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Digital learning ecosystems: subjects, spaces, practices and relations in the post-digital school

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Abstract: Digital learning ecosystem offers an interpretive framework capable of capturing the complexity of teaching-learning processes, understood as the dynamic interplay of heterogeneous variables: subjects, mediators, technologies, spatial and temporal dimensions, relational patterns and socio-cultural contexts. Drawing on an enactive, sociomaterial and post-digital theoretical perspective, this study investigates digital learning ecosystems, with particular attention to the integration of technology into instructional planning. A Mixed Methods Convergent Design was employed, combining Collaborative Research, including video-recording and co-explication interviews with N=11 teachers with a questionnaire collected from N=99 teachers of the host school and N=1023 Italian teachers. Data were analysed through thematic analysis, thematic narrative analysis, quantitative content analysis and bivariate statistics. Findings reveal that the ecosystem is structured around four interaction modes between teachers, students and devices and around multiple variables, visible and invisible, related to the digital learning processes. Despite sustained public investment in school digitalization, approximately 25% of the large sample never or rarely uses technology in teaching, citing difficulties in managing the ecosystem's multiple variables. The study proposes a framework to support teachers in designing intentional, situated and productive digital learning ecosystems.

Keywords: Digital learning ecosystem; Mixed Methods; Post-digital education.

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1. Introduction

Teaching and learning processes unfold within complex configurations shaped by the interplay of heterogeneous variables: the subjects involved, their experiences beyond the school walls, mediators, pedagogical practices, didactic mediation, technological devices, curricular design choices, institutional and cultural contexts and the time and space in which action takes place. Analysing these variables in their dynamic interdependence gives rise to an interpretive category capable of capturing the full complexity of the educational phenomenon: the digital learning ecosystem.

This paper reports on a research project whose aim was to identify, describe and analyse this construct by drawing on the practices and perceptions of the teachers involved. The inquiry was motivated by the need to understand how technology can be meaningfully and productively integrated into teachers' instructional planning

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within a systemic framework, focusing on multiple dimensions of the teaching-learning process. Thanks to substantial and recent funding initiatives (including PON, POC, PAR, the PNRR, Next Generation Classrooms, the PNSD for integrated digital teaching in Southern Italy, and the *Decreto Cura Italia*) schools have been able to acquire a considerable number of digital devices. However, for these resources to be effectively integrated into teaching practices, they must be incorporated into teachers' instructional planning. Teachers, in turn, are called upon to identify solutions that are sustainable within everyday school routines and, above all, pedagogically productive and meaningful in terms of fostering the acquisition of new competences.

2. Background

In 1935, Tansley introduced the term "system" to foreground the interactions among the elements inhabiting a given environment, drawing a distinction between biotic components (living organisms) and abiotic ones (non-living matter). His theorisation rapidly became a paradigm: the ecosystem cannot be partitioned into its constituent parts, nor conceived as their sum, but only as the interaction among them. Systems thinking revolutionised and moved beyond the Cartesian analytical paradigm (Capra, 2014), to the extent that it came to be regarded as a "plural paradigm" (Dozza, 2022, p. 15). For this reason, it has been adopted across many disciplines far removed from biology, such as computer science and economics (Pickett & Cadenasso, 2002; Daly, 2002). Education is among these fields: teaching and learning situations are animated by individuals who act within a small community, namely the classroom, which is not only a social system but also a physical space. Classrooms are, accordingly, «adaptive socio-technical systems, populated by technological species (tools, services, resources) and social agents (students, teachers, technicians) who interface with one another, reproducing what takes place in a biological ecosystem, within which two components interact: the biotic, composed of living organisms belonging to various species, and the abiotic, constituted by environmental elements: air, soil, temperature, light, and others» (Rossi & Pentucci, 2021, p. 261).

The interaction among components constitutes the conditio sine qua non. Viewed through an enactive lens (Rossi, 2011), the non-linear character of didactic action comes into focus: knowledge production is triggered by the interaction among subjects and between subjects and their environment and materials, not transmitted automatically and hierarchically from teacher to group. Didactic action is inherently autopoietic (Maturana & Varela, 1985): the teacher prompts the student towards change, functioning as a perturbator (Sibilio, 2013) and, viceversa, in a «co-evolution that follows from the accordance of teacher-learner actions» (Sibilio, 2020, p. 64). As a meeting point of multiple variables and of the diverse actors who inhabit it, the ecosystem thus takes shape as a Third Space, a site of negotiation of meanings (Bhabha, 1994; Flessner, 2014), serving as an aggregator, a space that encourages both learning and the production of artefacts and knowledge.

Within this framework, technology becomes a further element that teachers and students must engage with (Potter & McDougall, 2017), whether because it features in teachers' planning decisions or simply because, in the current post-digital landscape, the boundary between the digital and the non-digital has ceased to be meaningful (Eugeni, 2015; Jandric & Hayes, 2020; Moriggi, 2024; Lamb & Carvalho, 2024). We live onlife (Floridi, 2015) and within an infosphere (Floridi, 2017), in which the Third

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Space is osmotically porous to the reception of information, media languages, digital artefacts and virtual communicative channels.

The openness towards the external world, ontologically bound up with the very nature of the Third Space, means that every individual who inhabits this space brings along a personal experiential history that enters into dialogue with those of the other actors. The ecosystem is thereby in constant exchange with all the systems its inhabitants move through: family, peer networks, school, and even those with which only indirect contact is maintained, in a systemic conception of space that has been shown to exert decisive influence on human development (Bronfenbrenner, 1986; Bateson, 1976). The school is, in fact, a heterotopia: an autonomous space that «develops its own internal rules and specific languages, ways of being that are the product of the continuous interactions among the members of the community, of the symbols, the technologies employed, and the shared practices. Yet this system and its internal rules only make sense in constant dialogue with the external world, with which they are necessarily in relation» (Rossi, 2011, p. 130).

Beyond the interaction with other actors and with space, the digital learning ecosystem is defined by its engagement with artefacts, what might be called the abiotic dimension of the ecosystem. From a sociomaterial standpoint, objects interact with human beings and human beings interact with one another through objects; the latter must therefore be included in any analysis of human relations (Law, 1992; Latour, 2005). Objects interface through affordances, which constitute both their function and its social realisation: a device within the ecosystem is not merely a piece of hardware but carries the didactic purpose for which it has been chosen (Rossi, 2010). The sociomaterial approach resists classifying the world in binary terms (human/non-human, material/social), seeking instead to trace a relational ontology between them (Acton, 2017).

The dissolution of binary oppositions takes on additional significance today within the more-than-human framework: the boundary between the human and the digital, between the human and the technological can no longer be mapped with any confidence. For example, if artificial intelligence becomes an extension of the mind, capable of augmenting and enhancing human capacities (Ardizzi, 2025), the human being becomes something akin to a cyborg (Haraway, 1985; Rossi & Rivoltella, 2019). Ecosystems, therefore, do not simply bring biotic and abiotic actors into relation; they create conditions for the hybridisation of functions, actions and spaces of reflection in which it grows ever harder to distinguish the human from the artificial. On one side stands cognitive devolution to AI (Cioci, 2025b): certain cognitive and sensory functions now performed exclusively by the machine (such as spatial orientation). On the other stands enhancement (Benanti, 2023; Chiaratti, 2025; Mollick, 2025), the amplification of capacities that lie beyond any individual human mind: comparing thousands of texts in seconds, writing code without being a programmer, translating into languages one does not know, and so on. All of this takes place within the digital learning ecosystem, which the teacher must design and govern in such a way that social and material relations, and the post-digital, more-than-human condition, create conditions genuinely favourable to students' active learning.

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3. Materials and Methods

Studying digital learning ecosystems demands the observation and analysis of multiple interacting variables; a correspondingly complex and multi-layered research design was therefore required, one capable of addressing different focal questions through varied modes of data collection and analysis. The aim was not to isolate a phenomenon and describe it, but to devise rigorous strategies for rendering visible both the observable dimensions of the ecosystem (space, subjects, mediators) and its less visible ones (time, the relationship between devices and activities, the meaningfulness of instructional designs, the relationship between subject and activity, patterns of interaction, and so forth), as these unfolded before the researcher. Moreover, since the ecosystem is, as noted above, osmotic with respect to the external world, it was necessary to situate these variables in relation to both the institutional context of the school where the research took place and to the broader national context. This granularity, which is a defining feature of the ecosystem, required working with three distinct samples: N=1023 Italian teachers recruited voluntarily through social media channels and through the involvement of school institutions; N=99 teachers at the I.C. "M. Hack" school in Castellalto-Cellino (TE), which hosted the research; and N=11 teachers who took part in the Collaborative Research strand.

The research design was structured around a Mixed Methods approach, in the form of a Convergent Design (Creswell & Plano Clarke, 2018), in which the qualitative strand (data gathered through Collaborative Research and open-ended questionnaire items) and the quantitative strand (the same data analysed through quantitative methodologies, together with the closed questionnaire items) were fully integrated, including through crossover analysis (Ortalda, 2022; Hitchcock & Onwuegbuzie, 2020). Specifically, the codes produced through thematic analysis (Braun & Clarke, 2022) and thematic narrative analysis (Riessman, 2008) were converted into 0/1 dummy variables and subsequently related through bivariate statistics to respondents' demographic data (chi-square and Cramér's V). Additional statistical analyses (one-way ANOVA, Spearman correlation) were carried out, following verification of distributional normality, on Likert-scale self-perception data (1–10) concerning teachers' use of digital instruction and its relationship to demographic variables.

The research design, across its two phases and the analytical methodologies employed, is set out below in figg. 1, 2, 3.

Figure 1-2. Qualitative e quantitative phases of data collection

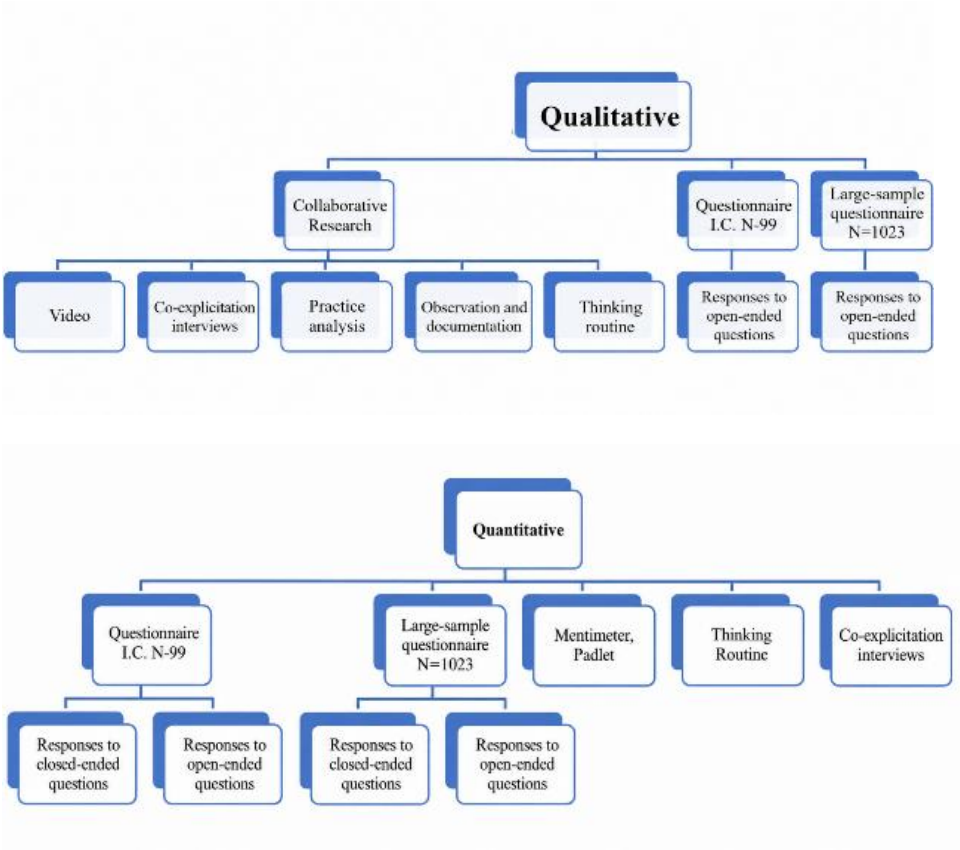
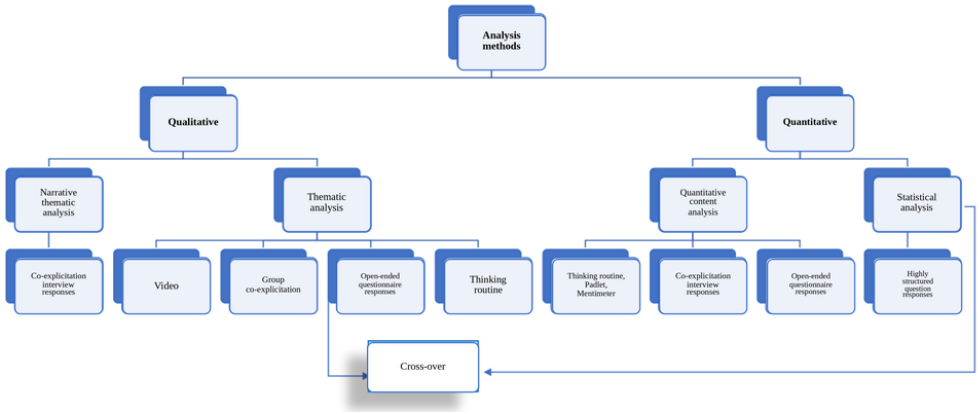


Figure 3. Analysis methods.



Collaborative Research (Desgangé, 1997; Vinatier, 2013a; Altet et al., 2006) provided access to an in-depth view of teachers' practice: their day-to-day classroom activity was video-recorded using both fixed and mobile camera angles. The recordings (approximately 60 hours of footage) were edited and subsequently viewed by the teachers themselves, who were thus able to identify, alongside the researcher, through

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a process of co-explication (Vinatier, 2013b; Vermersch, 2005), the variables at work within the ecosystem. The distinctive contribution of Collaborative Research lies in the reflective dimension it opens up: rather than simply collecting data, this approach involves working closely with practitioners who can observe their own classroom conduct, identify its strengths and limitations, and contribute to the analysis of the phenomenon under study in the search for effective solutions. It enacts what Damiano (2006) has called a New Alliance between the university and the school.

All analyses were conducted using dedicated software: IBM SPSS v. 28 for univariate and bivariate statistical analyses; MAXQDA 2022 for thematic analysis of the video material, interviews, and open-ended responses; and T-LAB 10 for quantitative content analysis. The computational efficiency of these tools facilitated the integration of the two research strands.

Finally, regarding the presence of three samples of varying size, it should be noted that each is capable of meeting the requirements of informational power (Malterud et al., 2016), since each corresponds to a distinct level of the research design. The small sample enables depth, being deployed in the qualitative strand, where data saturation is achieved through individual and group co-explication interviews and through video analysis; the medium and large samples move, in part, towards the quantitative domain, where the greater number of participants compensates for the constraints of closed-format or self-perception-based items. In the case of the I.C. sample, coverage relative to the reference population is substantial (99 respondents out of 130 teachers). As regards the N=1023 sample, account was taken of the total Italian teacher population which, in the academic year 2021/2022 during which the questionnaire was administered, amounted to 684317 individuals (Principali dati della scuola – Avvio Anno Scolastico 2021/2022). Using an online tool (https://www.calculator.net/sample-size-calculator.html), the required sample size at a 95% confidence level and a 3% margin of error was calculated at 1066 units. Turning to the characteristics of the 1023 respondents: the most represented age bracket is 45-55 (N=374); it should be noted, however, that those aged over 55 outnumber those in the 35-45 bracket (N=305 vs N=277), reflecting the state of the Italian teaching profession, a workforce that struggles to renew itself through the entry of younger practitioners. With respect to school level, the distribution is broadly symmetrical: pre-primary and upper secondary teachers are least represented (N=120 and N=128), while primary and lower secondary teachers are roughly three times as numerous, with N=395 and N=380 respectively. The final demographic variable considered is experience: novice teachers, those with fewer than five years in the profession, account for 13% of the sample. In light of the non-probabilistic nature of the sample and its imbalance with respect to certain characteristics of the school population, the descriptive results should be interpreted in exploratory terms. More specifically, the percentages reported in the contingency tables do not represent the distribution of the overall population, but rather describe the internal distribution of cases within specific subgroups, such as school level or age group.

4. Results and discussion

Across every research instrument, the ecosystem left identifiable traces: in the video analysis, for example, an initial structuring of the ecosystem became visible.

Figure 4. Themes emerging from video analysis.

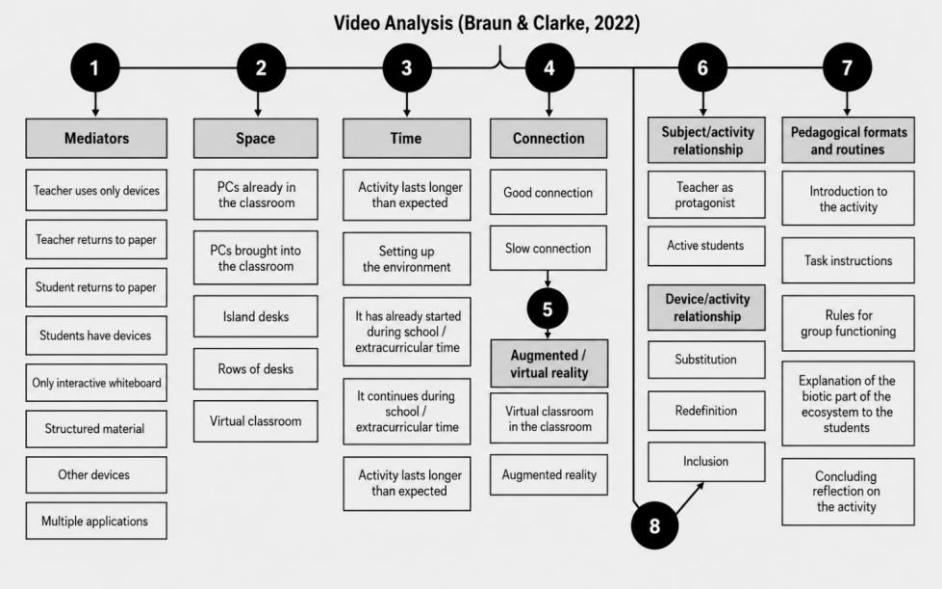


Figure 4 displays the themes (in grey) into which the numerous codes (in white) were aggregated. A first reading reveals the presence of readily foreseeable elements (space, tools, connectivity) alongside others that are less immediately apparent: relations, interactions, instrumental competences, unforeseen events, pedagogical formats. Space and mediators represent only some of the variables in play; even the video footage makes clear how consequential didactic choices are within teaching-learning processes and their associated interactions, in a chain mechanism in which each link must function as intended if the informational flow is not to be broken. Consider, for instance, the relationship between device and activity: the decision to incorporate a technological tool into a lesson must derive from the need to pursue a defined pedagogical objective. Computers, tablets and applications cannot be chosen for their entertainment value alone, or for a so-called "wow effect"; they must be meaningful with respect to the learning process, for instance by enhancing collaboration (enabling communication, sharing of artefacts, collaborative writing), generating artefacts (videos, digital presentations, podcasts, and the like), or developing students' critical awareness in searching for, selecting, and evaluating information online. The device thus ceases to function merely as a tool and becomes charged with the didactic purpose attributed to it (Rossi, 2010); it must be experienced as irreplaceable relative to analogue alternatives (SAMR model, Puentedura, 2003; RAT model, Hughes, Thomas & Scharber, 2006). If the same instructional design can be realised just as effectively on paper, there is little justification for the time and energy required to establish a digital ecosystem.

Setting up the environment is indeed costly, in several respects:

- Spatial logistics: devices must arrive in the classroom adequately charged; furniture must be arranged to facilitate exchange and collaboration among participants (Tosa, 2019; Weyland et al., 2019).

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- Time: students are not always proficient with the tools and may work slowly; preparing activities is often laborious; the network connection may fail.
- Energy: when unforeseen difficulties arise that teachers struggle to manage (Pentucci et al., 2023), the response may involve activating what have been called pedagogical formats (Pentucci, 2018), as an abrupt return to paper-based work or to conventional instructional schemas, thereby undoing the original design.

Time, in particular, proves to be an anxiety-laden variable for teachers: quantitative content analysis of the interview transcripts (Losito, 2007) identified it as one of the ten most frequent words, appearing in co-occurrence with terms such as "rush", "fall behind", and "not manage to finish".

Equally, if the teacher selects mediators without attending to their affordances in relation to the intended recipients, without, that is, situating operational and didactic choices within the actual context, students' instrumental competences will be stretched beyond their limits and the likelihood of completing the assigned task will be low.

Device selection is, moreover, shaped by the modes of interaction the teacher intends, consciously or otherwise, to enact. Four such modes were identified:

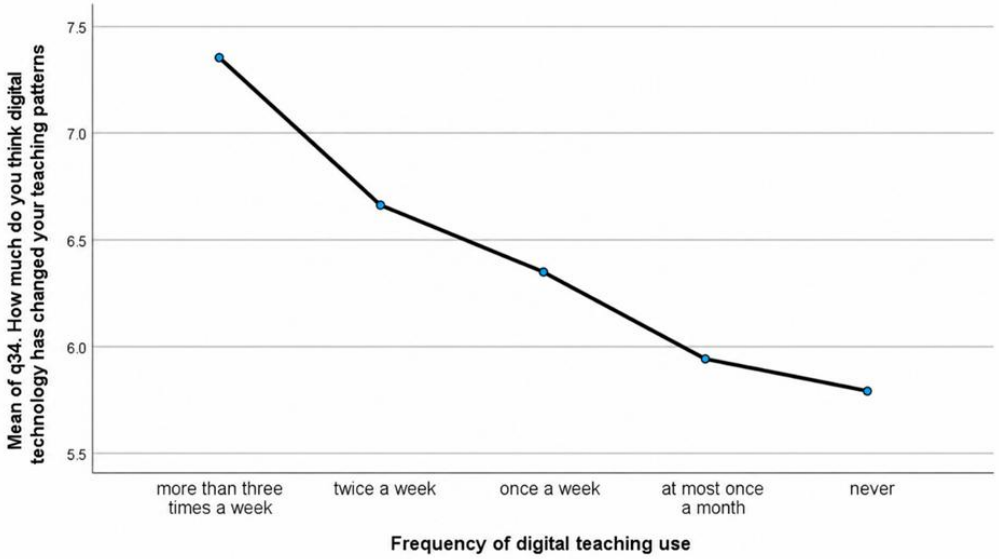
- Teacher as protagonist: the teacher uses the devices alone (e.g., presenting or playing a video on the interactive whiteboard) while students watch as an audience. Logistical demands are minimal, but so too is student engagement in the co-construction of knowledge.
- Teacher–student–device: the teacher calls individual students, one at a time, to the interactive whiteboard, computer, or monitor. Organisation here is also relatively simple, but classroom management is more demanding and may trigger disruptive behaviour among students waiting their turn. Each student's didactic and cognitive investment is, moreover, limited, mediated as it is throughout by the adult who inevitably holds the reins of the process.
- Student–device: every student has their own device. The logistical challenge is at its peak: a large number of devices must be transported to the classroom, or the entire group must move to a computer laboratory, which severs the use of technology from the fabric of daily school life (Papert, 2001). Each student is active and at the centre of the learning process, but the teacher must field every individual technical problem, every gap in instrumental skill, every cognitive difficulty.
- Student–student–device: students work in groups sharing one or two devices. Organisation is challenging but somewhat less so than in the preceding configuration, given the smaller number of devices required. Students support one another through peer tutoring (Topping, 1996) and the teacher can attend to the class as a whole, leaving small difficulties to be resolved through group negotiation and collaboration.

The analysis of the co-explicitation interviews confirmed the issues already discussed and also made it possible to uncover a number of background elements concerning teachers' design choices that would otherwise have remained invisible. For example, the interviews brought to light the role assigned to technology by teachers, their self-perceptions in terms of instrumental and pedagogical competences, their uncertainties, and the extent to which their choices were shaped by the resources actually available. In particular, the findings suggest that it is the presence of devices within the school setting that determines the design of the micro-planning process, rather than the other way around: teachers are required to adapt to the available resources and to construct their work accordingly. Similarly, the choice of

applications depends on the access granted by the institution to students' accounts, a condition that may significantly constrain teachers' creativity.

With specific reference to instructional design, however, the analysis of the questionnaire responses showed that, both in the medium-sized and in the large sample, the design of digital teaching activities is, in most cases, limited to the preparation of materials to be shared with students or, at most, to an outline of the steps to be followed (Cioci, 2025a). In practice, only a limited number of teachers attempt to anticipate and manage the multiple variables involved, by drawing on a variety of resources and proposing challenging and generative tasks. More importantly, the large-sample data revealed that, even after the COVID-19 experience, approximately 25% of the teachers interviewed never use technology, or use it at most once a month. Conversely, those who use it more frequently report positive effects in terms of changes in their own teaching schemes ($\varrho = 0{,}277$, $p < 0{,}001$). Teachers who do not use technology tend not to perceive it as effective (Fig. 5).

Figure 5. Frequency of digital instruction use by school level



The integration of digital tools into daily classroom practice thus remains far from settled or self-evident, notwithstanding the pandemic experience, the expansion of connectivity infrastructure (PON-FSRE Local Area Networks, wired and wireless, in schools, 2021), the broadening of the technological provision noted above and successive waves of teacher professional development (up to and including Ministerial Decree 66/2023). As teachers themselves explained in response to an open-ended question, this situation appears bound up with the difficulty of managing the variables that make up the digital learning ecosystem. A perceived lack of digital competence, low self-efficacy (Joo et al., 2018; Oddone, 2015), difficulty in setting up learning environments, the complex logistics of time management and the burden of administering student accounts all act as deterrents for the 25% of respondents who rarely or never engage with digital instruction.

5. Conclusions

The evidence gathered makes clear the sheer complexity of the digital learning ecosystem. Every variable bears on every other: time, space, processes, relations, pedagogical routines and more are interconnected, much like the interlocking gears of a clockwork mechanism. The first and central cog is interaction, which represents the very heart of the digital learning ecosystem and sets all the others in motion, which in turn activate further ones. The relations at play are anything but linear. A teacher who wishes to integrate technology into their classroom must reckon with logistical challenges, reflect carefully on the effects of technology on student learning and take account of what happens beyond school, particularly in students' digital lives. In a post-digital world, even those who choose not to use devices will be confronted by the presence of technology: it inhabits the classroom and the lives outside it of even very young students. The challenge for the teacher is to learn how to govern and orchestrate these variables, designing ecosystems with genuine intentionality. One productive pathway is to interrogate instructional planning across three dimensions:

- Biotic dimension: this dimension concerns the human resources available within the educational ecosystem, including, for example, the presence of co-teachers, colleagues or support staff who may assist in setting up and managing the learning environment. It also involves careful consideration of the learners themselves, so that the ecosystem can be as situated as possible. This requires taking into account their disciplinary, relational, and digital competence levels, as well as the interests, experiences, and personal histories they bring into the learning ecosystem. Within this dimension, attention must also be paid to the ways in which interaction can be fostered both among learners and between learners and the teacher-
- Organisational dimension: this encompasses the logistical elements to be managed, as the configuration of the physical space, the number and type of available devices, student accounts, applications and connectivity. These may appear to be peripheral or excessively pragmatic concerns; yet, as the data and literature demonstrate, in a sociomateriale and postdigital prospective, they constitute the abiotic dimension of the ecosystem and are in constant relation with the biotic dimension.
- Process dimension: this involves determining the function of technology within the learning process and selecting one of the four interaction modes described above. It is the dimension that brings the biotic and abiotic elements into relation with each other and with the knowledge to be co-constructed in the classroom. The meaningfulness of the design and of the decision to integrate technology can make or break the activity and, at the same time, determines whether students genuinely acquire new competences.

Teachers engaging with digital learning ecosystems can draw on these three dimensions as an orienting framework as they develop activities, ensuring that all the variables are brought into productive dialogue, with particular attention to maximising interaction among environment, actors, objects and the knowledge being constructed.

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