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A Holistic Pedagogical Model for STEM learning and education inside and outside the classroom

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Abstract. This article discusses how to innovate STEM learning and education in- and outside of the classroom. It proposes to use a holistic framework for pupil-centered learning processes called Learn STEM. It was developed by an international research consortium based on the findings from mixed methods research. The research included a literature review, semi-structured interviews and three online surveys with the participation of teachers (n=217), headmasters (n=24) and learners (n=354) from more than ten countries. Furthermore, the findings from the mixed methods research are also informing the international research consortium to design a teacher training programme and to develop an online course. This article provides first summaries of the research results related to the holistic pedagogical model and to the training programme. After a short overview of the final holistic pedagogical model Learn STEM, the paper presents one example how the holistic pedagogical model Learn STEM can be used for improving STEM learning and education outside the classroom. Finally, an outlook for future research is focused.

Keywords: Holistic pedagogical model, Learn STEM, STEM learning, STEM education.

1 Background

The whole world is changing in our so called "digital age": Thus, societies and their citizens are confronted with increasing demands (Organisation for Economic Co-operation and Development, 2016; Stracke, 2011; World Bank, 2016). More competitive 21st century work environments require the building and continuous improvement of strong competences and abilities, in particular within science, technologies, engineering and mathematics (STEM) (Stracke, 2014, 2019; Weinert, 2001). Thus, learner should develop profound knowledge, skills and competences that they can apply in all areas of life, with special focus on transversal competences such as team work, rational thinking

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and investigative and creative work (Dewey, 1966; European Commission, 2007; Piaget, 1953; Rousseau, 1968; Stracke, 2012a, 2012b; Vygotsky, 1988; Westera, 2001).

To address innovations in STEM education in schools, an international research consortium was established to address and improve the quality and efficiency of STEM learning and teaching (Stracke et al., 2019a). The research consortium designed Mixed Methods research and conducted it with the overall aim of the development of a holistic pedagogical model for learning STEM (Stracke et al., 2019b). To facilitate its introduction and implementation, a teacher training programme and an online course are planned. Therefore, the consortium consists of a combination of research partners, secondary schools and teacher training providers from six European countries.

This article presents briefly the design and methodology of the Mixed Methods research (section 2) and provides an overview of its key findings related to the pedagogical model (section 3) and the teacher training programme (section 4). In the following, the holistic pedagogical model Learn STEM will be introduced (section 5) and its application for STEM learning and education outside the classroom will be discussed through the example of the Tiny House project (section 6). The article concludes with an outlook on the next future activities, challenges and further research demands for innovative STEM education inside and outside the classroom (section 7).

2 Research design and methodology

The international research consortium Learn STEM started the Mixed Methods research with a literature review providing an in-depth overview of the current status of STEM education in schools and the needs for its changes and improvements. The research findings were quite homogenous: there is a huge demand for innovative STEM education as well as for related teacher training and it could be summarized that further research on learner-centered and competence-based pedagogies is required (see e.g., Harlen, 2015; Organisation for Economic Co-operation and Development, 2016; Vasquez, 2014; World Bank, 2016).

Thus, the research consortium has developed a strategy and plan for a three-year Mixed Methods research that integrates surveys and interviews. The overall objective of Learn STEM was to design a holistic pedagogical model based on informed the results from literature review, surveys and interviews to improve and innovate STEM education in schools in the future.

The pedagogical model was developed and continuously revised and improved in iterative cycles leading to 35 interim versions in total before a final draft was launched (Stracke et al., 2019b). Several interim versions were presented and debated with the audiences in interactive workshops at international conferences: Consequently, the final draft included the feedback from school researchers, teachers and headmasters.

Furthermore, the research partners have generated three surveys on STEM education: one survey for teachers, one for headmasters and one for learners. The surveys asked the three target groups similar sets of questions items with the same clusters and formulations in addition to the demographic questions. Through this design, the comparison of the question was guaranteed. All three surveys were implemented and published at the same time by the Learn STEM coordinator. They were online accessible for all interested persons worldwide opening on Friday, 22nd of February 2019 and closing on Friday, 14th of June 2019 after 16 weeks.

The following sections present the key findings of the Mixed Methods research related to the pedagogical model Learn STEM (section 3) and the teacher training programme (section 4).

3 Research results on the pedagogical model

Teachers, pupils and headmasters have been asked with respect to their beliefs of STEM, their opinion on the main aspects of the pedagogical model for innovative STEM education and the Learn STEM Inquiry Learning packages with some more detailed examples of STEM Teaching. The majority of participants has been pupils (354) with a bias from the Netherlands (111), followed by teachers (217) with a bias from Portugal (111) and 24 headmasters from six participating countries.

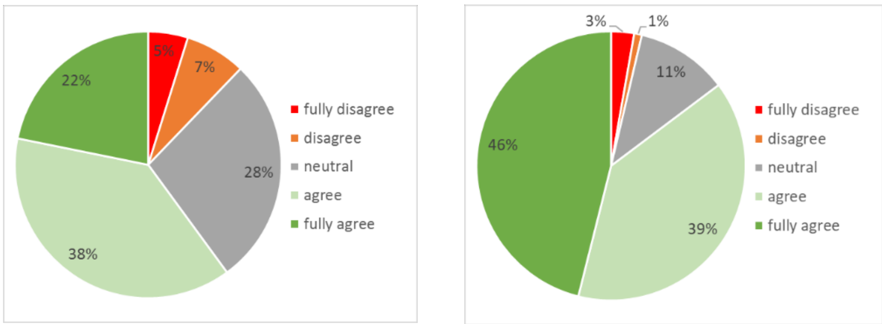
The largest group of pupils was in the age from 14-17 (69.4%), whereas the largest group of teachers was between 45-54 (40%) and headmasters between 55 and 64 (45.8%).

A relatively large part of pupils could not decide whether their STEM education is exciting or boring (49%). Only 32.8% found it exciting. This contrasts to 51% of the learners who recognize the importance of STEM since they stated that STEM is important for the future employability and career opportunities. These data may point to the rather large human potential, which can still be explored and developed in order to increase motivation and enthusiasm for STEM. The view is supported by the results of 39% who would like to have more STEM education in their schools and 41% who cannot decide. The latter rather large group of learners seems to correspond to the large number of pupils who are not satisfied with the way STEM is taught nowadays. The present situation in school is good only for 33% and 23% do not like the way how STEM education appears in and outside the lessons.

The approaches how to improve STEM educations in the developed pedagogical model are well received by the learners. Most importantly, 60% of the learners support the idea of practical exercises in order to increase and develop STEM interest and ability. 57% state that real life projects are helpful to learn STEM topics and also 57% are motivated to work in groups with their classmates to search for solutions (and only 9% disagree on that).

The response to the training aspects in STEM education has been more divers since 45% think that repeating tasks and content is helpful to obtain a good learning outcome but 14% disagreed on that. The same picture appears when the learners are asked about self-controlled learning without a prescribed curriculum since 32% like this idea, but 20% dislike it and the majority cannot decide. This indicates that the usage of new approaches in STEM education is not only a challenge for teachers, but also for learners since they need to be become more independent and responsible.

Although 53% of the teachers are not teaching STEM 62% would like to increase the time devoted to STEM education in school and 76% want to see this integrated in the school vision and policy. Interestingly the teachers, who have been asked in the 6 different countries with rather different educational systems, have strongly agreed on the most important aspects of the pedagogical model developed in the Learn STEM project. 85% support the concept of practice during the learning process. Fig. 1 illustrates the response of teachers and learners to the question of the usefulness of practical exercises during STEM education. Clearly the high potential of this area for future developments can be seen. But also more than 75% agreed that STEM education should be complex, social and process-oriented. Even 69% support the idea of holistic STEM education.



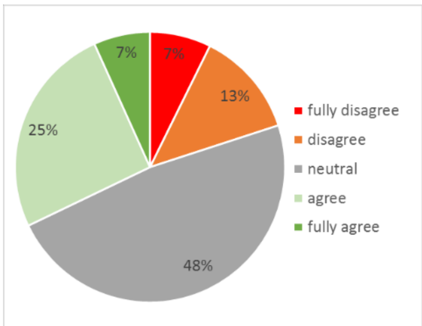
A) B)

Fig. 1. Responses on practical exercises by A) the learners and B) the teachers.

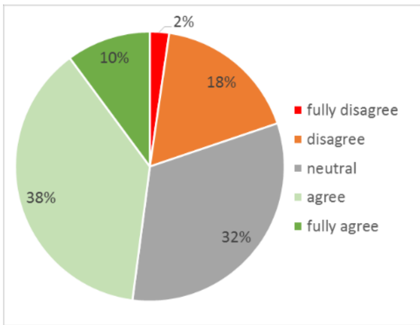
The overall support of the developed pedagogical model is rather clear with 74% agreement on the usefulness of the approaches for enhancing the quality of school education. However, in few aspects the picture is more divers. 48% think that STEM education should be self-regulated by the learner, whereas 20% disagree and 32% are not decided. Fig. 2 compares the response on the question concerning the self-regulation of teachers and learners. It points to the necessity of changing the established roles of teachers and learners or at least modifying them. 57% of the teachers support the concept of repeating tasks and content as essential in the STEM learning process, whereas 19% disagree on that. The opinions on the balance between specialized topics and general knowledge vary significantly since 34% recognize too many specialized topics, 21% disagree and 45% are neutral with this.

Interestingly the group of headmasters – although not very large – is most supportive for the new concepts in STEM teaching. Here 96% would like to increase the time spent for STEM topics and 79% want to increase the quality in STEM education. Here the importance of the STEM area for the future development of the society is very well recognized. Concerning the five aspects of the Learn STEM model: Complex, holistic, process-oriented, practical and social, 88% are supporting these ideas. 92% think that the model is useful for improving STEM education in the schools.

The headmasters are also open to new conceptual ideas in implementing improvements in STEM education and agree with 76% that the process should be self-regulated. They also recognize that repeating tasks and content is helpful to the learning process with 50% agreement. However, with respect to the balance between general overview and many specialized topics the result is also divers as for teachers and learners: 41% state too much focus on specialized topics and 30% disagree.



A)



B)

Fig. 2. Results of the survey by A) learners and B) teachers on the question whether self-regulated learning without prescriptive curriculum is helpful in STEM education

In addition to the survey personal interviews have been carried out in the different focus groups. Here there have been 58 participants, with teachers as the largest group (36). In general, the situation of STEM education in school has been reflected and the main ideas of the pedagogical have been discussed. Beside the points, which have already been analysed after the questionnaire, some new aspects have been evolved during these personal discussions. Interestingly the discussions did not question the proposed approaches, but concentrated constructively on the implementation of the model and how potential difficulties can be overcome. Obviously the pedagogical model has met actual demands and wishes of learners and teachers as well. One can group the discussion points accordingly:

a) Aspects which are connected to humans
Teachers are not trained for self-regulated and interdisciplinary STEM teaching. In several countries they need to overcome borders between different disciplines and they need to learn to work together with teachers of other subjects. Teachers will also have to accept to become learners since not all actual subjects will have a backing by the study course they chosen previously.
Learners are also not trained for self-regulated learning and thus, have to learn to work on projects and take responsibility. This might be complicated by the fact that many pupils do not know in which direction the professional career will go after school; thus, it is very important to connect STEM education with everyday life problems.

b) Institutional aspects and regulations
In many countries the aim to have motivated and well-trained pupils is well recognized, but a tight curriculum hinders flexibility in developing new approaches in school. Engaged teachers have to find a compromise between training for exams and the personal development of pupils. For interdisciplinary work several teachers have to work together which also needs organization and planning in the school.

c) Technical and financial aspects
Since practice during the learning process is so important, the technical basis for experiments in the different fields is essential. This is not only connected to computers, but mainly to hands on experiments in physics, chemistry, biology, engineering or interrelated topics. Here new ideas for collaboration of schools or schools with research institutes or companies are necessary. However, also governmental institutions need to be approached.

The mixed method research, which has been performed in the six participating European countries, has clearly shown the necessity for improvements in STEM education. It also verified that a more holistic approach with interdisciplinary focus, aspects of self-regulation, practical experiments and training modules is an attractive way to go. The surveys and the interviews have also allowed a further specification and development of the five basic characteristics of the pedagogical model which will be shortly explained in the following section 5. Before, the section 4 will present an overview of the findings from the Mixed Methods research on the training programme.

4 Research results on the teacher training

In order to define a training programme valid for different European countries and in line with the European policies, based on a common methodology and set of instruments, the partners conducted a survey and interviews during the focus groups with different types of stakeholders: school management, school staff and students. The presence in some interviews and/or focus groups of teacher trainers, curriculum developers and policy makers strengthened the results of the inquiry and attributes a validation to the conclusions and recommendations. The results of these interviews, together with the analysis results, were used for defining the concrete skills and competencies trainers need for being able to successfully teach STEM using the Learn STEM Model.

An important aspect of the research was to discover what content should be included in the teacher training programme in the view of teachers and principals. The results from the teachers and the principals were very much in line and did not include any contradiction. When we look at the ranking, given in both survey groups, to the content that needed to be included in the teacher training programme, we notice a very similar image (Table 1).

Table 1. Top 7 of the content that needs to be included in the Teacher Training Programme.

	Teachers	Principals
1	Development of interdisciplinary modules	Development of interdisciplinary modules
2	Soft skill enhancement	Soft skill enhancement
3	Open content material	Learner-centred pedagogics
4	Learner-centred pedagogics	Self-regulated competence building
5	Self-regulated competence building	Holistic view on STEM
6	Curriculum design	Curriculum design
7	Holistic view on STEM	Open content material

The only small difference is that teachers attribute a higher importance to the development of open content material then the principals, while principals value more the holistic view on STEM.

In some countries the educational material is provided by Ministries of Education, official Education Authorities, educational publishers or networks of schools. In other countries the teachers have the autonomy to develop their own educational material. As in the participating countries, STEM is recently introduced, there still is no established tradition of providing good examples of STEM content. This can explain the higher need teachers express, to have access to have to open content material.

The society requires every time more that schools prepare the learners to understand general ideas, rather than accumulate specialised knowledge. Also the emphases on the ethical component of STEM and its contribution to the learners' personal development are asked by the society. Principals are responsible for the general policy of the school and that way they tend to have a broader helicopter view on the school. That way they are more sensitive towards demands and thus to a holistic view on STEM.

Based on the analysis of the online survey, interviews and/or focus groups of the teachers and principals, the teacher training programme must at least include aspects of pedagogics, didactics and assessment. A short introduction on the rationale why STEM is needed, can be useful. Teachers and principals ask to develop fresh, sprinkling ideas and examples to implement real life STEM education with research activities and a cyclic approach.

Teachers and principals want to include the development of interdisciplinary modules, soft skill enhancement, learner-centred pedagogics, self-regulated competence building, curriculum design and the holistic view on STEM next items in the teacher training programme. The teachers also favour the development of open content material. This question is addressed through the Inquiry Learning Package that also is a part of the intellectual outcome of the project.

When selecting or presenting examples and exercises in the teacher training programme, one must be aware of gender-related background. The teacher training programme should also prepare teachers to tackle gender in their STEM teaching. This conviction was reported to us during the interviews and focus group with teachers and teacher trainers. While principals didn’t bring this up spontaneously, they all agreed when this idea was discussed.

The survey, interviews and focus group with the learners, revealed that the learners believe their teachers could make STEM subjects more interesting by changing or adjusting the pedagogical and didactical approaches. The learners are pointing towards the importance of a modern and challenging learning environment in which real life and practical exercises are included. In a STEM project the different topics should be present and the focus of the project should be oriented to the exploration and research, rather than purely to the end result or end product. The use of activating teaching methods, less frontal teaching, development of the 'investigation skills', stepping away from 'lecture-style' teaching and moving towards more practical exercises, are the most common given examples the learners bring fort worth, to make STEM teaching more attractive. Practical exercises such as experiments, computer work will increase the interest of the learner in STEM (survey results: fully disagree and disagree: 12%).

A second reported set of aspects relates to the education system and the school organisation. Interesting and effective STEM teaching needs a certain degree of autonomy and flexibility. When the curriculum rigidly decides on the content and didactical approaches of every lesson, when the teachers are strictly obliged to follow text books with prescribed exercises, a motivating and qualitative level of STEM teaching cannot be achieved. Learners ask for a flexible school organisation that allows outside activities, study visits to laboratories, research centre or enterprises. A flexibility that empowers their teachers to include also non-formal learning, multi-media, iterative learning, practical work and more experiments into their STEM teaching.

And finally, learners report that the use of traditional assessment methods where only the result is evaluated, isn't consistent with the idea of a process-oriented approach where learners discover STEM in a self-regulated and creative way through exploration and creation. Especially learners from countries with an examination system, based on a very detailed list of content, are afraid that this central assessment doesn't reflect their learning progress, their gained STEM knowledge and their build STEM skills. This is for sure the case when the final evaluation still is composed out of separate subject goals, and not inspired by the interdisciplinary character of STEM-learning. This concern was also brought up during some interviews with teachers and principal.

In summary, the survey results of the teachers and principals are mainly focussed on the improvement of the pedagogical and didactical knowledge and skills. Teachers also emphasise the need of having access to open content material. The analysis of the learner's survey indicate that their motivation can be enhanced by being offered activating, practical and real life teaching in a flexible educational environment with an appropriate assessment. We took this in account when editing the teacher training programme, STEM examples and STEM exercises. This resulted in a proposed structure (Table 2):

Table 2. Learn STEM teacher training programme.

Modules	Structure
1. Introduction: Why STEM learning in schools?	Introduction Presentation of the four subjects of STEM
2. Pedagogical characteristics	Introductory exercise Explanation of the Pedagogical Model and its 5 elements Exploration of the Pedagogical Model using an existing STEM lesson Reflection on the use of Pedagogical Model Reflect about the whole cycle Continuation in peer-cooperation
3. Didactical realizations	Introduction Human Centred Approach Scaffolding Open, problem-based learning Closed methodologies Additional training methodologies
4. Assessment approaches and tools	Why do you assess Who will assess? What to assess? When to assess? Ways to assess?

5 The holistic pedagogical model

The pedagogical model Learn STEM focuses on the learner who shall become the owner of their own learning processes (Stracke et al., 2019b). Thus, the role of teachers needs to change: teachers should facilitate such learning processes and act as coaches. However, teachers may also guide and supervise the learning process. Learn STEM can be combined with other approaches and methodologies to learn and teach STEM.

Learn STEM is based on educational theories and positions and focuses mainly on the following five characteristics of the learning process (Fig. 3):

- Complex
- Process-oriented
- Holistic
- Practical

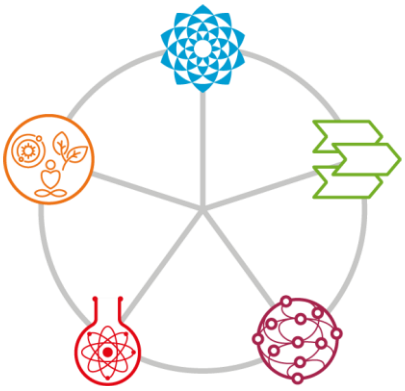


Fig. 3. The pedagogical model Learn STEM.

- Social

Learn STEM addresses three core elements: knowledge, skills and competences. Learners can gain STEM knowledge and build STEM skills. Through their reflection and iterative training, learners can build STEM competences following the principles of assimilation and accommodation. As presented in Learn STEM, the learning process should be interdisciplinary and holistic. Learning is considered as a process with iterative quality improvement cycles. Accordingly, Learn STEM allows flexibility for the teachers who can act more as a coaching mentor or as an instructing tutor depending on the situation in their intended STEM learning and given educational system.

Training modules for teachers help them to support learners solidifying acquired algorithms and knowledge and gaining confidence in using them. Practical courses are valuable tools for the learners during the learning processes as they allow to expand knowledge as well as to develop practical skills. In everyday life tasks, learners can demonstrate and use their knowledge and skills and successfully apply their developed competences in new situations.

Learn STEM incorporates The complexity of STEM learning activities is integrated in Learn STEM and relates them to the diverse STEM disciplines as well as to other (STEM) areas: Learn STEM connects STEM education and learners with our society and offers insights into the complex relationships between STEM and the whole society.

Through that approach, Learn STEM wants to discover and to stimulate the interests of STEM learners and their ability and motivation handling different perspectives of science, technology, engineering and mathematics. As a consequence, Learn STEM may encourage more pupils to select and follow a career in STEM professions. This may help to meet the demands of the society including the search for innovative scientists and engineers who are well educated, motivated and able for critical and design thinking as well as orientated to problem solving.

In order to stimulate the interest in STEM topics STEM education has to take steps out of the class room. This is on the one hand connected to topics which relates STEM topics to everyday life problems, but it also comprises the contact to companies and research institutions. By this the learners will be in a new environment and come in contact with new topics and problems. This can create attention and stimulate the engagement with STEM-related content. Besides that, the contact to persons, who are working in the STEM field, can help to open professional perspectives for the learners and to develop own aims and objectives.

6 Example for using Learn STEM outside the classroom

In this section, we present one example for the usage of the holistic pedagogical model Learn STEM outside the classroom (Stracke et al., 2019a, 2019b). It is used in the Agora school in Roermond located in the south of The Netherlands. The school is following a learner centered approach where pupils learn in small communities on challenges. These challenges are based on the interests of the pupils and most of these challenges are created by themselves. The teachers are called coaches and support the pupils in the learning process by guiding them through the different steps they have to make to solve their solutions for challenges. Experts are also involved in the process. These experts are expert in a specific domain.

In this case we want to explore the case of the Agora "Tiny House" project. This case is a typical case how pupils, experts and coaches learn in realistic challenges. The five pupils are between fourteen and fifteen years old. The team is completed with one coach and two experts in the domain of government and engineering.

The idea of the project Tiny House was born during a workshop on sustainable houses done by a parent of one of the pupils. He asked to help building a sustainable house with him, where he could live with his wife and children (Fig. 4).

Fig. 4. Workshop on sustainable houses.

A Tiny House can be described as a complete home with only the really necessary spaces for easy living but also sustainable. Natural energy sources are used such as sunlight, geothermal heat, etc. They are consciously built and inhabited based on the need to live a simpler life, less focused on consumption and with a smaller ecological footprint. The design and construction of small homes make smart use of space and innovative technologies. A Tiny House is max. 50 m2, ideally (partly) self-sufficient, of good quality and aesthetically built, functioning as a full-time inhabited home. Being mobile is not a condition but often a means, being completely off-the-grid is a possibility but not a requirement.

A big challenge for pupils to build a real product, the tiny house that meets the expectations of the client. The case was complex, because this was not a very easy challenge. A lot of different components are part of this case:

1. The construction and the layout of the tiny house concerning sustainability.
2. Finding solutions for basic needs like collecting energy, water management, heating the house with sustainability in mind.
3. Finding investors to finance the production of the tiny house.
4. Finding a location to place the tiny house.

To solve these problems, the team works in an agile and iterative way working and learning in different sub-teams. Every Wednesday morning the team came together for having a meeting. To guide the process, they have followed the Design Thinking method. Following this method, the pupils had to empathize, define, ideate, prototype, and test their products. Pupils were partly responsible of a part of the project. They have worked and learned from and with their experts. During the period of this project pupils have learned about how to connect to other partners outside the project, how to present their idea to potential investors and how to get in dialog with the government about finding a location. They also have updated or upgraded their knowledge and skills about how to construct a sustainable tiny house with all the requirements and restrictions (Fig. 5).

Fig. 5. Prototype of a tiny house.

The prototype of the tiny house has been realized by the team. The next step is to build the real tiny house and to find a location to live. More about the Tiny House project can be found at their website online: https://www.tinyhouse-agora.nl

7 Conclusions and outlook

The paper introduces the holistic pedagogical model Learn STEM for innovative STEM education and explains its usage outside of the classroom through the Tiny House project. The pedagogical model Learn STEM was developed based on the findings from Mixed Methods research designed and realized by the international Learn STEM research consortium. The Mixed Methods research combined an in-depth literature review with interviews in focus groups and three online surveys for teachers (n=217), headmasters (n=24) and learners (n=354). The paper presents first results from the comparison of the surveys for teachers and headmasters: Teachers and headmasters share a similar perspective on the current STEM education with specific interesting differences. Overall, the grading on the usefulness of the pedagogical model Learn STEM was very positive by the teachers (74% fully agreed or agreed) and even better by the headmasters (92% fully agreed or agreed).

Accordingly, the findings from the Mixed Methods research, the international research team designs a training programme and an online course for teachers and headmasters. The objective is to initiate a debate on future innovative STEM education and learning in schools following the five characteristics from the introduced pedagogical model Learn STEM: complex, process-oriented, holistic, practical, and social. Research has analysed the opportunities for (open) online education and the needs and preferences to use it in (STEM education within) schools as well as lifelong learning (Stracke et al., 2017). The design and fulfilment of the appropriate quality is currently the main challenge for (open) online education (Stracke, 2019): The re-usage and adaptation of international standards such as first ISO norm for technology-enhanced learning ISO/IEC 40180 (2017) and the Quality Reference Framework (QRF) for online courses and learning support the design of online education (Stracke et al., 2018). These first international quality standards were already applied and used as basis for the holistic pedagogical model Learn STEM presented in this paper. Furthermore, the online course for the teacher training programme of Learn STEM will also benefit from them.

It can be concluded that further research is required to precisely focus the specific requirements of school teachers and headmasters how they can introduce and facilitate pupil-centered STEM education with different approaches of open and closed methodologies inside and outside the classroom that is following the five principles of the pedagogical model Learn STEM.

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