Digital Resources in Science, Mathematics and Technology Teaching – How to Convert Them into Tools to Learn

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Abstract. This paper deals with the problem of why many teachers take up little educational benefit from digital resources, despite their potential to help create learning environments with greater student engagement and stimulating intellectual challenges. A systematization of the main factors identified in the literature is made. Starting from a framework based on the idea of conceiving any educational resource as an artefact that can be used as a tool, and extending the concept of instrumental orchestration, guidelines are proposed for using digital resources as epistemic tools to learn and a research program to be implemented.

Keywords: Digital resource · Science and technology · Epistemic tool · Learning classroom · Artefacts orchestration

1 Why Many Teachers Take up Little Educational Benefit from Digital Resources?

There is a great diversity of educational resources available to learn Science, Mathematics and Technology (SMT) [1]. However, the SMT teacher does not always take advantage from its educational potential [2, 38]. Although there is extensive work on the use of educational resources in SMT [3, 4], its use in SMT teaching practices has, among others, two types of gaps that need to be better understood and solutions to be found:

(1) The educational benefit of the digital resources to learning is not taken advantage of, in many situations, because teachers consider them less attractive [2], or because teachers do not recognize them to have a central role in the learning that offers students a space of autonomy and productive engagement [2, 5, 6].
(2) The use of digital resources in SMT teaching practices lacks a theoretical and practical framework that supports this process in order to promote improvements in learning. It is necessary to extend the studies on "epistemic tools" (tools for creating ideas and building knowledge [4] in professional contexts, including that of scientific research), where they are most studied, to the formal teaching context of SMT [7].

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These two gaps can have a common origin: SMT teaching is marked by pedagogical approaches (even those based on constructivist perspectives of learning) centered on established knowledge rather than on open epistemic practice that prepare students to deal with what is not yet known [7, 18].

2 Factors Which Explain the Little Educational Benefit for S and T Learning When Digital Resources Are Used

Design [20] plays a crucial role to take advantage of digital resources. Drijvers [20] gives account of three interrelated design levels: (i) the design of the digital technology; (ii) the design of corresponding tasks and activities; and (iii) the design of lessons and teaching. In addition, literature has drawn attention to factors linked to students' knowledge and skills [21, 23].

2.1 Factors Related to the Quality of Digital Resources

A first step, relevant in the use of digital tools in the learning of SMT, is that design enhances the technical mastery of using digital resources for solving mathematical (and sciences) tasks, and the conceptual understanding of the scientific concepts involved [20]. Therefore, digital resources characteristics and affordances should be adequate to the learning situation in which they are incorporated [20]. However, pedagogical and didactic principles should guide design, rather than the digital resources limitations or properties [20].

In [34] several criteria were proposed to evaluate the quality of digital resources. They concluded that not all digital resources have the necessary qualities. Therefore, the first step is to choose the digital resources that maximize the possibilities of obtaining educational benefit (scientific, technical and didactic qualities, and quality of interactivity and usability) [34].

2.2 Factors Related to Students' Expectations and Skills

The use of digital resources by students requires not only that they master the technology, but mainly a greater knowledge of the contents involved in the task (the concepts, their relations and properties) [23]. Another important aspect for students to be successful in the use of digital resources is the degree of adequacy of students' digital skills to the degree of requirement of the resource itself [21].

2.3 Factors Related to the Exploration Guide

The guidance degree of the task is a matter of debate [24, 25]. There is, however, some consensus that a certain guidance degree is necessary and is more effective for student learning [26–29, 31]. Research has shown that this subject is complex and has to be adapted to students' previous knowledge and to their own experience [30].

2.4 Factors Related to Teacher's Mediation

The use of digital resources in an educational context presupposes that this integration is done in a flexible and coherent way. This is part of the teacher role, as well as promoting students' motivation and engagement in tasks [20]. How they take place in teaching practices essentially depends on the actions and beliefs of teachers [15, 38].

Teaching with technology is different and the role of the teacher is widely recognized in promoting learning situations with digital resources with educational benefit. These changes require the engagement of teachers in a process of professional development [20]. However, according to [38] many teachers will only expend this effort of training when they are convinced of the benefits in terms of learning outcomes.

Several authors highlight the importance of a specific educational environment to take advantage of digital resources, such that facilitates technology usage in an inquiry-based, constructivist manner [38]. Nevertheless, many studies point that digital technologies are "more often used to simply enhance traditional practice" [38]. Other authors [23] claim that teachers may focus on technology and give students little opportunity for mathematical (or science) learning or, on the contrary, focusing mostly on the content and not provide any technology instructions at all.

3 Fundamentals of an Alternative Framework that Permits Facing a Digital Resource as an Epistemic Tool

Everything said next presupposes that the digital resource has the scientific, technical, didactic and usability qualities referred to in [34]. Placing digital resources with interactivity potential at the center of SMT learning (formal and non-formal contexts of learning) may allow for a certain cultural contextualization of learning [4]. In addition, it opens up a field of experimentation in the sense that it allows to verify what is viable, allowing private ideas and perceptions to become public [8] through speech, writing, and productive engagement [6]. Several studies point to the possibility of the use of any digital resource as an "epistemic tool" [7, 9–11]. Even without the concern of using resources as epistemic tools, several studies have been carried out to attribute to the resources a new centrality in SMT teaching and learning [12–17].

3.1 What Is an Artefact, a Tool and an Epistemic Tool?

An artefact is an entity or product of human creation, with embedded knowledge and, in general, with a specific purpose (e.g. sum algorithm, lamp and model) [4, 7–10]. An artefact is, therefore, an entity that is external to the human being and part of the collection of entities created by him/her. A digital resource is an artefact of whatever characteristics and qualities, even if conceived and realized using ICT. A stone or a piece of tree branch are not artefacts: they are objects. However, they can be used as a hammer, that is, as a tool.

As pointed out in [9, 10], our cognition is distributed between individuals and artefacts and largely skill-based and tool-using. When an artefact is used to solve a certain task, that artefact becomes a tool. It is the use for a certain purpose that gives the

artefact the status of tool [4, 7]. Therefore, a tool is closely linked to an activity and the use of a tool is directed to the action to obtain a concrete result [7].

In the educational context, transforming the status of a digital resource into a tool can only be done with a task that is authentic and challenging for the students. The algorithm of the sum, instantiated, or not, in an applet, or the model of the photoelectric effect instantiated in a simulation, by themselves, are just artefacts. Both have embedded knowledge. Only when used to solve a task they become tools. The artefacts used as tools to solve a task do not need, a priori, the mobilization of the knowledge embedded in the artefact [9], although it is necessary to mobilize relevant knowledge of the subject [10] for the activity that is being carried out. Therefore, using an artefact in the context of a task with a given purpose, and from which a product (another artefact!) results, confers to it the status of a tool.

If the activity with artefacts, using them as tools, is framed within a "setting of practical action working with representations and a certain materiality to produce knowledge and practices to produce this knowledge", we are within the framework of an epistemic practice [7]. Epistemic practices need a system of knowledge production as practice of solving non-routine problems [7]. The artefacts used in this context and for this purpose acquire the status of epistemic tools [4, 7].

3.2 Conditions to Use a Digital Resource as a Beneficial Tool

Based on [2, 8] we elaborated the concept of "beneficial tool". We defined it, tentatively, as a way of resource use that triggers the students' actions dealing with and solving a problem by allowing them to have cognitive and perceptive experiences that help them externalize, visualize and refine ideas. That is, using a digital resource as a beneficial tool allows to take advantage of its use in terms of interaction, visualization, cognitive and sensory experiences.

Using a digital resource as a beneficial tool is the first level of taking advantage from its educational potential. For this, some conditions are required:

- The digital resource has to have interactivity potentialities and other characteristics identified in [34].
- The task must be designed in order to propose a stimulating challenge and the digital resource is of great help to solve it [22, 33].
- The action taken with the digital resource must mobilize the students' available knowledge [7, 10].
- All action must have a purpose and a clearly identified outcome must result from it [7].
- The use of the digital resource should allow for a field of experimentation of ideas and actions, and should open up the possibility of new cognitive and sensory experiences to emerge [8].

3.3 Instrumental Orchestration

The transformation of an artefact into a tool involves a process of instrumental genesis defined as "the co-emergence of schemes and techniques for using the artefact" [15].

However, studies showed that this process does not occur by itself. The teacher has a relevant role in creating and guiding the learning situations [23], in particular the intentional and systematic organization and use of the digital artefacts in a learning environment [15]. The idea of instrumental orchestration so as "to point out the necessity (for a given institution – a teacher in her/his class, for example) of external steering of students' instrumental genesis" was introduced in 2004 [19].

Trouche [19] considered two elements within an instrumental orchestration: (i) didactical configuration ("a configuration of the teaching setting and the artefacts involved in" the environment) and (ii) exploitation mode ("the way the teacher decides to exploit a didactical configuration for the benefit of his or her didactical intentions"), to which [15] added another: (iii) didactical performance (involves all the teacher performances within the classroom). This last element "constitutes a critical enrichment of the instrumental orchestration model" to enable an orchestration to constitute itself as an artefact for the teacher, and that evolves in different implementations and adaptations in the classroom [4].

Monaghan, Trouche and Borwein [4] stated there are six orchestrations types, most of them established in [15], but not seen as exhaustive: technical-demo, explain-the-screen, link-screen-board, discuss-the-screen, spot-and-show, and sherpa-at-work. The first three are "teacher-centred" and the last three "student-centred", having in mind who dominates the discourse and the action [15, 23].

The instrumental orchestration is a conceptual scheme that embodies the process of becoming a digital resource as a beneficial tool. In the next section, we will extend this conceptual scheme.

3.4 Converting Digital Resources into Tools to Learn

Starting from the idea that a digital resource is an artefact and remembering that an artefact is an entity with knowledge embedded with a specific purpose [4, 7] we have to admit that a digital resource, although with recognized educational potential, does not allow, per se, for educational advantages [15]. Something more is needed. Usually this something else is an exploration guide of a certain digital resource to take educational advantage to learn SMT [31]. An exploratory guide needs to have the artefact status, that is, to embed knowledge of research in science and mathematics education (and others), and not just professional knowledge. This point is fundamental and exploration guides do not always have embedded didactic knowledge.

In other words, the exploration guide must itself result from an epistemic activity combining professional practice and knowledge produced so that it becomes an epistemic artefact [7]. As such, it needs to be flexible and open enough to be used in different cultures [7]. Still, it is well known that another difficulty is for teachers to take ownership of the exploration guide and to acquire the conviction that they can use it [37].

Guiding Principle 1 - A Digital Resource Needs to Have Other Aggregated Epistemic Artefact(s) to be Used for Educational Purposes

From the following, the first idea to be retained is: to take educational advantage of a digital resource, it is necessary to combine another epistemic artefact with embedded knowledge (let us call it exploration guide [31]) with explicit and clear articulations to

the digital resource. In particular, the artefact "exploration guide" should help enrich the potentialities of using artefacts "digital resources".

Corollary 1.1: A digital resource may have various added "exploration guides" artefacts according to learning objectives, educational level, educational context, etc. That is, a digital resource, if combined with different "exploration guides" artefacts, serves different purposes.

In addition, to take educational advantage of a digital resource it is necessary that it be used as a tool. That is, used as an artefact that allows solving problems/tasks. To convert a digital resource into a tool it is necessary to: (a) be used by the students and not by the teacher, and (b) be an activity oriented by a task/problem. This conversion presupposes several changes in the conception and practice of teaching [32]: from passive learning to active learning, from learning concepts to learning in context, from formal abstraction to scaffold abstraction.

Guiding Principle 2 - A Digital Resource Becomes a Tool if Used Effectively to Solve a Task/Problem in a Setting of Learning in Context

From the above, a second idea is to be retained: in order to take educational advantage of a digital resource it is necessary to convert the "digital resource" artefact into a tool. That is, to allow students to use it effectively in an orchestrated activity in a setting of learning in context and oriented towards a task/problem that is authentic and challenging for students [33]. The artefact "exploration guide" should allow the digital resource to be used as a tool in the sense that it allows the execution of actions that trigger answers (e.g. visualizations, calculation of results [13]) that provide digital resource users with an ever closer or more elaborate reply to the task/problem.

Corollary 2.1: A digital resource cannot be used as a tool if there is no authentic and challenging task/problem to solve [33].

Corollary 2.2: A digital resource, when used with an exploration guide, is not a tool if it does not give authority to students when they use it to solve the task/problem [6]. That is, the guidance degree of the exploration guide must allow the use of digital resources by the students with authority.

Corollary 2.3: A digital resource when used with an exploration guide is not a tool if it is not clear what the expected product of the activity is.

Lastly, a student can perform a task without learning anything relevant or new with it. Therefore, it is not enough to use the digital resource as a tool. It is necessary to use the digital resource as a tool to learn, that is, in the context of an epistemic activity. For this to happen, another layer of artefacts is needed: (a) an epistemic artefact that helps to link action and task resolution ("exploration guide" artefact) and (b) an artefact to extend what is learnt to other similar situations or even different situations, since the concepts and procedures learnt can be formulated in a more abstract way to produce conceptual artefacts and, eventually, other.

In other words, an artefact is necessary that, when used, becomes an epistemic tool to shape inquiry action and knowledge production juxtaposing physical and symbolic affordances in order to solve the problem [7]. Therefore, it is necessary that the didactic characteristics of the activity developed in the classroom are consistent with this

epistemological approach. In particular, it is necessary to consider the dimensions of production (learning occurs or not by the development of an artefact) and negotiation (learning occurs through discourse with students or negotiated among participants) [35].

We have a longer artefacts chain that must be orchestrated: (a) "digital resource" artefact; (b) "exploration guide" artefact to allow use as (a) a tool; (c) "epistemic tool" artefact to connect (a) with (b) in view of different situations other than those. We extend the concept of instrumental orchestration [4, 15, 19] so that the use of digital resources is: (a) student-centred; (b) inserted in a context of epistemic practices triggered by an authentic task that allows the production of knowledge.

Guiding principle 3 - A Digital Resource Must be Inserted in an Orchestrated Chain of Artefacts, Used in a Setting of Learning in Context of Epistemic Practices, to Allow Connecting the Actionable Knowledge with the Knowledgeable Action

The use of the digital resource needs an artefact orchestration (see Fig. 1):

- "Digital resources" artefacts (type a) with "exploration guides" artefacts (type b) that focus students on action based on previous knowledge (actionable knowledge – knowing what to do, how to do, why to do [7]); and,
- Artefacts type (b) with epistemic artefacts (type c) that focus students on what can be learned from the action (knowledgeable action – using artefacts to describe, explain, and make explicit underlying principles or models, using symbolic representations [7]).

The artefacts orchestration of different artefacts should be centred on epistemic practices and procedures that allow the students to move beyond what is known. Among epistemic practices are awareness activities such as describing a phenomenon or event, or performing operations with representations that create conditions for interpreting, arguing, modelling, or even communicating a result.

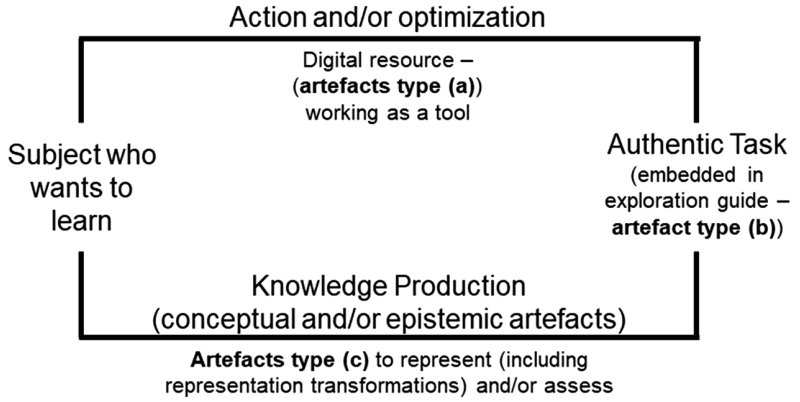

Fig. 1. Artefacts orchestration to connect actionable knowledge with the action knowledgeable in the learning context of epistemic practices.

Corollary 3.1: A digital resource is not a tool to learn if it does not allow action with meaning and relevance to solve a problem that results in an outcome (conceptual or epistemic artefacts).

Corollary 3.2: A digital resource is not a tool to learn if there are no epistemic practices from which a theoretical approach becomes relevant and necessary.

Corollary 3.3: A digital resource is not a tool to learn if there is no orchestration of the different types of artefacts (orchestration of artefacts type (a) with type (b) and type (c)) that can lead to a virtuous cycle of acting-assess-represent-optimize [7, 36], where learning occurs by the development of an artefact [35] and/or by the representation of different levels of conceptualization (description, explanation, principles and theories) [7].

4 Key Points to a Change in Teaching Practices and Research

In this section, we present three examples of how the ideas presented in Sect. 3 can be instantiated. It is also discussed what aspects need to be considered in a research program that seeks answers in order to take advantage of the many available digital resources. Some of them, even without being designed for educational purposes, can be used for educational purposes.

4.1 Examples of Some Practice Change Projects

The examples reported in this subsection are the result of research with the general goal of taking advantage of available resources, first turning them into tools and then into epistemic tools.

Example 1 - The Use of Visual Representations: From an Artefact to an Epistemic Tool. Visual representations are not the most common representations used in mathematics teaching and learning. However, visual representations are artefacts (entities that result from human creation, with embedded knowledge), and therefore, with an appropriate exploitation mode and didactical performance, could become a tool, a beneficial or an epistemic tool. That is what Montenegro, Costa and Lopes did in [39]. The authors were interested in investigating the impact of the use of visual representations in teaching and learning early algebra (with 18 students aged between 10 and 13). To do so, an instrumental orchestration was designed, with characteristics (a), (b) and (c), and resulted in the artefacts orchestration presented in (d):

(a) Didactical configuration: use of a visual representation of a pattern in a task taken from the students' textbook in a 40-min session, with the didactic aim of consolidating and reviewing the learning achieved in the topic of Sequences and Regularities;
(b) Exploitation mode: explore in two previous lessons some visual and numerical growth patterns, focusing on the analysis of regularities, in different systems of representations, and on the relationship between this and other pre-achieved knowledge. In the third lesson, the students solved the task involving the visual

pattern, in groups of four. As usual, the teacher circulated among the groups to ensure that productive work was being done but having in mind students should conclude the task with the maximum autonomy in the time available.

(c) Didactical performance: the teacher intervened in both groups when she noticed discontinuities in the groups' activity. Only one group explicitly requested the teacher's help. The teacher intervention was in the sense of showing the potential value in exploring the visual representation. As her suggestion of taking a closer look to the drawings to find similarities and differences did not work, she highlighted what was constant from one figure to the next, drawing and talking to the students. After some interaction, "the students exclaimed 'Ahhhhh!'", [39] and quickly solved the problem.

(d) Artefacts orchestration: artefact type (a) is the visual representation; artefact type (b) is the task and the teacher exploitation mode and didactical performance; together they promote the actionable knowledge, and visual representations appropriated by students become epistemic tools, since they started to use them on their own initiative in other situations. The paper [39] in which the study research is presented constitutes a new artefact that can be used as a tool by those who read and use it in their professional or research practices. Moreover, the virtuous cycle goes on.

Example 2 - Culture as Didactical Resource: An Example of a Complete Virtuous Cycle of Artefacts. Claiming that the ancestral culture of the students can be an engaging element for the learning of mathematics, a research study [40] was implemented with the objective of understanding how teachers from the north of Portugal appropriated intentionally created resources (artefacts), giving prominence to the cultural context. The researchers created artefacts, which they called transverse resources, taking account of the cultural context and in order to allow the mathematical content to be adapted to different levels of schooling. These transversal resources were presented and explained to several teachers and were worked by them in a continuous training course, giving rise to new resources (artefacts) that they applied to their students. Thus, an instrumental orchestration was designed composed by: (a) the transverse resources and the new resources (didactical configuration); (b) the continuous training course and the teaching mode that each teacher chose to apply the new resource, mainly solving tasks in groups (exploitation mode); (c) the interactions done by a researcher in the continuous training course and the ones done by each teacher, participant in the study. In fact, there were many instrumental orchestrations, a first one designed by researchers that transformed the artefacts – transversal resources – into tools, beneficial tools and epistemic tools; and the ones originated by this and designed by each teacher to implement "his/her" artefact – the new resource. Results showed that some of the teachers appropriated the transversal artefacts as beneficial tools and went further creating new artefacts with the same objective but clearly different from the transversal resources, closing the artefacts orchestration cycle (see Fig. 1) presented in Sect. 3.4. Other teachers, although not creating a completely new resource, did several modifications having into account his/her students, and others just made minimum adaptations to the transversal resources.

Example 3 - Influence of the Guidance Degree of Exploration Guide to Use a Computational Simulation on Learning Outcomes. The work of [26] consisted in studying the influence of the guidance degree of exploration guide to use a computational simulation on learning outcomes concerning the physical state of matter at microscope level with students aged 9–11. The study was of a quasi-experimental type, with pre- and post-test, in four groups of students: one with minimal guidance degree of exploration guide, one with high guidance degree and two with the same moderate guidance degree.

Artefacts Orchestration to Mobilize Actionable Knowledge

(a) Didactical configuration: Once the digital resource to be used was chosen ("states-of-matter-basic" simulation of PhET project), the researchers studied the characteristics of the simulation: usability, scientific aspects, possible simulation circumstances that can induce alternative conceptions, interactivity possibilities, variables that could be studied, and constraints inherent in the simulation itself. It was only with this study that it was possible to design exploration guides with different guidance degrees. First of all, it was necessary to concentrate efforts to conceive an authentic task from the perspective of the students. At this point the teacher's experience was decisive. The established task was the same for all exploration guides.

(b) Exploitation mode: The next step was to determine the guidance degree for each type of exploration guide. As it is well known, this is a matter of debate because of the complexity of the subject and the reliance on not easily controllable circumstances. The research effort of [26] focused precisely on studying the influence of the guidance degree of exploration guide to use the computational simulation on learning outcomes, in particular as regards conceptual recognition or elaboration. The results indicate higher gains in the groups that used an exploration guide with a moderate guidance degree, as compared to the remaining two groups.

(c) Didactical performance: Precisely because the researchers are aware of the fact that an exploration guide with moderate guidance degree has a greater possibility to develop higher quality learning but is more dependent on the didactical performance of the teacher, is that the didactical performance of a same teacher was studied in groups of distinct students, using a same exploration guide with moderate guidance degree. The results obtained show fluctuations in student performance that need to be studied in more detail.

Artefacts Orchestration to Produce Knowledge. The research of [26] is ongoing. The next phase is to study how different groups of students can use simulations with exploration guides with a moderate guidance degree. The teaching didactical performance will be first decisive for creating a learning context of epistemic practices. Another decisive aspect is that the learning context is marked by the need to obtain products (conceptual or epistemic artefact or new practices). Finally, it is necessary that epistemic artefacts be used to represent operations with simulations, their results and how to transform representations or to make practices explicit and aware that lead to the construction of practical and theoretical knowledge (see Example 1).

4.2 Key Points for a Research Program to Convert Digital Resources in SMT Teaching into Tools to Learn

As we said earlier, a digital resource, per se, does not guarantee that we will take educational advantage of it. The first difficulty is the intrinsic quality of the digital resource. The second difficulty is how to convert a digital artefact resource into a tool for educational benefit. The theorization proposed by [4, 15, 19] on instrumental orchestration lacks several theoretical and practical insights. And, finally, connecting actionable knowledge with knowledgeable action in the learning context of epistemic practices is something that is glimpsed from the theoretical point of view, but still lacks more theoretical and practical deepening.

Although we know the aspects mentioned in the three examples above, the "artefact orchestration" to produce knowledge remains a challenge because it imposes changes in the teacher's teaching practices and in his/her performance and can also lead to the reformulation of the exploration guide. Many aspects of this "artefact orchestration" are unclear when a digital resource is regarded as an epistemic tool. We are convinced that this line of work is, however, very promising, for its openness to designing and establishing effective principles of effective learning settings that are focused on epistemic practices and use digital resources. These learning settings allow developing a new range of competencies demanded in various sectors, such as critical and creative thinking.

The research program we propose has three axes and presents four outcomes, and is strongly based on the scheme in Fig. 1.

Axe 1 – Identify the educational potentialities of any digital resources, including those that were not designed for formal educational purposes, and those that were designed for non-formal educational purposes (e.g. serious games).

Axe 2 – Study how an artefact, a digital resource, can be converted into a tool, taking into account the concepts of authentic task, guidance degree of the exploration guide, and how these can be articulated in an adequate didactical configuration, exploitation mode, and didactical performance.

Axe 3 – Study how to convert the conventional learning settings into learning contexts of epistemic practices to produce knowledge (conceptual artefacts), practices, and outcomes (epistemic artefacts), in which digital resources play a central role because they allow for distributed cognition [7–10].

Outcomes 1 to 3: An epistemic artefact per axis which allows any teacher to: (a) choose a digital resource (b) design an adequate didactical configuration, exploitation mode, and didactical performance, (c) design a learning context of epistemic practices to produce knowledge (conceptual artefacts), practices, and outcomes (epistemic artefacts), in which digital resources play a central role.

Outcome 4: An epistemic artefact, which allows any teacher to link the three epistemic artefacts referred above.

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