deepening) (see Article II). This within-teacher variation underscores that practice is fluid and situational, with teachers flexibly shifting their purposes depending, e.g., on the student group, lesson aims, or time constraints (Karaseva, Siibak & Pruulmann-Vengerfeldt, 2015): a phenomenon entirely consistent with contemporary discourse arguing meaningful DTI happens through constant adaptation (see Dron, 2023).

In essence, the heterogeneity of practice validates the understanding that DT's educational value is always mediated by human intentions (Bower, 2019). Technologies only achieve agency in an educational setting through human design choices and teachers' coordinated use with students as co-participants (Dron, 2022). The SEEP model posits that the Process layer is characterised by reciprocal interactions, and the DigiEfekt findings indicate that DTI is co-constructed with students.

The heterogeneous learner ecologies observed demanded constant interpretation and adaptation from teachers. For example, as digital trace data revealed age-shifting student usage patterns (see Opanasenko, Pedaste & Siiman, 2022, 2023), such as the sharp rise in focus on formal test completion in older grades, which are downstream indicators of teachers' pedagogical choices as the function and value of a digital resource, such as the Opiq platform, are not inherent to the technology itself but are assigned through usage. The teacher's decision on when and how a platform like Opiq is incorporated into lessons directly shapes the student's mode of engagement. Faced with diverse students and their needs, teachers must continuously adapt their DTI approach (Navas-Bonilla et al., 2025). This relational, responsive work, which is the core of the proximal process, reinforces the necessity of a model that accounts for the reciprocal dynamics between educator, learner, and technology.

4.1.3. Evidence for Chronosystem: Temporality of Integration

The inclusion of the Chronosystem is the second critical conceptual refinement, extending the static models that preceded SEEP by explicitly accounting for the fact that integration is not only a dynamic process but a process unfolding across time. The indicative empirical evidence that motivates this refinement was presented in Section 3.3.2; what follows interprets that evidence in light of the theoretical literature on temporality in teaching. This temporal dimension is essential for understanding how teachers evolve in their DTI practices. As Lachner, Backfisch, and Franke (2024) argue, DTI is a developmental trajectory shaped by growing professional competence and pedagogical vision. However, while their model acknowledges temporal development, SEEP's Chronosystem goes further by embedding time as a structural layer within a broader ecological framework. In this view, the teacher acts as an orchestrator of technologies, adapting their methods to utilise technological affordances in conjunction with emergent pedagogical needs (Dron, 2023). Without this temporal dimension, analyses risk misinterpreting variability as purely dispositional or contextual, overlooking the crucial role of time-structured processes in shaping DTI.

At the micro-time scale, qualitative field notes captured numerous examples of teachers making in-the-moment adaptations to their planned DT use (Chapter 3). These immediate shifts, triggered by real-time cues like student disengagement, spontaneous questions, or technical friction, altered the type and depth of the learning activity within minutes. Indeed, previous research has noted that enacted practice can diverge from espoused beliefs or intentions because actions are shaped by a confluence of situational factors, e.g., tool availability, lesson-specific learning goals, assessment demands, and time pressures (Karaseva, Siibak, & Pruulmann-Vengerfeldt, 2015). Such minute-to-minute adjustments highlight that enacted practice emerges from complex, real-time instructional decision-making, where the Process layer operates at its highest frequency. This phenomenon is often described as reflection-in-action, a key component of reflective practice (Suphasri & Chinokul, 2021), whereby teachers notice and respond to students' learning in real-time, revising their activities within the context (Schön, 1983/2017), which, as Eraut (1995) argues, is better understood as time-sensitive metacognitive control, where routine, intuition, and rapid monitoring guide adaptive moves within dynamic learner ecologies. Other empirical work in Estonian classrooms has shown this interpretive process in action: teachers move from identifying patterns in classroom cues to applying pedagogical knowledge that explains them, rather than jumping directly from observation to decision (Saar & Laanpere, 2022).

The meso-time influences were evident in the recurring patterns and routines observed over weeks and months. Student Opiq usage logs revealed distinct temporal strategies (e.g., fast-drop, systematic use) that reflected the curricular pacing orchestrated by teachers over the school year. These consistent patterns, which are downstream proxies for the teacher's orchestration decisions, show how integration is paced, sustained, or abandoned over medium timeframes as teachers determine whether, when, and how digital resources are integrated (e.g., for short-term revision, ongoing formative assessment, or project work), thus setting the temporal rhythm for student engagement. This aligns with findings from Wohlfart and Wagner (2023), who demonstrate that teachers' digital integration follows cyclical patterns shaped by pedagogical goals and classroom rhythms, reinforcing the idea that DTI evolves through sustained, context-sensitive decisions. Meso-time highlights that meaningful DTI is not just about isolated, high-level use, but about the recurring, consistent embedding of tools over time, recognising that regular DTI is necessary for meaningful developmental change.

Finally, at the macro-time scale, DTI is profoundly situated within socio-historical trajectories. The decades-long Estonian digitalisation strategy (see Põldoja, 2020) has largely removed infrastructural barriers, allowing teacher choices to be driven by pedagogical purpose rather than necessity, which formed the background, while the COVID-19 pandemic acted as a major sociohistorical shock (see also Chapter 3). Our interview data indicated that this event profoundly influenced the use of technology, leading to post-pandemic phenomena such as digital fatigue among staff and students, prompting some teachers to reduce DT despite availability, a post-pandemic re-evaluation of technology's value also noted by Reyes-Rojas & Sánchez (2025). Conversely, some pandemic-era innovations, particularly those enabling flexible participation and differentiated pacing, were retained as they were valued for their pedagogical potential at the moment. More broadly, however, macro-time conditions act on practice not only through dramatic disruptions but also through the slower, more diffuse pressure of ongoing policy debates, such as those around teacher professionalisation and workload, that shape how teachers perceive their professional standing and, in turn, their willingness to exercise the situated judgment that the Process layer describes. This demonstrates how accumulated experience, captured by the Chronosystem, reconfigures feasible practices and meaningful goals for current enactment.

Taken together, the three timescales also reveal something about phronesis itself. Practical wisdom is not acquired once and applied; it is developed through the recurring exercise of judgment across micro-time moments, consolidated into meso-time routines, and continually reshaped by macro-time shifts in tools, pedagogies, and policy. The Chronosystem layer makes this developmental character of phronesis visible, and resists the tendency to treat DTI as a skill teachers either possess or lack at a single point in time.

4.1.4. Evidence for the Refined Person Layer

The disaggregation of the Person layer, meaning reconceptualising the educator through three analytically distinct dimensions (Attributes, Capacities, Dispositions), is the third critical refinement. IIts empirical warrant comes from Article IV's predictive analyses, detailed in Section 3.3.3, which are themselves diagnostic of what kind of model is needed. The analyses revealed that digital readiness and digital attitudes, the two predictors modelled, did not operate as correlated indicators of a general "digital-mindedness" construct but as analytically distinct predictive pathways, each aligned with a different kind of practice. Attitudes drove the motivational pathway, where DT was used to sustain student interest and affective engagement; readiness drove the cognitive pathway, where DT supported reasoning, modelling, and sustained inquiry. These two dimensions conceptually map onto Bronfenbrenner's framework, where capacities act as resource characteristics that provide the necessary mental, experiential, and skill-based conditions required for proximal processes, while attitudes function within the affective-motivational dimension that drives actions based on needs and values (Bronfenbrenner & Morris, 2006).

The two pathways converged at the depth end of the practice space, where meaningful integration required teachers to bring both orientation and capacity; and, revealingly, they diverged sharply at the substitution end, where higher readiness predicted movement away from rather than toward simpler motivational uses of DT. This patterning is precisely what a single-bundle representation of teacher characteristics would obscure: readiness and attitudes are not interchangeable indicators of the same underlying property but distinct forces that shape practice in different parts of the pedagogical terrain. SEEP's Capacities/Dispositions distinction is the structural response to this finding.

A second feature of Article IV's analytic design speaks to a further structural choice within the Dispositions dimension. Self-efficacy was treated not as a covariate on the same plane as readiness and attitudes but as a weighting variable, following Bandura's (2001) theoretical claim that efficacy is the proximal mechanism through which other personal characteristics are translated into action. The theoretical implication of that analytical choice is that efficacy does not predict DTI in the same way readiness or attitudes do; it modulates whether readiness and attitudes get mobilised into practice at all. In SEEP terms, efficacy and similar force characteristics belong analytically with motivational Dispositions but function differently from value orientations or pedagogical commitments. They do not determine what teachers want to do, but how strongly they pursue it. The internal layering of Dispositions in SEEP, preserving Bronfenbrenner's original distinction between content and force, is motivated by precisely this kind of finding: personal characteristics are not all on the same plane, and flattening them erases the distinction between what supplies content for practice and what supplies intensity.

The most consequential finding for the relationship between the Person layer and the rest of the model, however, is what remained unexplained even after readiness, attitudes, and efficacy were all accounted for. Article IV concludes that even among self-efficacious teachers with comparable readiness and attitudes, DTI enactment varied considerably, and that integration is not a uniform outcome of teacher dispositions but a situated process negotiated between those dispositions and the classroom conditions in which they are enacted. This conclusion is reinforced by a finding from the broader DigiEfekt data: Pedaste (2022) reports that while teachers largely agreed they possessed the necessary technological skills and infrastructure, they perceived significant environmental constraints, such as a lack of time for planning and insufficient school-level encouragement to use DT. The gap between what teachers aim for and what they perceive their classroom and school contexts as supporting is precisely what one would expect if teacher agency were not a stable personal property, but something achieved situationally, when conditions allow (Leijen et al., 2020). A teacher with high readiness and clear pedagogical intentions can still find that the ecology of a particular lesson, a particular cohort, or a particular school day does not afford the practice she would otherwise enact.

This represents the analytical purpose of the Process layer within the SEEP framework. The Person layer specifies what each teacher brings to the moment of integration, the resources, orientations, and intensities available to be mobilised to enactment (Biesta & Tedder, 2007), but it does not, on its own, determine what each teacher does with what she brings. That determination emerges at the intersection of Person and Process, where personal dimensions meet the activities, roles, relations, and features of a specific Microsystem. Here, teachers must apply situation-specific skills, bridging the gap between their dispositions and observable performance by perceiving classroom cues, interpreting them, and making real-time pedagogical decisions (Kasepalu, Saar, & Tammets, 2024). Through situated orchestration, teachers engage in PR&A to adapt their initial instructional designs to the unfolding, unpredictable realities of student practice (Goodyear & Dimitriadis, 2013; Shulman, 1987).

These elements are transformed into the observable configuration of moves that an observer sees in a classroom. Considered this way, the refined Person layer in SEEP is inseparable from the Process layer that sits next to it: the two are complementary elements of a single explanatory mechanism, and the fact that variation Article IV could not be reduced to personal characteristics alone serves as the empirical indication for the necessity of the Process layer in explaining DTI. It is also, in philosophical terms, the signature of phronesis: a practical wisdom that cannot be decomposed into the traits that enable it because it is constituted in the encounter between person and situation.

Taken together with the evidence for the Process layer (4.1.2) and the Chronosystem (4.1.3), the evidence for the refined Person layer substantiates SEEP's three core theoretical claims: that Process is the mediating mechanism through which conditions become practice, that the Chronosystem is the temporal dimension across which practice consolidates and evolves, and that the Person is a structured set of analytically distinct dimensions that stand in constitutive relation to the Process layer rather than carrying the explanatory burden alone. What these claims imply for how DTI should be studied, supported, and enacted is the subject of the implications that follow.

4.2. Implications

The implications of SEEP unfold across six domains: theory (4.2.1), research (4.2.2), pre-service teacher training (4.2.3), professional development (4.2.4), school-level practice (4.2.5), and policy (4.2.6). They are ordered from the conceptual to the institutional, on the grounds that everything the latter sub-sections ask of teachers and schools depends on the frameworks the earlier ones establish.

4.2.1. Implications for Theory

SEEP repositions DTI as dynamic and relational rather than fixed, emphasising that it is exercised through the ongoing interpretation and balancing of multiple, sometimes competing, demands. This emphasis on enactment explains how divergent practices emerge: teachers' judgments are filtered through subject traditions, curricular aims, institutional cultures, and student needs. By foregrounding these situated negotiations, SEEP re-frames the discourse, prioritising the explanation of enactment over the cataloguing of conditions.

This theoretical repositioning places SEEP in dialogue with contemporary perspectives that similarly stress the inseparability of pedagogy, technology, and context. For instance, Fawns (2022) argues for an entangled pedagogy where DT, pedagogical values, and institutional contexts co-constitute practice, challenging deterministic models of integration. Similarly, Burnett and Merchant (2020), drawing on sociomaterial theory, highlight how digital practices emerge through the interplay of material artefacts and social relations, resonating also with Technology-Mediated Learning theory (Bower, 2019), which underscores that educational value is always mediated by human intentions. These views also converge with the phronetic tradition in educational philosophy (Bardone & Bauters, 2017; Kinsella & Pitman, 2012), which locates the quality of teaching in situated practical judgment rather than in the generic application of methods or tools. SEEP complements these views by offering a structured ecological-processual-temporal lens that preserves the value of mapping systemic layers while specifying the mechanisms (interpretation, adaptation, and temporal iteration) and re-specifying layer boundaries (e.g., defining the Microsystem as the instructional environment) through which context becomes consequential in practice (in comparison to the SETI model). In this sense, SEEP complements rather than replaces the SETI model.

The explicit incorporation of the Chronosystem (i.e., Time) adds a vital temporal dimension, accounting for micro-, meso-, and macro-level change. This allows SEEP to model DTI not just as a situated act, but as an evolving trajectory shaped by immediate interactions, recurring routines, and long-term historical shifts. This developmental perspective explains how practices consolidate, drift, or transform over time, providing a richer understanding than static snapshot models allow and underscoring the necessity of longitudinal research designs capable of capturing these dynamics. Aligned with this view, Lachner, Backfisch, and Franke (2024) offer a nuanced understanding of how teachers' professional competencies, pedagogical vision, and responsiveness dynamically interact with classroom realities. SEEP expands upon such dynamic interaction models by explicitly adding the temporal and processual dimensions, showing how these competencies are interpreted and enacted over time within specific contexts. Integrating Time helps explain why integration trajectories diverge even among teachers who start from similar profiles, as decisions are continually shaped by evolving curricular aims, institutional cultures, and emergent student needs across different timescales.

These refinements also carry implications for how educational innovation is conceptualised. Rather than scaling successful practices uniformly, systems might focus on building capacity for local adaptation (Coburn, 2003; Harris & Jones, 2018), investing in the structures and cultures capable of sustaining long-term, context-sensitive development. SEEP's temporal framing underscores that meaningful integration unfolds over years, not months, making innovation a distributed, responsive process rather than a standardised rollout.

A final theoretical implication follows from these refinements: while SEEP was generated from the specific puzzle of DTI variation under digitally mature conditions, its structural features, referring to the situated orchestration, disaggregated person characteristics, bidirectional context, and embedded temporality, are not confined to that case. The broader reach of this claim is developed in the Conclusion.

4.2.2. Implications for Research

The theoretical advancements embedded in the SEEP model, namely the explicit inclusion of the Process layer and the Chronosystem, reorient educational technology research away from descriptive, fragmented snapshot studies that merely catalogue contextual factors and toward a more holistic and explanatory way of capturing dynamic enactment and temporal synergy. The field has historically suffered from under-theorisation, often relying on atheoretical designs focused primarily on implementation based on "common sense" assumptions (Hew et al., 2019) and calls for deeper theorisation of practice (Morrison-Love & Patrick, 2025). SEEP addresses this limitation by emphasising process-capturing methodologies that embrace temporal influences.

Operationalising Proximal Processes

Grounding research in SEEP requires treating the dependent variable not as the mere presence of technology but as technology-in-use: the situated orchestration of moves, decision points, and iterative adaptations through which teachers and learners co-construct DTI activity. This reframing shifts the focus from static indicators of access or tool usage to the quality and dynamics of enactment. This mandates a move beyond merely listing contextual factors toward prioritising the empirical investigation of these proximal processes, which must be studied with attention to their context-sensitive and bidirectional nature (Merçon-Vargas et al., 2020). Practically, this means defining and measuring enactment with explicit indicators (e.g., interpretation, adaptation, reciprocity) and collecting data at the time scale where these indicators vary, from activity-level minutes to lesson or unit sequences.

To capture this inherent complexity, research should adopt holistic approaches that enable dynamic, synergistic analysis. For example, at the micro-time scale, studies should capture within-lesson dynamics, including minute-by-minute shifts in task design, scaffolding, and feedback, through methods that surface pedagogical reasoning while reducing recall bias, such as microgenetic video analysis (see Copur-Gencturk & Atabas, 2024) or immediate stimulated-recall interviews (see Lyle, 2003). At the meso-time scale, research should track routines, purpose shifts, and appropriation patterns across weeks and units through repeated brief observations, rolling teacher logs, and process mining of platform analytics, which function as behavioural proxies for orchestration (e.g., usage frequencies, feedback cycles). Teacher inquiry frameworks (Kasepalu, Saar, & Tammets, 2024; Saar & Laanpere, 2022) offer one concrete methodology for operationalising this kind of process research: teachers themselves function as researchers of their own practice, collecting and interpreting data across iterative cycles, which makes the evolving logic of enactment visible in ways that detached observation cannot. In reporting, researchers should provide a logic of enactment (e.g., what decisions were made, when, for whom, and on what cues) rather than simply listing used tools. This aligns with calls for situated technology-in-use research that captures the interplay of teacher agency, student engagement, and DT in real-time instructional contexts.

Inquiry approaches like theorising practice, which often rely on abductive reasoning, are essential for generating explanatory insights from persistent professional challenges (Morrison-Love & Patrick, 2025). Unlike applying existing models deductively or inducing generalisations from isolated observations, abductive theorising begins with puzzling phenomena and iteratively constructs plausible explanations grounded in practice. As Morrison-Love and Patrick (2025) argue, this should be treated as a rigorous, practice-focused research process that integrates personal practical theories, reflexive dialogue, and literature. Hofmann, Paavola, and Rainio (2024) further develop abduction as a multi-layered methodology, highlighting its dynamic, "back-and-forth" movement between empirical data and conceptual development. Their work demonstrates how this abductive inquiry enables researchers to move from lived experience to theoretical insight through iterative, lateral analysis, making it particularly suited to capturing the complexity of DTI. Together, these perspectives reinforce SEEP's emphasis on theorising as a generative tool for bridging the theory-practice gap and capturing the localised, dynamic nature of DTI.

Improving Understanding of Causality

Understanding causality in DTI research remains a significant challenge, as the field has historically struggled with a lack of theory (Hew et al., 2019) and a predominance of cross-sectional studies that limit robust causal evidence (Weidlich, Hicks, & Drachsler, 2024). To address this, the SEEP framework proposes a shift toward research designs that evaluate effectiveness in relation to pedagogical goals (the intrinsic logic of the Process layer) rather than merely documenting technological presence in the Context layer. This distinction is crucial, especially considering that educational investment decisions are rarely evidence-driven and that effect sizes in education are highly context-dependent (Wu, 2023).

Methodologically, SEEP calls for holistic, dynamic designs that can capture the DTI as it is enacted in real-world settings. Mixed-methods programmes should combine pattern-seeking quantitative analyses with abductive theorising from practice, enabling mechanism-rich explanations that bridge the theory–practice gap (McGrath, 2023). This approach aligns with recent calls for practice-focused inquiry, where theorising practice becomes a method for generating explanatory insights from persistent professional challenges (Morrison-Love & Patrick, 2025). Abductive reasoning, in this context, allows researchers to move beyond surface-level correlations and engage with the occurrent pedagogical logic that underpins DTI use.

To substantiate causal claims, future research must adopt a longitudinal design, to account for reciprocal relationships, and experimental designs to manipulate variables in order to test causal mechanisms directly (Scherer, Siddiq, & Tondeur, 2019). These approaches are essential for capturing synergy, where the combined effect of PPCT is greater than the sum of its individual contributions. This requires moving beyond simple linear models toward dynamic structural models tracing how beliefs, contexts, and enactment evolve over time and interact dynamically, which explicitly test interaction effects and feedback loops. Bronfenbrenner and Morris (2006) emphasise that principal effects are often interactions, underscoring the need for designs that reflect this complexity.

Longitudinal research designs are particularly suited to estimating bidirectional influences among beliefs, contexts, and enactment, while accounting for contextual factors operating within the nested educational environments (Wohlfart & Wagner, 2025). Mediation models are essential for understanding how initial person-context configurations shape the enactment of DTI and how that enactment, in turn, influences beliefs and environments, acknowledging that a teacher's practices can reshape their own beliefs or the school context, not just the reverse (Tondeur et al., 2017). Moderation models further allow researchers to test whether stable teacher characteristics or contextual factors enhance or constrain the effectiveness of sustained DTI, particularly in relation to temporal attributes of the Process layer such as consistency and frequency (Xia, Yu, & Li, 2024). Together, these methodological advancements enable a more ecologically valid and causally robust understanding of DTI, supporting the development of explanatory models that reflect the dynamic, reciprocal nature of teaching and learning with technology.

Evaluating Effectiveness

DTI impact studies differ in intervention duration, technological scope, educational context, and samples (UNESCO, 2023), and meta-analyses routinely report substantial variation in effect sizes (Wu, 2023). To keep such heterogeneity interpretable, so we can see for whom, when, and under what conditions DTI best delivers value, pre-registration of purpose-specific hypotheses and analysis plans is essential. This practice prevents the averaging of incompatible aims, clarifies causal claims, and aligns with a discovery-oriented approach in developmental science, in which hypotheses must carry sufficient explanatory power to warrant empirical testing (Bronfenbrenner & Morris, 2006).

Moreover, the effectiveness of DTI must be evaluated relative to stated pedagogical purposes (OECD, 2023a). DTI success is profoundly shaped by the intentionality with which technology is integrated. Teachers, as the best experts due to their context-specific knowledge, must make reflective, informed decisions about DTI. In SEEP terms, the Person dimension, capacities and dispositions actively shape integration trajectories. Because teachers' practices are complex and adaptive, often shifting pedagogical orientations in response to situational demands (Tondeur et al., 2017), intervention research should treat teachers as agents and co-designers rather than passive recipients. Such designs yield deeper insight into how to develop adaptive expertise, recognising that teaching methods, technologies, and purposes are entangled and require ongoing revisiting of goals and contexts to inform choices (Fawns, 2022). This reorientation moves evaluation beyond predicting intentions toward documenting actual implementation, which is mediated by situated processes and pedagogical reasoning.

Since DTI is a means to improve teaching and learning, not an end in itself, evaluation should reflect system goals such as equity and inclusion (Navas-Bonilla et al., 2025; Samaniego López et al., 2025) and ultimately attend to student outcomes (Boeskens & Meyer, 2025). Because the value of DT often emerges from ongoing, situated interactions, outcome measures must be sensitive to classroom dynamics; otherwise, studies risk obscuring mechanisms or misattributing effects within complex contexts (UNESCO, 2023).

Accordingly, SEEP calls for explicit alignment between intended aims and a layered outcome architecture spanning proximal, intermediate, and distal indicators. We understand proximal indicators to capture immediate instructional effects of DTI (e.g., cognitive demand, student engagement, classroom interaction); intermediate indicators to reflect sustained behavioural and cognitive changes, such as the transfer of learning strategies, persistence in task completion, and equitable participation; and distal indicators to encompass long-term educational outcomes, including academic achievement, self-regulation, and enduring interest in learning. This stratified approach is reinforced by Forsström et al. (2025), who emphasise that the pedagogical impact of DT unfolds over time, from immediate engagement to long-term achievement, highlighting the need for differentiated indicators to capture the full trajectory of technology-enhanced learning.

Moreover, Time itself must also be theorised and measured: at micro-time, researchers trace continuity and disruption within lessons; at meso-time, they analyse the periodicity and regularity of DTI routines across weeks or months, recognising that recurring patterns of digital use, including student-generated ones, serve as downstream proxies for teachers' orchestration decisions over medium timeframes. Together, these design and measurement commitments make effectiveness claims more interpretable, comparable, and useful for improving practice.

4.2.3. Implications for Pre-Service Teacher Training

The following subsections translate SEEP's conceptual commitments into recommendations for how DTI should be supported at different levels of the educational system. These are offered as implications derived from the model and the Estonian evidence, not as prescriptions applicable to all contexts. Moreover, what follows directly here is not a set of empirical findings about pre-service training but a set of implications the SEEP framework carries for how future teachers should be prepared, extrapolated from the argument that DTI is constituted through situated pedagogical reasoning rather than delivered by tools and competence alone. These implications converge with existing research on teacher education and position pre-service training as the moment at which novice teachers acquire, or fail to acquire, the dispositions and habits of mind that will shape their later practice.

The most fundamental implication is that a processual, ecologically grounded view of DTI reframes pre-service preparation from training on tools to cultivating teachers' PR&A in context. The location of DT preparation in the curriculum matters as much as its content: it should not be a discrete module separated from the rest of teacher education, but a thread running through all subject methodologies and field experiences, so that future educators encounter technology as an embedded pedagogical tool rather than as a standalone topic. This infusion approach is directly supported by the Synthesis of Qualitative Data (SQD) model developed by Tondeur and colleagues (Tondeur et al., 2019), which identifies six strategies for preparing pre-service teachers to integrate DT meaningfully: teacher educators acting as role models, structured reflection on technology's pedagogical role, learning technology by design, peer collaboration, scaffolded authentic field experiences, and continuous feedback. Each of these strategies targets a different element of the design-enact-reflect cycle through which the Process layer operates, and programmes that treat DT as a standalone course tend to satisfy at most one or two of them. Programmes that infuse DT across their structure can satisfy all six, which is what SEEP's processual commitments call for.

A second implication concerns the cultivation of self-efficacy. Article IV identified self-efficacy as the proximal mechanism through which readiness and attitudes get mobilised into enacted practice, which means that pre-service programmes need to provide structured opportunities for novice teachers to experience successful technology-mediated teaching before they enter their first classrooms. Microteaching, simulated lessons, observation of accomplished models, and rehearsal in low-stakes settings are the mechanisms through which this efficacy develops (Tondeur et al., 2019). Without such rehearsal, pre-service teachers can complete a programme with high readiness and positive attitudes, but lacking the embodied confidence that turns those resources into action. This gap needs to be closed at the level of situated agency rather than at the level of abstract competence, which means that efficacy-building opportunities must be structural features of pre-service curricula rather than optional extensions.

Closely related, SEEP's emphasis on the Process layer as dynamic, moment-to-moment enactment means that theoretical knowledge about DTI is insufficient on its own. Pre-service teachers require scaffolded, authentic field experiences in actual classrooms to overcome the divide between knowing about technology and actively teaching with it (Ertmer & Ottenbreit-Leftwich, 2010; Tondeur et al., 2016). Collaborative "learning by design" approaches, in which pre-service teachers co-create and test technology-enhanced curriculum materials, help mitigate the anxiety associated with new tools and build the adaptive capacity on which the Process layer depends (Tondeur et al., 2019). These experiences are also where novice teachers first encounter the gap between planned and enacted practice that their future careers will require them to navigate continuously, and the earlier they encounter it under scaffolded conditions, the more productively they can learn to work within it.

A third implication is that the cultivation of pedagogical reasoning of the kind SEEP foregrounds is a gradual, non-linear achievement. It cannot be hurried by compressing reflection into checklists, by reducing field placements to compliance exercises, or by treating teacher education as a series of performative tasks aligned to standards. Pre-service programmes should adopt what Ailwood and Ford (2021) describe as a slow pedagogy approach: deliberately giving novice teachers the temporal and intellectual space to connect deeply with the practice of teaching, to sit with uncertainty, and to develop the phronetic judgment that distinguishes a teacher who can use a tool from one who knows when not to. This is a structural commitment as much as a pedagogical one, requiring programmes to defend the time and contemplative space that genuine reasoning development demands against pressures to credential more teachers more quickly. Pre-service education is where that capacity either begins to develop or is foreclosed.

A fourth implication is that a processual view of DTI obliges pre-service programmes to be honest with novice teachers about the cultures of the schools they will enter. Many novice teachers begin their careers in settings where institutional pressures, collegial scepticism, time scarcity, and uneven leadership make the kind of reflective, iterative practice SEEP describes difficult to sustain (Stewart & Jansky, 2022). Pre-service programmes should explicitly discuss these systemic pressures, equip candidates with strategies for navigating them, and help them build external support structures such as virtual professional learning networks and access to research-informed resources that can sustain their practice when their immediate institutional environment does not (Diab & Green, 2024). Anticipating, rather than ignoring, the friction between idealised pre-service preparation and the realities of in-service practice is itself a SEEP-consistent move: it acknowledges the Mesosystem, Exosystem and Macrosystem layers as conditions teachers must learn to navigate.

Finally, the relationship between teacher education programmes and the schools where their graduates will teach should be strengthened into genuine partnerships rather than the more common arrangement where universities supply student teachers and schools supply placement sites. Of course, productive school-university partnerships require deliberate structural investment from both sides (McGrath, 2023). Where such structures exist, shared communities of practice that bring pre-service teachers, in-service teachers, teacher educators, and school leaders together around common pedagogical questions allow each group to learn from the others (McGrath, 2023). For example, they give pre-service teachers access to the situated knowledge that classroom practice generates, and give in-service teachers access to the conceptual resources that university-based research provides (McGrath, 2023). For research knowledge to reach practising teachers at scale, intermediary mechanisms are needed: mentor teachers trained in research-informed methods, curated research summaries embedded in professional development materials (Brown, White, & Kelly, 2021), and teacher inquiry frameworks that scaffold evidence use (Kasepalu, Saar, & Tammets, 2024; Saar & Laanpere, 2022). Such partnerships are also among the most effective ways to cultivate an orientation toward continuous inquiry into one's own practice that positions teachers as agentive professionals capable of changing school cultures rather than as technicians who reproduce them (Schnellert & Kozak, 2023). From a SEEP perspective, this scholar-practitioner orientation is what allows the Process layer's iterative design-enact-reflect cycles (Suphasri p& Chinokul, 2021), which can be decomposed into six recurring moves: clarify purpose, design for that purpose, monitor learning, pivot responsively, routinise successful moves, and continue monitoring, to take root in a teacher's career-long practice rather than fading after the formal pre-service period ends, and it provides the natural bridge to the implications for professional development that follow.

4.2.4. Implications for Professional Development

Where Section 4.2.3 addressed the initial formation of pedagogical reasoning, in-service professional development concerns its sustained cultivation within the institutional constraints and opportunities of actual schools. The principles are continuous, situated, iterative, and collaborative, but the conditions differ: in-service teachers have classrooms to experiment in, colleagues to learn with, and institutional cultures to navigate. This subsection, therefore, focuses on what those conditions specifically demand.

The first need is for classroom-embedded experimentation. Unlike pre-service teachers who rehearse in simulated or scaffolded settings, in-service teachers can test pedagogical designs directly, observe their effects on actual students, and revise in real-time. Professional development should exploit this by organising learning around authentic problems drawn from teachers' own practice (Amemasor et al., 2025). The goal is not to implement a prescribed model but to deepen technological pedagogical reasoning: pressing beyond how to operate tools toward when, why, and how particular tools can advance specific learning goals in a given subject and setting (Niess & Gillow-Wiles, 2017). Recognising this as complex knowledge work legitimises the intellectual and temporal space teachers need to plan, test, analyse, and refine orchestration, especially with soft technologies whose effects depend on pedagogy rather than artefacts (Dron, 2023).

The second need is for coaching cycles and structured peer critique. Whereas pre-service teachers develop through observation and microteaching, in-service teachers benefit from sustained coaching relationships with mentors, peers, or instructional coaches that unfold across weeks and terms rather than in isolated sessions. These relationships make pedagogical reasoning visible and improvable through representations of practice: student work, classroom video, task designs, and platform analytics that serve as shared objects for reflective dialogue (Amemasor et al., 2025). Platform analytics deserve particular emphasis here. Tools such as learning management systems and e-textbook platforms generate data on student engagement patterns, task-completion trajectories, and interaction frequencies. As other empirical research in Estonian schools has shown that teachers' use of such analytics depends on their situation-specific skills, meaning their capacities to perceive, interpret, and make decisions about classroom phenomena, which develop through iterative, collaborative inquiry into practice (Kasepalu, Saar, & Tammets, 2024; Saar & Laanpere, 2022). When embedded in coaching or collaborative planning routines, these analytics function as reflective instruments or downstream proxies for orchestration decisions that teachers can examine, discuss, and adjust. This transforms digital trace data from an administrative record into a pedagogical resource that feeds directly into the design-enact-reflect cycle (Suphasri & Chinokul, 2021).

The third need concerns the institutional conditions that enable or constrain professional development. The SEEP model's Exosystem and Macrosystem layers highlight that even well-designed professional development will fail if institutional structures work against it. Successful DTI is driven by teachers' pedagogical intentionality and willingness to act as reflective professionals (Prestridge, 2017), but that willingness requires conditions that support it. Institutions should provide the intellectual space to integrate theory, disciplinary knowledge, classroom data, and practical wisdom, as developing pedagogical reasoning is a complex intellectual endeavour that demands sustained engagement across multiple forms of knowledge (Morrison-Love & Patrick, 2025). Concretely, this means that school leaders and policymakers must attend to the conditions that make reflective practice possible: timetable structures that protect collaborative planning time, workload allocations that do not crowd out experimentation, and accountability cultures that treat pedagogical risk-taking as professional growth rather than deviation.

4.2.5. Implications for Practice

For schools and teachers, SEEP translates into a practical imperative to restructure institutional environments (Exosystem) and daily routines (Microsystem) so that continuous reflection, collaboration, and adaptive decision-making become structurally possible rather than individually heroic. This subsection addresses three interconnected school-level conditions: time and infrastructure, leadership culture, and collegial collaboration.

Decisions about timetabling, workload, and digital infrastructure directly shape whether teachers have the space to experiment, collaborate, and reflect. Insufficient time is a primary barrier to professional learning (Minea-Pic, 2020), and leaders must actively orchestrate schedules that embed collaborative planning, protect lesson-preparation blocks, and provide room for professional and curricular development (Bećirović, 2023). Equally, school leaders should ensure that qualified technical support is available so that troubleshooting does not consume instructional time (Spiteri & Chang Rundgren, 2020). Without these structural preconditions, even well-designed professional development will struggle to take root.

School leaders hold a pivotal role in translating national policies (Macrosystem) into concrete goals and supportive actions at the school level; failure to do so is one of the main barriers to turning policy into educational change (Wohlfart & Wagner, 2023). Beyond resource management, strong leadership establishes a culture of sharing, experimentation, and trust around DTI (Gottschalk & Weise, 2023; Timotheou et al., 2023). This means creating conditions in which staff are empowered to take risks with technology, framing unsuccessful attempts as opportunities for learning rather than grounds for sanction (Pettersson, 2017). Leadership should model process-oriented accountability, asking "What did we learn from this?" rather than focusing solely on easily quantifiable metrics such as the number of tools deployed (UNESCO, 2022).

Furthermore, as the SEEP model highlights the Mesosystem, the crucial links between the classroom and other contexts, particularly collegial collaboration, are key to shaping practice. The professional discourses, shared values, and collegial relationships that characterise this layer shape how educators evaluate situations and make pedagogical decisions, and through sustained engagement with them, teachers achieve the agency to navigate and reshape their practice (Biesta & Tedder, 2007; Leijen et al., 2020). Isolation is the enemy of improvement, and teachers should not be working alone (McGrath, 2023). Structures such as peer-observation cycles, lesson study, and self-study groups can make innovation a collective professional project rather than an individual burden (Gallagher et al., 2011; Jiménez Sierra et al., 2023). Professional learning communities foster collective expertise, peer support, and reflection, which are associated with high levels of teacher satisfaction (Osorio Vanegas, Segovia Cifuentes, & Sobrino Morrás, 2025), and they enable teachers to study their own pedagogy and strengthen their professional identity by positioning them as researchers of their own practice (Gallagher et al., 2011). Mentorship programmes, where experienced educators guide less-experienced colleagues, provide the continuous, contextually relevant support that keeps pace with rapidly evolving technologies (Amemasor et al., 2025). Peer-to-peer connections are crucial for transmitting new ideas and practices across a school (Reich, 2020; Karaseva, Siibak, & Pruulmann-Vengerfeldt, 2015).

Beyond these within-school structures, teachers should be engaged in reflective practice that examines the dynamic interactions between content, pedagogy, and technology (Niess & Gillow-Wiles, 2017; Suphasri & Chinokul, 2021). School leaders should conceptualise professional development as a holistic system that coordinates formal, informal, and independent learning (Barton & Dexter, 2020). Teachers often seek informal and independent learning because it offers just-in-time, contextually relevant advice that compensates for the sometimes misaligned content of formal programmes; implementing leader-initiated but teacher-led learning allows teachers to drive the content and ensure relevance (Barton & Dexter, 2020). Finally, these collaborative structures should be enriched through cross-sectoral partnerships, connecting schools with higher education institutions, community organisations, and industry to bridge the theory-practice gap and validate teachers' practical expertise alongside theoretical research (McGrath, 2023).

4.2.6. Implications for Policy

The implications for teacher development, school practice, and classroom enactment discussed above all depend on policy frameworks that enable rather than constrain them. The policy agenda should balance infrastructure investment with educator capacity development to cultivate processes and relationships that allow high-quality pedagogy to flourish over time (Hanifah, Arnyana, & Margunayasa, 2025). Meaning that at the policy level, investment in infrastructure and competence-building is necessary but insufficient to guarantee meaningful DTI alone (OECD, 2023a). The Estonian case demonstrates that even when access and skill barriers are removed, deep variation in practice persists (Chapter 3), challenging the common "if we build it, they will come" logic. Aligning with SEEP, policy should build temporal space (Chronosystem), social infrastructure (Mesosystem), and organisational conditions (Exosystem) so that technology serves sustained, equitable improvement in teaching and learning by design, not by assumption.

Effective policy implementation hinges on coherence of purpose, policy, and practice across the macro, meso, and micro levels (Butler et al., 2024), as they require coordination across different domains, levels of government, and between various stakeholders (Abildinova et al., 2024; Gottschalk & Weise, 2023). Policy failure often results from insufficient thought dedicated to the implementation process at the local level (Gottschalk & Weise, 2023; Hanifah, Arnyana, & Margunayasa, 2025). Implementing digital policies requires a local ability to allocate resources and technical support, preventing the widening of the gap between national ambitions and practical implementation (policy-implementation gap) (Hanifah, Arnyana, & Margunayasa, 2025). Policy initiatives must be tailored to the specific cultural and contextual needs of the educational setting to enhance relevance and effectiveness (Abildinova et al., 2024).

Policies informed by SEEP must therefore pivot decisively from provision to process, moving away from easily quantifiable measures focused solely on device distribution or internet access toward indicators of pedagogical process quality (Gottschalk & Weise, 2023), e.g., the frequency and quality of PR&A cycles, the density and reciprocity of collaboration within and across schools, evidence-informed refinements to tasks and assessments, and patterns of equitable learner engagement across subgroups. In practical terms, systems should monitor whether teachers iteratively plan-enact-reflect with data, whether ideas travel through professional learning communities and inter-school networks, and whether technology-supported designs are closing participation and outcome gaps. Policy must therefore actively support the Mesosystem by prioritising the creation of structural conditions for reflection, collaboration, and adaptation. This includes establishing processes to encourage open, accessible, two-way communication among local authorities and schools (UNESCO, 2023) and promoting teacher-led learning circles and professional learning communities (OECD, 2023a).

Creating such conditions means deliberately engineering the enabling environment. Teachers need time and autonomy for planning, experimentation, reflection, and refinement; rigid, top-down mandates tend to suppress the very PR&A they aim to promote (Dron, 2023). The shift in focus should move beyond one-time training events towards ongoing, practice-embedded approaches that support teachers' evolving understanding of how technology can serve their specific needs. Policies must provide intellectual space and time to allow teachers to develop as creative, agentic, learning professionals (Morrison-Love & Patrick, 2025). Structured mentorship and continuous feedback are crucial for enhancing teachers' confidence and proficiency in DT use (Amemasor et al., 2025).

As professional learning communities and community-based learning environments foster shared expertise, enabling educators to exchange best practices, reflect on experiences, and collaboratively develop innovative digital instructional strategies (Amemasor et al., 2025), policies should actively support the establishment of such communities and promote opportunities for collaboration and peer learning among teachers within a school and across different schools (UNESCO, 2023). Local education officials can formally promote school clusters or networks specifically designed to exchange expertise and resources. Policy transformation should actively support collaborative practices for teachers and partnerships at the school organisational level (McGrath, 2023).

Policy should provision collaborative planning into timetables, safeguarding professional discretion for trying and iterating new approaches. Beyond episodic workshops, systems must actively fund, stabilise, and evaluate sustained, school-based professional learning communities, peer-coaching cycles, and inter-school communities of practice that strengthen Mesosystem interconnections for shared knowledge construction. Whole-school reflection tools (e.g., SELFIE) can keep the digital ecosystem in view, helping educators surface strengths, bottlenecks, and blind spots, and then feeding those insights back into PR&A cycles at classroom and department levels (UNESCO, 2022). This approach demands a mindset of “policy ambidexterity,” separating the focus on refining current knowledge from experimenting with new practices, creating space for transformation to take hold (McGrath, 2023).

Moreover, as integration trajectories unfold over meso- and macro-time, a long-term perspective (Chronosystem) is essential, requiring multi-year commitments that create space for unlearning entrenched routines and embedding new ones. Policy should treat integration as programmatic, not project-based: stable funding lines, rolling multi-year goals, and light-touch accountability that values cumulative improvement over one-off compliance. Progress markers can be staged, looking at early indicators (e.g., increased collaboration density), intermediate indicators (e.g., evidence-informed refinements spreading across teams), and longer-term outcomes (e.g., sustained equitable engagement and achievement gains).

4.3. Limitations

The novelty of this dissertation is primarily a theoretical-conceptual contribution (the SEEP model), supported by indicative empirical evidence with methodological complexity that introduces several inherent limitations that contour the dissertation’s claims.

First, the findings are shaped by contextual boundaries. The empirical results originates from Estonia, a digitally mature context with strong infrastructure, supportive policy, and low barriers (see e.g., Pedaste & Bardone, 2023). This specific setting strengthens the dissertation’s processual claim: variation in DTI is more likely a matter of PR&A than an artefact of barriers. However, this choice narrows the dissertation’s external validity, limiting direct transferability to less mature or more heterogeneous systems. In such contexts, barrier remediation remains a necessary precursor before analytic attention can shift to enactment. Consequently, transfer to other contexts should be treated as a theoretical generalisation, requiring further testing. Furthermore, while our data spans multiple subjects and grades, it does not cover all educational settings (e.g., special and vocational education), meaning the evidence is indicative rather than exhaustive.

Second, significant limitations arise from design and measurement constraints. The core challenge lies in the epistemological difficulty of capturing in-the-moment pedagogical reasoning. Our instruments (observations, interviews, and surveys) are theory-aligned but indirect. Key proximal processes (interpretation, adaptation, reflection) are operationalised using methods with known trade-offs. For instance, self-reports (e.g., surveys, interviews) introduce the risk of recall bias (Suphasri & Chinokul, 2021), social desirability (Debnam et al., 2015), and post-hoc rationalisation (Jarcho, Berkman, & Lieberman, 2010), where teachers articulate a logical justification for an action rather than their true in-the-moment thinking. Similarly, classroom observations are susceptible to reactivity (the Hawthorne effect; Cook, 1962), where the presence of researchers may alter the very practices being studied. While triangulation across the methods mitigates these threats, it does not eliminate them (Campbell et al., 2018). Moreover, the majority of the data were cross-sectional or collected over a short time window, limiting visibility into how DTI routines consolidate, decay, or drift over longer temporal spans.

Third, analytic and interpretive choices impose further boundaries. The operationalisation of processual reasoning from complex data is an inherently interpretive act. For example, while inter-coder reliability checks were employed to ensure consistency, the conceptual complexity of the phenomenon means that our analysis represents one of several possible valid interpretations of the data. The practice profiles reported, for example, depend on defensible but not universal decisions regarding concept selection, data coding, and clustering thresholds. While stability checks suggest the partitions are robust, they should be treated as useful abstractions within a relatively homogeneous sample (Fuller & Schulz, 2021), not as fixed, objectively existing categories. Likewise, the associations linking teacher readiness to specific DTI designs are non-experimental and unmeasured confounders (e.g., institutional norms, assessment pressures) may account for part of the observed relationships. Where directional interpretations are offered, they should be treated as theory-led, testable propositions. Some subgroup analyses also approach the limits of statistical power and should be interpreted with caution, despite the application of multiple-comparison controls.

Although the dissertation has clear limitations, the convergent findings still constitute evidence to make the case that PR&A is the proximal mechanism through which provision and disposition are converted into classroom practice. That said, a stronger claim requires more evidence across contexts and timescales to show that enactment is primarily shaped by teachers' purpose-setting and goal-framing, content demands, learner characteristics and readiness, classroom activity structures and norms, tool affordances and constraints, assessment and curricular pressures, time and pacing, and the teacher's adaptive expertise and professional vision, all interacting within institutional and policy contexts over micro-, meso-, and macro-time.

Replication in less digitally mature systems, longitudinal and quasi-experimental designs, and richer process-tracing would further substantiate the argument; accordingly, the limitations point to a concrete agenda for future work: (1) richer process-tracing (e.g., interaction analysis, think-alouds, targeted sense-making probes, learner artefact trajectories) to capture proximal processes in situ; (2) longitudinal designs following the same teachers across semesters/years to observe consolidation, drift, and feedback loops to provide insights to the impact of Time; (3) cross-context replication, especially in lower-resource, special, and vocational settings, to test the transferability of SEEP's claims; (4) quasi-experimental and micro-randomised interventions (e.g., natural experiments) for stronger causal leverage on specific enactment moves; (5) open instruments and shared benchmarks (e.g., rubrics, codebooks, annotated exemplars) to improve comparability and allow for cumulative evidence; and (6) practice-linked pilots aligning professional learning and policy to process indicators (e.g., goal-framing, orchestration moves, responsiveness), with evaluation focused on enacted practice rather than enables and predictors alone.

5. CONCLUSION

The core claim of this dissertation is that meaningful DTI is not determined by provision or attitudes, but is constituted in practice through teachers' situated PR&A as it unfolds over time. In Chapter 1, the dissertation opens by situating a global paradox: after two decades of heavy investment and policy momentum (Butler et al., 2024), many classrooms still translate DT into only modest gains (Reich, 2020), or into uses that reproduce paper-era pedagogy in new wrappers (Selwyn, 2022). Systems oscillate between optimism and pushback, with some scaling back device-centric initiatives and demanding stronger evidence of meaningful use (UNESCO, 2023). The tension is not about whether technology can help, but about how it is enacted so that it reliably deepens learning (Wu, 2023), expands participation (Gottschalk & Weise, 2023), and supports equity over time (Samaniego López et al., 2025). That framing, moving from access to enactment, set the aim for the dissertation: to reconceptualise DTI. Instead of treating DTI as the downstream effect of favourable conditions, the dissertation conceptualises it as an emergent, situated, and dynamic process constituted in everyday teaching and unfolding over time. Because the problem is one of enactment, a theoretical vocabulary was required that speaks to mechanism, not merely to context.

To address this need, the dissertation proposed the SEEP model in Chapter 2. SEEP is a PPCT-informed refinement of the SETI model (Crompton et al., 2024) that centres Process, embeds Time, and disaggregates the Person into three analytically distinct dimensions (Attributes, Capacities, and Dispositions) to explain how classroom practice actually unfolds. Whereas earlier maps emphasised layers and influences but were thin on how practice is produced, SEEP positions enactment, and teachers' situated PR&A (Shulman, 1987), at its core. As argued in Chapter 2, meaningful integration is not guaranteed by policies, infrastructure, or attitudes (UNESCO, 2023); it is made in the Microsystem through iterative decisions, adaptations, and shifts in roles and relationships that accumulate across micro-, meso-, and macro-time.

The empirical foundation, provided in Chapter 3, for the dissertation's claims is derived from the DigiEfekt study in Estonia, a digitally mature context used as a critical case. Because access, skill, and policy supports are largely in place, the observed variation is argued to be more processual than structural. Findings show that, despite a broadly uniform baseline of high digital readiness, attitudes and self-efficacy, teachers enacted six distinct practice profiles differentiated primarily by pedagogical purposes, namely operational improvement, motivational engagement, and cognitive deepening, showing that the reason for tool use meaningfully shapes the manner of use (Articles III and IV). Predictive analyses (Article IV) showed that digital readiness and digital attitudes did not predict practice in correlated ways: readiness aligned with cognitively demanding profiles, while attitudes aligned with engagement-oriented ones. This differential prediction motivates the disaggregation of personal characteristics into Capacities and Dispositions in SEEP, reflecting the empirical finding that what teachers are equipped to do and what they are oriented toward doing operate as distinct dimensions of the Person rather than a single underlying construct.

DTI is thus an outcome of agentic interpretation (see also Leijen et al., 2020) rather than passive compliance. Moreover, enactment is fluid and situational (see also Karaseva, Siibak, & Pruulmann-Vengerfeldt, 2015), since a single teacher can be associated with multiple lesson-level practice types across lessons (Article II). DTI emerges as co-constructed with students and requires ongoing interpretation and adaptation (see also Fawns, 2022), which underscores the reciprocal character of DTI.

Moreover, Time is constitutive of these patterns. The Chronosystem explicitly accounts for how integration unfolds across temporal layers. Our results showed that at the micro-time layer, qualitative field notes capture on-the-fly adaptations, such as tool switching, unplanned simulations, and reconfigured roles triggered by emergent cues (Raave et al., 2022). At the meso-time layer, student usage logs exhibit distinctive temporal strategies, for example, fast-drop patterns and systematic patterns, aligned to curricular pacing orchestrated by teachers across weeks and months (Opanasenko, Pedaste & Siiman, 2022, 2023). At the macro-time layer, practice reflects sociohistorical trajectories, including Estonia's digitalisation strategy and pandemic shock that produced digital fatigue alongside retained hybrid-learning innovations (Articles I and III). Because DTI unfolds in time, improvement depends on structures that allow high-quality processes to accumulate and stabilise rather than on single interventions.

SEEP was developed abductively, through a sustained dialogue between the conceptual machinery of PPCT and the patterns of variation observed in classrooms where structural conditions for DTI were already in place. From that dialogue, the dissertation contributes a multi-faceted argument. Conceptually, it reframes DTI as a dynamic practice rather than a static outcome, specifying mediating mechanisms, namely purpose setting, orchestration moves, adaptive pivots, and role reconfiguration, through which capacity (provisions and predispositions) becomes enacted pedagogy. This process view accords with research that treats teaching (Emans et al., 2025) and DTI as a dynamic and situated phenomenon (Fawns, 2022), moment-to-moment adaptation grounded in teacher sensemaking and agency (Biesta, Priestley, & Robinson, 2015; Parsons et al., 2018), with pedagogical reasoning-in-action as ongoing interpretation and decision-making (Forkosh-Baruch, Phillips, & Smits, 2021), and with classroom orchestration as the real-time coordination of activities and resources under multiple constraints (Dillenbourg, 2013) to achieve a purpose (Dron, 2022).

Empirically, it shows that substantial heterogeneity persists under enabling conditions, displacing deficit narratives and recentering enactment as the locus of improvement. Methodologically, it demonstrates how to capture what actually changes by aligning method to mechanism and time, and it operationalises process quality via layered indicators, proximal, intermediate, and distal, rather than just measuring the static conditions around it. Practically, it specifies an improvement architecture in which design-enact-reflect cycles (Suphasri & Chinokul, 2021) convert capacity into durable pedagogy, and in which enactment equity, the equitable distribution of participation quality and cognitive demand, becomes a visible, monitored aim.

The implications of this DTI reconceptualisation are significant. For policy, in contexts where structural barriers are low, differences in DTI are less about missing resources and more about how teaching is enacted. The implication is straightforward: policy should redefine success from provision to the quality of pedagogical processes. Evaluation should privilege changes in enacted practice and learning, not tool usage counts, because, on this account, durable gains come from tuning the mechanism of enactment rather than from the transient affordances of any single technology (Dron, 2023).

DTI depends on the time and social infrastructure needed for iterative cycles to take root (McGrath, 2023), including regular collaboration, access to coaching, and a baseline of trust that permits experimentation. At the school level, professional development should be situated and practice-based (Amemasor et al., 2025), revolving around coached cycles grounded in classroom artefacts so that PR&A becomes visible and improvable (Jiménez Sierra et al., 2023). This applies equally at the pre-service level, where the preparation of future teachers should shift from training on tools toward cultivating the situated reasoning and embodied confidence through which technology becomes pedagogically meaningful. Investing in pre-service preparation is investing in the habits of judgment that teachers will then exercise across their careers.

This also redirects investment: policy and leadership should prioritise structures that scaffold the mechanism (time for planning and reflection, formative data flows, coaching cycles, collaborative norms, and timetable designs that permit iteration), and professional training and development should emphasise adaptable techniques that work across different tools, ensuring skills remain relevant as platforms evolve.

For research, the priority is to study the logic and flow of enactment (Hofmann, Paavola, & Rainio, 2024) rather than to catalogue tools and usage. This means documenting why a teacher made a particular move, what classroom cues triggered it, and how the move affected student learning. Methods should be grain-aligned so micro-time decisions within a lesson can be connected to meso-time routines across weeks and to macro-time shifts across terms or years.

What generalises from this work is a theory of how capacity becomes practice through the interlocking proximal processes of purposeful goal-setting, deliberate orchestration moves (Dillenbourg, 2013; e.g., task design, grouping, timing, monitoring, questioning, transitions), and adaptive adjustments in response to emergent evidence, iterated and stabilised over time (Parsons et al., 2018). In other words, tools are interchangeable carriers; the engine is teachers' PR&A as it unfolds at micro-time (within a lesson), consolidates at meso-time (across sequences and terms), and is shaped by macro-time structures (policies, assessments, scheduling). In this sense, the mechanism SEEP names at its core is what the Aristotelian tradition calls phronesis: the practical wisdom to discern the right action in particular circumstances that cannot be settled by rule alone (Kinsella & Pitman, 2012). Thus, when the tools change, e.g., from an e-textbook to a learning management system, or from slideware to generative-AI assistants, the underlying iterative mechanism remains: clarify purpose → design for that purpose → monitor learning → pivot responsively → routinise successful moves → continue monitoring. This reframes improvement: progress is not about logging more tools or features, but about strengthening process indicators such as clarity of goals, cognitive demand of tasks, quality of monitoring and feedback, timeliness of adaptations, and the reflective routines that scaffold them.

This dissertation argues that in DTI, what ultimately matters is the teachers' capacity to interpret evidence, adapt in context, and steward improvement across time, enabled by protected time for joint planning and reflection (Minea-Pic, 2020); coaching cycles and peer observation; tool-agnostic, practice-centred professional development that rehearses transferable enactment moves (Ajani, 2024); leadership that reduces initiative overload and creates a safe-to-try culture (Pettersson, 2017; Timotheou et al., 2023) and accountability to reward what is valued in quality DTI (UNESCO, 2023): teachers attuned to their learners and context who use evidence to set purpose, orchestrate, and adapt so that DTI can be meaningful within its context (Parsons et al., 2018). Accordingly, this dissertation argues for trusting teachers as the best experts of their own classrooms (Emans et al., 2025), rather than prescribing practices to them, for providing the time, support, and professional infrastructure that enables them to enact with full professional agency.

In conclusion, the dissertation moves the conversation about DTI from mapping conditions to explaining how integration is enacted and when it consolidates into durable pedagogy. SEEP offers a model that both explains why DTI varies under comparable conditions and helps us understand what teachers are actually doing when they integrate digital tools in the flow of practice. Meaningful DTI is not bestowed by favourable conditions; it is enacted, co-constructed, and sedimented over time. If educational systems seek technology that deepens learning, expands participation, and advances equity, they must invest steadily in the everyday cycles through which teachers and learners make pedagogy together, and in the temporal and social infrastructures that allow those cycles to compound.

A final note on what SEEP contributes beyond the DTI case. The model was developed from the puzzle of why DT integration varies under digitally mature conditions, and the indicative empirical evidence presented in this dissertation comes entirely from that case. Yet the structural features the model offers, situated orchestration, the disaggregation of personal characteristics into Attributes, Capacities, and Dispositions, the bidirectional treatment of context, and the embedding of multiple temporal scales describe how teachers convert any new resource, strategy, or pedagogical demand into actual classroom practice. In this sense, DTI is best understood as the empirical case through which SEEP was generated, not as the limit of what SEEP explains. The dissertation's broader contribution is to teacher education and pedagogical practice generally: it offers a vocabulary and a structure for examining how teachers exercise situated agency in the face of any new instructional challenge, of which the integration of DT is one consequential and currently pressing example.

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SUMMARY IN ESTONIAN

Sotsiaal-ökoloogiline rakendusprotsessi mudel (SÖRM)

Sissejuhatus

Digitehnoloogia (DT) on haridusmaastikku põhjalikult muutnud, pakkudes uusi viise teadmiste loomiseks ja omandamiseks. Hoolimata pikaajalistest investeeringutest seadmetesse ja koolitustesse, on tehnoloogia tegelik rakendamine ja selle mõju jäänud ebaühtlaseks ning oodatust väiksemaks. Tehnoloogia potentsiaali ja selle tegeliku kasu vahel püsib lõhe, mis on valdkonnakeskne lahendamist vajav probleem. Seni on liigselt keskendutud küsimusele, millised tingimused (näiteks seadmed või oskused) on digitehnoloogia kasutamiseks vajalikud. Kuigi tingimused on olulised, on tähelepanuta jäänud protsess ise ehk see, kuidas ja miks õpetajad neis tingimustes tegelikult tegutsevad ja oma õpetamist kujundavad.

See vaatenurk viib meid tagasi Aristotelese „praktilise tarkuse“ ehk froneesi juurde, mis tähistab oskust teha konkreetses olukorras õigeid otsuseid, mida ei saa teha pelgalt reeglitele tuginedes. Just see protsess on lüli DT kasutamiseks tingimuste loomise ja DT mõjusa kasutamise vahel. Kuni me ei mõista piisavalt klassiruumis toimuvat, on raske luua mõjusaid koolitusi või kujundada hariduspoliitikat. Kuna DT kasutamine ei ole ühekordne sündmus, vaid ajas arenev praktika, on vaja raamistikku, mis sellega arvestaks. Käesolev doktoritöö täidab selle teoreetilise lünga, väites, et just protsessi mõistmine aitab ületada lõhet DT potentsiaali ja mõjusa kasutamise vahel. DT tegelik väärtus peitub selles, kuidas ja miks seda kasutatakse.

Doktoritöö eesmärk ja uurimisküsimused

Doktoritöö eesmärk on kahetine: töötada välja sotsiaal-ökoloogiline rakendusprotsessi mudel ehk SÖRM (originaal ingl k *socio-ecological enactment process* ehk *SEEP* mudel) ning pakkuda sellele esmast empiirilist kinnitust. Nende eesmärkide saavutamiseks püstitati kolm omavahel seotud uurimisküsimust, mis uurivad (1) DT rakendamise kontseptualiseerimist, (2) õpetajate DT kasutamist ning (3) individuaalsete tegurite rolli DT kasutamisel.

Töö järgib abduktiivset lähenemist, kus empiirilised tulemused näitasid DT kasutamises varieeruvust, mida senised staatilised mudelid ei ole suutnud seletada, suunates otsima uut, protsessikeskset raamistikku. Käesolevas töös esitatakse kontseptuaalne mudel (ptk 2) enne empiirilisi tulemusi (ptk 3), et pakkuda lugejale vajalik sõnavara ja raamistik empiiriliste tulemuste tõlgendamiseks.

Metoodika

Väitekiri tugineb riikliku uurimisprojekti „DigiEfekt“ (2020–2023) andmetele. Uurimistöö viidi läbi Eestis, kus DT kasutamiseks on tehnilised takistused suures osas ületatud, õpetajatele on pakutud süsteemset koolitust ja neil on suur otsustusvabadus. See võimaldas keskenduda küsimusele, kuidas õpetajad oma vabadust ja olemasolevaid võimalusi tegelikus praktikas kasutavad.

Doktoritöö põhineb kombineeritud meetodil, kus empiirilise tuumiku moodustavad autori publikatsioonid (Artiklid I–IV), mis toetuvad 169 põhikoolitunni (3., 6., 9. klass; eesti keel, matemaatika, loodusained) vaatlusele, 79 õpetajaga vaatlusjärgselt tehtud poolstruktureeritud intervjuudele ning õpetajatega läbi viidud küsitlustele (hoiakud, digivalmisolek, enesetõhusus). Tervikliku SÖRM-i empiiriliseks põhjendamiseks sünteesiti autori uuringute andmeid koos projekti uuringute tulemustega, mis kasutasid teisi andmeallikaid (nt Opiq platvormi logiandmed ning info õpilaste digipädevuse kohta).

Andmeid analüüsiti kolmel viisil: (1) klasteranalüüsiga leiti erinevad tundide tüübid; (2) latentsete profiilide analüüsiga (LPA) rühmitati õpetajad, (3) regressioonanalüüsiga (MLR) uuriti, millised tegurid neid rühmi mõjutavad.

Tulemused ja arutelu

Esimesele uurimisküsimusele vastates (ptk 2) arendati välja SÖRM, mis defineerib DT rakendamise kui pideva, olukorrast lähtuva ja ajas areneva protsessi. SÖRM-i alusel kujuneb DT rakendamine reaalsuses välja seitsme komponendi vastastikmõjus: õpetaja (isik), tema tegevused (protsess), vahetu õpikeskkond (mikrosüsteem), seosed teiste keskkondadega (mesosüsteem), institutsionaalne keskkond (eksosüsteem), ühiskondlikud tingimused (makrosüsteem) ja ajaline mõõde (kronosüsteem).

Teise uurimisküsimuse analüüs (ptk 3) näitas, et DT kasutamine jaguneb kaheks tasandiks. Esmalt, tundide tasand, kus nähtus neli erinevat õpetamisviisi (nt „Süvendav“ ja „Motiveeriv“) (vt Artikkel II). Õpetajad ei kasuta igas tunnis sama meetodit, vaid kohandavad oma tegevust paindlikult vastavalt tunni eesmärgile ja olukorrale (vt Artikkel I ja II). Teisalt, õpetajate tasand, kus eristus kuus üldist pedagoogilist suundumust (nt „Süvitsi sukeldujad“ ja „Tõhususe insenerid“), mis näitavad õpetaja keskmisi eelistusi (vt Artikkel III). Kõige olulisem järeldus tekkis nende kahe tasandi võrdlemisel: kuigi õpetajatel on oma väljakujunenud eelistused, muudavad nad oma tegevust igas tunnis vastavalt vajadusele. See näitab, et tehnoloogia kasutamine ei ole jäik stiil, vaid dünaamiline protsess.

Kolmandale uurimisküsimusele vastates (ptk 3) selgus, et individuaalsed tegurid küll suunavad, kuid ei määra õpetaja profiili (vt Artikkel IV). Digivalmisolek ennustas tugevalt nõudlikumate DT meetodite kasutust, samas kui positiivsed hoiakud olid seotud pigem motivatsioonile keskendunud profiilidega. Siiski jäi suur osa DT kasutamise varieeruvusest koostatud mudelitega selgitamata, mis kinnitab, et lõplik praktika kujuneb välja vahetus protsessis, kus õpetaja kohandub konkreetse klassi ja tunni vajadustega.

Järeldused ja panus

Töö põhisõnum on, et DT rakendamine on aktiivne tegevus, mitte passiivne tagajärg. DT mõtestatud rakendamine ei ole ressurssidega tagatud staatiline tulem, vaid dünaamiline otsustusprotsess õpetaja eesmärkide, õpilaste vajaduste ja konteksti vahel. Teoreetiline panus on SÖRM, mis pakub terviklikku raamistikku DT rakendusprotsessi mõistmiseks ja selgitamiseks. Ainult tingimustele keskendumine ei selgita, miks praktikad isegi DT kasutamiseks soodsas keskkonnas nii suuresti varieeruvad. SÖRM täidab selle lünga, lisades varasematele staatilistele mudelitele protsessi kihid.

Väitekirja peamine teoreetiline panus on SÖRM-i väljatöötamine, mis pakub senisest terviklikumat raamistikku digitehnoloogia rakendamise mõistmiseks. Erinevalt varasematest ökoloogilistest mudelitest selgitab SÖRM, kuidas pedagoogilised praktikad tegelikkuses kujunevad, varieeruvad ja ajas muutuvad. See teoreetiline raamistik ulatub DT rakendamisest kaugemale, pakkudes sõnavara ja struktuuri õpetajate olukorrapõhise agentsuse uurimiseks mistahes uue pedagoogilise väljakutse ees. See tähendab, et SÖRM-i abil on võimalik kirjeldada, kuidas õpetajad teisendavad mistahes uue ressursi, strateegia või pedagoogilise vajaduse tegelikuks klassiruumipraktikaks.

Empiiriliselt näitab töö, et isegi digitaalselt küpses haridussüsteemis nagu Eesti püsib suur varieeruvus selles, kuidas tehnoloogiat tegelikult rakendatakse. Täpsemalt, kuigi õpetajatel on oma eelistatud pedagoogilised suundumused ehk profiilid, kohandavad nad oma praktikaid igas tunnis paindlikult vastavalt olukorrale ja eesmärkidele. Leiti, et kuigi individuaalsed tegurid nagu digivalmisolek ja hoiakud suunavad õpetaja valikuid, ei määra need lõplikku praktikat. See kinnitab töö põhiväidet, et tähenduslik tehnoloogia rakendamine on teadliku pedagoogilise otsustamise, mitte ressursside olemasolu automaatne tulemus.

Praktilises plaanis soovitab töö suunata hariduspoliitika, koolijuhtimise ja professionaalse arengu fookuse tingimuste loomiselt rakendamisprotsessi toetamisele. Kuna soodustavad tingimused on Eestis suures osas juba olemas, tuleb edaspidi keskenduda just protsessi kvaliteedile. Õpetajatele tuleb tagada nende kõige olulisem ressurss ehk aeg koos struktuurse toega ühiseks planeerimiseks, katsetamiseks ja refleksiooniks. Konkreetselt tähendab see näiteks õpetajate tööplaani integreeritud koostööaega, usaldusliku ja eksperimenteerimist soosiva koolikultuuri kujundamist ning üleminekut ühekordsetelt koolitustelt pidevale praktikapõhisele toele läbi õpikogukondade ja mentorluse.

Kokkuvõttes näitab SÖRM, et tehnoloogia hariduslik väärtus realiseerub vaid õpetaja tegevusvõimekuse ja praktilise tarkuse kaudu. See võimekus tugineb õpetaja kogemustele ja selgele sihile, kuid saab päriselt avalduda vaid turvalises koolikeskkonnas, mis soosib katsetamist ja ühist õppimist. Praktikas tähendab see oskust mõista klassiruumis toimuvat ning leida tasakaal oma pedagoogiliste veendumuste ja keskkonna seatud raamide vahel, aga ka oskust tunda ära hetk, mil tehnoloogia toetab päriselt õppimist, ning vabadus lähtuda olukorrast ja õpilasest, mitte harjumusest või välisest survest.

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