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ORIGINAL PAPER

Promoting pre-service teachers' professionalism in steam education and education for sustainable development through mathematical modelling activities

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Abstract
To successfully solve the complex challenges facing us in the 21st century, people with expertise in the science, technology, engineering, arts and mathematics (STEAM) fields and other fields are needed, especially for their interdisciplinary way of thinking and working. These competencies should be learned in school, which first implies teacher education to that effect. In this article, a detailed theoretical reflection on the connections or overlapping areas between STEAM education and the dimension of sustainability in a model-like way is presented. It is also argued that mathematical modelling can be a possible instrument for promoting pre-service teachers' professionalism in STEAM education and education for sustainable development (ESD). Based on authors' developed model of this theoretical framework, an ESD-modelling seminar was created for pre-service mathematics teachers in which they also worked on that ESD and STEAM-based modelling problems. In the written reflections on the seminar, which were used as the survey instrument within the conducted empirical study, the teachers presented their subjective views on the connection between modelling and ESD. Based on an evaluation of these written reports by type-forming qualitative content analysis, three teacher profiles for handling ESD within mathematical modelling were developed. These types of teachers illustrate a strong awareness of promoting STEAM and ESD through modelling activities in their upcoming teacher life.

Keywords STEAM · Education for sustainable development · Teacher professionalism · Mathematical modelling · Empirical study

1 Introduction and research questions

Guiding the principles of sustainable development, the Sustainable Development Goals (SDGs) provide an orientation for the complex and global challenges facing humanity in the 21st century. The equally diverse references to STEAM subjects (Science, Technology, Engineering, Arts, Mathematics) in the SDGs suggest the need for the expertise of people from STEAM disciplines to meet these challenges. For this reason, in many countries, the educational importance of STEAM education has become anchored in the agendas of educational institutions and schools from kindergarten onwards, for example, in the USA by the National Research Council (2014) or in Germany by the Ministry Conference (KMK, 2003). In addition to the promotion of STEAM education over the past 15 years, the educational concept of education for sustainable development (ESD) has attracted attention. Because of worldwide discussions on climate change and the accompanying media presence regarding environmental protection movements, this concept has become very important, especially for younger people. This approach calls for and promotes a redesign of education within a framework oriented towards the global SDGs anchored in Agenda 2030 (United Nations [UN], 2015). The international discussion on the connection between sustainable development and education had its first significant debate at the UN Conference on Environment and Development in 1992. In the following years, the topic experienced international recognition through various international resolutions (UN, 2015), for example, in the call for the UN Decade of ESD (2005–2015) in 2002 and

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the subsequent World Action Programmes (WAP), Sect. 4.7 became visible: ‘By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through ESD’ (ICCROM, 2022, p. 1). ESD has a complex characterisation, so the core aspects in the sense of UNESCO (2015) are clarified here. Briefly, ESD means that key issues of sustainable development are included in teaching and learning (e.g. climate change, poverty alleviation and sustainable consumption). It also requires participatory teaching and learning methods that motivate and empower learners to reflect on their behaviour and take action towards sustainable development. ESD should consequently promote competences such as critical thinking, imagining future scenarios and making decisions cooperatively.

Sustainable development does not follow a predetermined pathway, ‘Sustainable development, if it is going to happen, is going to be a learning process’ (Scott & Vare, 2007, p. 192). Hence, education policy should aim to promote learning processes that encompass sustainable development with a view to the perspectives of inter- and intragenerational justice, dimensions of sustainability (economic, ecological, social and cultural), local and global perspectives, vision and participation orientations (action orientation), and awareness of the problems relevant to sustainability. Worldwide, there is now a mandate to integrate SDGs into ESD in schools and lessons.

The demands for both high-quality and, preferably, inclusive STEAM education (Kelley & Knowles, 2016) can be similarly transferred to ESD from scientific and educational policy perspectives. This is subject-related and is presented in detail in the Orientation Framework for Global Development Education of KMK (2016), among others. An integrative (learning) approach is favoured in each case (English, 2016; Honey, et al., 2014). This means that the STEAM disciplines and issues in the field of sustainable development are not taught as though they are detached from context. The thematic scope of an ESD topic enables interdisciplinary or cross-disciplinary teaching, in addition to purely subject-related teaching of a topic. Furthermore, complex ESD topics also offer the possibility of constant deepening and process-oriented work through changing perspectives. This will be possible, for example, through a modelling problem regarding the aluminium industry in Brazil, which is presented later in this paper. In the area of STEAM research, there are already good examples of implementing ESD in teaching (Hobbs, et al., 2017). In the area of ESD, there is still a need for considerable evidence-based developments in all educational areas, especially in the sense of ‘from project to structure’, which requires institutional anchoring instead of a project-like approach (de Haan, 2002, 2006; National Platform on Education for Sustainable Development, 2017). Although teaching examples for ESD and their testing in practice have been researched worldwide—especially since the UN Decade of ESD—and scientific concepts and examples of good practice have been communicated, there is still a lack of research in the field of ESD (Dahl, 2019). There is research on effective teaching and learning, and on evidence-based best-practice examples that can serve as role models for teachers of all school types regarding ESD (Firth & Winter, 2007; Dahl, 2019). More specifically, there are no evidence-based investigations on the teaching and learning of ESD through mathematical modelling, particularly in pre-service mathematics teacher education. Hence, there is a need for our theoretical considerations and empirical study. Regarding our study aim, we argue that the findings and examples of interdisciplinary learning and teaching of STEM can be transferred to teaching modules on sustainable development in schools and teacher education settings (Pitt, 2009). As a starting point for teaching sustainability issues, the focus is on complex and real issues, which in turn require the professional knowledge and expertise of people from STEAM disciplines to address. In this framework, learning and teaching in an interdisciplinary and authentic way is a promising approach in the context of mathematical modelling. This applies to both STEAM and the ESD context (Borromeo Ferri & Mousoulides, 2017; Hallström & Schönborn, 2019).

Therefore, the aim of the current paper is to determine the connections or overlapping areas between STEAM education and the perspectives of sustainability in a model-like way. Our focus is on the expansion of STEAM education through mathematical modelling. This will enable interdisciplinary mathematics learning, a refocusing of STEAM education (Doig, et al., 2019) and a new focus on ESD. In a model presented in Fig. 1, we illustrate that, for example, curricular framework conditions, as well as teachers and learners, can be decisive input factors for this reorientation of STEAM education and the application of mathematical modelling. Through this integrative learning approach, the desirable output of a qualitative education can be achieved that is oriented towards the relevance of today’s issues and makes a comprehensive and transformative claim on the education system.

The model in Fig. 1 was fundamental because it formed a central basis for the development of the ESD-modelling seminar. The theoretical foundation was the first step, which led to the second step of seminar development. This, in turn, led to the central research question of our research agenda. For authentic learning and teaching to be possible, Hallström and Schönborn (2019) strongly emphasise the need for appropriate and purposeful teacher training. Since we now assume that teacher expertise is the most important factor for the effective implementation of inclusive STEM

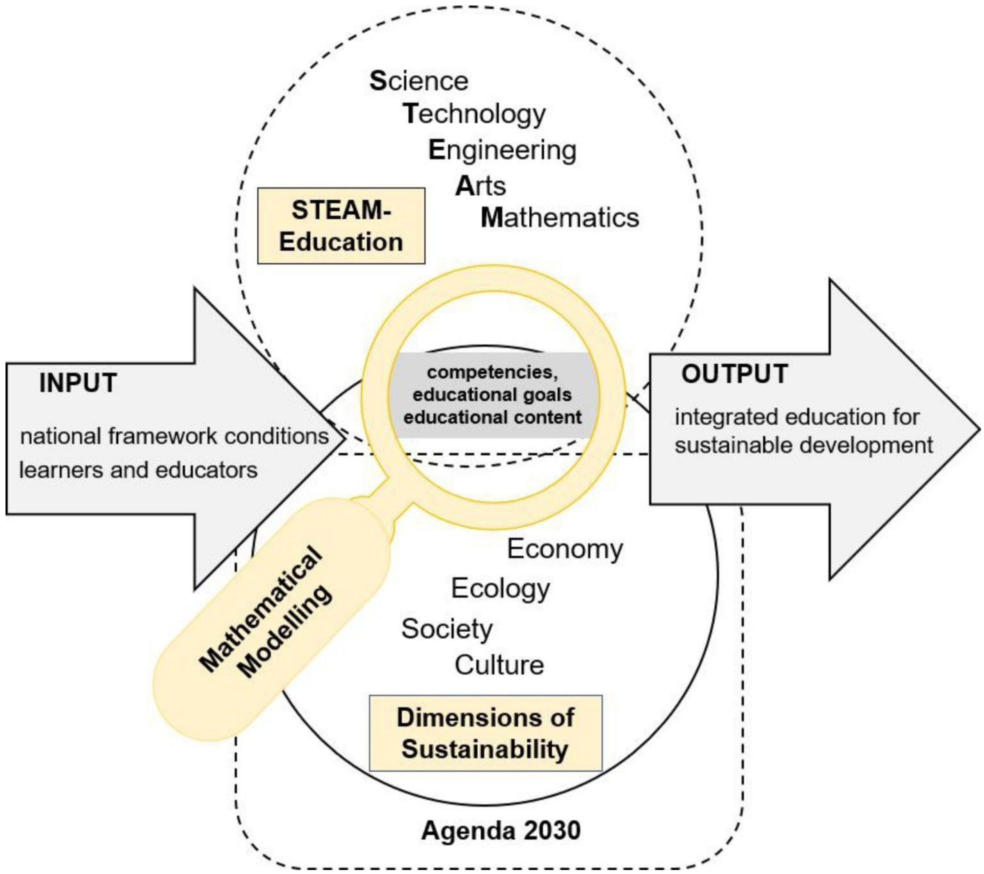


Fig. 1 Mathematical modelling in the context of STEAM and ESD

education (Honey, et al., 2014), which is also transferable to ESD, the demand for teacher professionalisation forms the starting point of our empirical study.

To explore one of the many gaps in the research literature, the current paper presents a seminar for pre-service mathematics teachers that was designed and then conducted by the authors for teaching and learning ESD through mathematical modelling. A qualitative study was carried out to analyse pre-service mathematics teachers' written reflections following the seminar in which the pre-service mathematics teachers linked STEAM education with ESD and mathematical modelling as an integrative learning approach to teaching. As a result of the analysis of these subjective assessments, three teacher types regarding teaching and learning ESD through mathematical modelling were identified. These findings provide interesting insights into how complex STEAM education in the context of ESD is evaluated by pre-service mathematics teachers regarding their future teaching.

The central research question arising from the authors' developed model on the basis of which the ESD-modelling seminar was designed is as follows:

- How can the already-developed theoretical model be used to support pre-service mathematics teachers in developing an integrative approach to STEAM education and ESD through mathematical modelling?

After the theoretical background, which includes the presentation of the developed model and methodology, the empirical study and the university seminar are described. This is followed by the results. In the discussion and outlook at the end of the article, the need for research on teacher education regarding ESD is once again emphasised. Finally, reflections are provided regarding how these challenges can be met in the future.

2 Theoretical background

Mathematical modelling seems to be a possible instrument for connecting the ESD and STEAM education in an integrative and interdisciplinary way.

But what are the connections or overlapping areas between STEAM education and ESD? Both approaches seem to be closely linked, but on which levels? The aim was, therefore, to build a theoretical model that clarifies these connections and overlapping areas in a holistic way. This model will also be used as a basis for the development of teacher education curricula. Furthermore, the model formed the basis for the development of the ESD-modelling seminar for the empirical study on which the paper is based.

In the following sections, we will cover the components—STEAM (education) and the dimensions of sustainable development—as the basis for ESD, which are first briefly described individually. Finally, their overlapping areas and interdependencies will be clarified. In particular, the overlap between the two components, as shown in Fig. 1, demonstrates their high degree of agreement in terms of promoting competences, goals and content for teachers and learners with regard to an integrative STEM and ESD education.

This core area of both components is also the centre of the effect chain of the desirable teaching-learning processes for a reorientation of education towards ESD, which is researched with 'the magnifying glass' of mathematical modelling as a mediator or instrument. But this effect chain starts with what we call the input (left arrow in Fig. 1), which includes prerequisites, such as national framework conditions and the specificities of learners and educators. The output (right arrow in Fig. 1) from this core overlapping area, describes the intended goal of integrative learning and teaching from ESD and STEAM education.

The magnifying glass—mathematical modelling—is finally described in terms of teachers' competences in mathematical modelling.

2.1 The components of STEAM education, SDGs and ESD

The acronym for science, technology, engineering and mathematics (STEM) is widely known. The importance of STEM education is a worldwide consensus (Vasquez et al., 2013), but for more than a decade now, the acronym has been expanded with an 'A' to STEAM. The young generation must be effective contributors to society in the future—in the sense of educational scientists, mastering twenty-first century skills has been seen as trend-setting and should be promoted as early as possible (Kennedy & Sundberg, 2020). Skills such as creativity, communication, innovation and entrepreneurship play a role here. These areas already illustrate an expansion of the STEM disciplines, indicating that 'arts' in the broadest sense are necessary to find solutions to complex questions arising from different perspectives (Khine & Areepattamannil, 2019). Therefore, STEAM education has been described as 'an approach to learning that uses Science, Technology, Engineering, the Arts and Mathematics as access points for guiding student inquiry, dialogue and critical thinking' (The Institute for Arts Integration and STEAM, 2022, p. 1). The extension of STEM into STEAM plays a central role in our ESD approach and is thus also shown in the model in Fig. 1. A brief look at the UN's (2015) 17 SDGs illustrates this necessary expansion, because the SDGs form the basis and orientation of sustainable development with an equal weighting and ranking of ecological, economic and social impacts. The pursuit of SDGs, sustainable development and, ultimately, ESD requires more than pure STEM disciplines to address the complexity and challenges of our time.

Sustainability has become the dominant topic in many areas of politics and is gaining importance in social life. In this context, as educational institutions, schools have a relevant role to play in the ESD process because the transformation towards a more environmentally and socially compatible lifestyle must be created and then supported by society. At the 70th UN General Assembly, the 17 SDGs were adopted as part of the 2030 Agenda (UN, 2015). ESD has thus emerged from international policy making; see UNESCO (2002) World Programme of Action on Education for Sustainable Development (WAP ESD 2015–2019) and the new UNESCO ESD programme 'Education for Sustainable Development: Towards Achieving the SDGs' (ESD for 2030) (UNESCO, 2020). It is the task of educators and educational theorists to develop the concept of ESD for all learners in schools and for teacher education. This implies a renewed reflection on education, its functions and its institutional and structural anchoring (UNESCO, 2002).

Now, it becomes clear what we mean by the described input of the effect chain in Fig. 1. The above-described requests are central input factors regarding, for example, national frameworks. Furthermore, one must take teachers and learners into account.

2.2 STEAM education, ESD and their interdependencies

What are the connections or overlapping areas between STEAM education and ESD? This question is interesting because both approaches are used many times, but often side by side, as they are closely linked. We argue that we cannot consider the components independently of each other and also need to highlight their specifics.

STEAM education presents as a close cooperation of science, technology, engineering, mathematics and, through the 'A', political science, visual arts or philosophy, to name a few. The pedagogical approaches of these disciplines can contribute to teaching the criteria and content of sustainability or implementing the ESD concept in the educational process. Likewise, the use of sustainability contexts in STEAM education could stimulate critical discussions in the socio-educational space, creating new opportunities for ESD. Thus, it is also incumbent on an integrated STEAM approach to transform education into an innovative environment for sustainable development. Thinking about the extent to which STEAM education can be promoted by teaching the dimensions of sustainable development, the current paper focuses on how ESD is carried out through the STEAM disciplines and taught through modelling tasks as a central activity. There is no clear answer in the literature about the interdependencies between STEAM education and ESD. For example, Hopkinson and James (2010) indicate that some STEAM examples are suitable for integrating ESD into science and related curricula. Pitt (2009) used the term 'blurring boundaries' to indicate that STEAM and ESD are virtually inseparable and mutually dependent. For Hopkinson and James (2010) and Pitt (2009), ESD is successfully implemented when teaching activities are linked to the core activities of the STEM disciplines. In a theoretical reflection, Yu (2012) argued that 'ESD starts when STEM stops', indicating that the social sciences are missing in STEM, which, in turn, ESD covers. The latter shows the importance of the STEAM approach, which is evident in our model, because the strong overlap of both approaches is obvious and necessary.

This discussion shows that STEAM and sustainable development share competencies, educational goals and content, which is argued to be the core overlapping area within the effect chain.

In Germany, for example, the inclusion of mathematical modelling in the national educational standards for mathematics (KMK, 2003) provides the (legal) framework to develop ideas and concepts in a bottom-up process to shape policy-initiated ESD. It is precisely the still missing educational theories and internationally uniform definition for ESD that can enable a new orientation of STEAM education in the sense of sustainable development, with mathematical modelling as a potential connecting core piece to the perspectives of sustainability. Appropriately adapted and expanded teacher education can lay the foundation for discourses on ways of thinking, skills, values and attitudes in the sense of active participation in the transformation movement of the 2030 Agenda.

The magnifying glass in the model, with mathematical modelling as the core, is the central aspect of ESD and teacher competences.

2.3 Mathematical modelling to promote ESD: the promotion of corresponding teacher competencies

Mathematics can be used to better understand and solve real-world problems and phenomena. In the process known as mathematical modelling, a real-world problem is simplified and transformed into a mathematical problem, which is then solved and related to reality (Niss & Blum, 2020). The modelling sub-competencies needed for mathematical modelling, such as understanding the problem, simplifying, mathematising, working mathematically, interpreting and validating, are usually visualised as circuits running through various modelling cycles (Borromeo Ferri, 2006). Modelling competencies form the basis for successfully working on real problems and must be mastered by teachers and students. In the literature, there are many approaches to teaching modelling competencies—for a current overview regarding the conceptualisation of the term, see Cevikbas et al. (2022).

To classify mathematical modelling in the context of ESD, it is important to look at the perspectives of mathematical modelling (Kaiser & Sriraman, 2006). Relevant here in particular are socio-critical modelling, contextual modelling and realistic or applied modelling, as these illustrate, in our perspective, a direct link to ESD. Socio-critical modelling pursues a critical understanding of the world and questions the role of mathematical models. In contextual modelling, content-related and process-related goals are in the foreground, which offer the learner incentives for processing, argumentative discussion and the development of their own concepts because of their proximity to reality. Realistic or applied modelling also pursues content-related goals with the motivation to solve realistic problems and, thus, to combine an understanding of the real world with modelling competencies. This type of modelling focuses on real and, above all, authentic problems from industry and science, which are only slightly simplified.

Thus, modelling problems represent a prototype for interdisciplinary mathematics learning. English (2009) clarified, 'Because of their interdisciplinary nature, modelling problems provide a rich platform for student research projects' (p. 171). English's statement provides the basis for integrative learning and teaching in ESD through modelling problems because 'by using modelling problems, teachers can work with their students in crossing the boundaries between disciplines' (Borromeo Ferri & Mousoulides, 2017, p. 906).

Looking back now at the previously described connections (see Section 2.2) between STEAM(-education) and ESD, and then connecting mathematical modelling (MM), which is an interdisciplinary activity due to its task format, leads to the conclusion regarding the research aim of this study: *the interdisciplinary nature of MM in ESD contexts*. For ESD teaching, this means that teachers need to have both teaching competencies for modelling and multi-layered knowledge of sustainable development, especially in specific contexts. This interdisciplinary dimension is one of two dimensions that form the basis for analysing the data in our study (see Section 3.4., Table 2).

Previous findings for increasing teachers' pedagogical content knowledge for mathematical modelling through seminars have been empirically confirmed (Borromeo Ferri, 2019; Greefrath et al., 2021). The necessary and empirically operationalised teacher competencies for modelling are described in Borromeo Ferri and Blum's model's (2010) four dimensions—theoretical, task, instructional and diagnostic—each of which has three sub-facets.

The possibilities for integrative teaching and learning of ESD and mathematical modelling through their shared inherent interdisciplinarity have been clarified previously. However, both mathematical modelling and ESD use multiple perspectives to achieve outcomes on several levels, for example, in terms of defining new goals or changes in structuring mathematics lessons or by developing modifications to the educational system and society to achieve Agenda 2030. Therefore, we consider the second dimension of the link between ESD and mathematical modelling for the data analyses, namely *the multilevel goals of ESD and MM* (see Sect. 3.4., Table 1).

2.4 The model: mathematical modelling in the context of STEAM and ESD

As a foundation for ESD, based on the previous descriptions of the components of STEAM education and the aspects of (non)sustainable development of the SDGs and their interrelationships and overlapping areas, the effect is visualised in the model in Fig. 1.

To date, background information on the SDGs, sustainable development and ESD has barely been integrated into the curricula for teacher training in mathematics at universities in Germany. There are also no best-practice examples of teaching and learning ESD through mathematical modelling. Empirical findings from pre-service mathematics teachers on how their ESD learning process is reflected through modelling are lacking. Therefore, how the theoretical model can be used to support pre-service mathematics teachers in developing an integrative approach to STEAM education and ESD through mathematical modelling is the focus of our research.

Table 1 Steps of the qualitative type-forming content analysis

1. Determine the meaning, purpose and focus of typing.	5. Allocate all cases of the study to the types formed.
2. Select the relevant dimensions of type formation and determine the feature space.	6. Describe the typology, the individual types and in-depth individual case interpretation.
3. Code or recode the selected material.	7. Analyse the relationships between types and secondary information.
4. Determine the method of type formation and construction of the typology.	8. Determine the complex relationships between types and other categories.

3 Design and methodology of the study

To obtain empirical evidence on the extent to which a seminar on mathematical modelling in the context of ESD promoted pre-service mathematics teachers' views of teaching and learning ESD through modelling activities, a qualitative study was conducted (Creswell, 2008).

3.1 Sample and data collection

The sample included 14 pre-service secondary school mathematics teachers, with an age range of 19 to 21 years. The pre-service mathematics teachers were all in their second year of study and attended a compulsory seminar on mathematical modelling led by the second author. This seminar ran in parallel to the compulsory practical semester, in which the pre-service mathematics teachers visited the school in a teaching capacity for half a year, were supervised by their mentors in the school and performed their own teaching. All pre-service mathematics teachers agreed to participate in the study. They were aware that the written reports that they were to prepare after the seminar would be used in anonymised form for data analysis.

The seminar was a crucial intervention for answering the research question. All pre-service mathematics teachers had basic knowledge of mathematical modelling from their first year of study, because the topic of modelling was covered in a compulsory lecture series and was part of an examination. In contrast to mathematical modelling, the pre-service mathematics teachers had little pre-knowledge related to STEM/STEAM (education), the 2030 Agenda, the SDGs, ESD or concepts of teaching using an ESD approach. The acronyms were known but nothing further, and none of the pre-service mathematics teachers had ever participated in a course that dealt with this topic.

3.2 Description of the seminar

The seminar that both authors conducted was a modification of the empirically validated mathematical modelling seminar developed by the second author (Borromeo Ferri, 2018). In cooperation with the first author, who is a teacher of mathematics and chemistry and has intensively studied the topic of ESD in the context of the Sustainable Development Cooperation' Master of Arts programme at the Technical University of Kaiserslautern, a more integrative approach to the seminar was created. In addition to the integrative STEAM approach, the central background of the SDGs and the ESD was addressed. Specifically, the students worked in a team and solved modelling tasks. In this way, the question of what contribution mathematics teaching—specifically mathematical modelling—can make to the successful establishment of ESD could be specifically addressed. Figure 2 shows the central contents of the four seminar units.

Because of the COVID-19 pandemic, pre-service mathematics teachers were not able to teach self-developed ESD-modelling tasks. Each teaching unit of the seminar lasted four hours and was held one week apart. After eight weeks, the pre-service mathematics teachers submitted their written work. According to examination regulations, the papers that had to be given to the second author as the seminar leader were not graded. Therefore, passing the course was a matter of successfully completing the report according to the given guidelines. Only after all pre-service mathematics teachers had successfully submitted their reports and had them checked by the second author, the first author, who was not involved in the assessment process, anonymised the data for analysis.

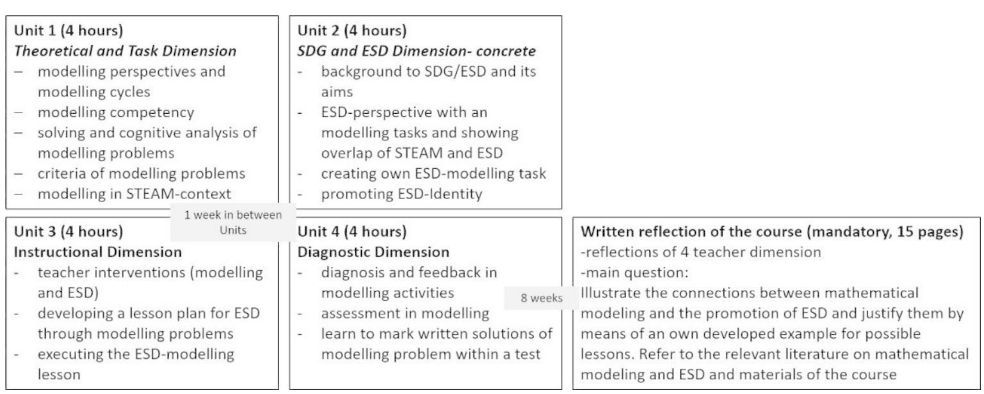
To illustrate the integrative ESD approach through modelling, we provided a selected example of an ESD-modelling activity within the seminar. The situation in which we find ourselves in the 21st century demands an examination of the regional and global consequences of our actions, as well as an understanding of and argumentative advocacy for change, to be able to transition into responsible, reflective and democratic action. Following these basic ideas and based on the SDGs and the guiding principle of sustainable development, we designed corresponding modelling tasks for teacher training. With these modelling tasks in the context of ESD, the Pre-service mathematics teachers and, later on, the learners should be motivated, among other things, to put themselves in the position of other people, to find and appreciate the value of encounters and objects in everyday life and to reconsider their value judgements. Because the pre-service mathematics teachers worked on several ESD-modelling problems, the ESD perspectives were discussed, which is crucial for reflecting on the connection to mathematical modelling.

As an introduction to the modelling activity, with its ESD focus, a modelling example was developed on the topic of e-mobility. The pre-service mathematics teachers were informed about the aluminium industry in Brazil via a short film; they then discussed the positive and negative effects of the aluminium industry on Brazil and its population. The aspects identified ranged from the positive economic development of the country to the negative social effects caused by the aluminium industry, especially regarding the health of the people living and working there, to the negative ecological and global consequences of the destruction of the rainforest. After working through the perspectives of sustainability, the Pre-service mathematics teachers were then given the below task. This modelling problem also serves as an example for use in secondary schools and can be addressed using digital tools and the internet for research purposes.

> Aluminium is needed to build an electric car. It is extracted from the raw material bauxite that is mined in Brazil and the aluminium oxide produced there. This is done with the help of fused-salt electrolysis in Germany. An important question is: How much energy is consumed on this path to the finished aluminium metal? Argue and provide a mathematical justification for how relocating the entire production of aluminium to Brazil could contribute to increased sustainable development in Brazil.

When working on a possible solution, the pre-service mathematics teachers were guided by the phases of the modelling cycle, according to Borromeo Ferri (2018). A possible solution cannot be presented in detail, so only parts will be given. We deliberately limit ourselves to the first part of the task—how much energy is consumed until the finished aluminium metal product is produced. Assumptions can first be made regarding the energy consumption of transporting aluminium oxide from Brazil to Germany. The distance, the heavy oil consumption of the freighter and its loading capacity are central variables. Furthermore, there are considerations to be made regarding how much aluminium oxide is needed for a midrange e-car. For this, central assumptions and research are helpful, such as aluminium consumption for an e-car and the proportion of aluminium in the alumina.

Fig. 2 Seminar: Teaching ESD through mathematical modelling



A final consideration in this context is how much energy is needed for electrolysis to extract aluminium from alumina. Research, for example, from the internet, can provide the data. Based on these data, mathematisation can take place using very simple models, which are limited to the areas of multiplication, division and the application of the rule of three. Furthermore, competencies in dealing with quantities, in the sense of conversion, are required. As a result, the following can be formulated: For an e-car, 20 L of heavy oil are needed to transport the aluminium oxide and 7500 kWh of electricity are needed for the electrolysis to extract the aluminium. Because 20 L of heavy oil has a calorific value of 220 kWh, the energy consumption for transport is hardly significant in comparison. The total energy consumption of 7720 kWh for the production of the required aluminium from the extracted aluminium oxide for an e-car corresponds to about 48,000 km, driven at a consumption rate of approximately 16 kWh/100 km.

The second part of the modelling task requires a review of the impacts on the sustainability dimensions of both countries if the aluminium process is transferred from Germany to Brazil. This includes, for example, a comparison of electricity generation for the energy-rich aluminium electrolysis process in Brazil (hydropower from reservoirs) and Germany (nuclear power, fossil fuels), addressing both the countries' culture-dependent ecologies and economies and the fact that 'all perspectives of sustainability can only be understood from the respective cultural context of the discourse conducted' (de Haan, 2002). Thus, re-service mathematics teachers and learners are confronted with 'the analytical aspects of the ecological dimension, the action aspects of the economic dimension and the primarily normative aspects of the social dimension' (de Haan, 2002). The open-endedness of this task, including possible real-life references and broad learning contexts, motivates us to link our knowledge of the criteria for sustainability with that of (non)sustainable development processes. For any subject from the natural sciences (chemistry, biology, physics) to the humanities (ethics, religion, political science), the task can be implemented in interdisciplinary teaching concepts.

Table 2 Dimensions and characteristics

Dimensions	Characteristics
The interdisciplinary nature of MM in ESD contexts	I. ESD for MM contextual and meaningful II. ESD topics to promote mathematical terms/concepts III. MM as a tool for achieving ESD goals in the classroom
The multilevel goals of ESD and MM	(1) Focus on social problems through STEAM/ESD (2) Further development of the education system (3) Teaching mathematical content/modelling competencies

3.3 Data collection

The data collection was based on the written reflections of the pre-service mathematics teachers on the following concrete task: Clarify the connections between mathematical modelling and the promotion of ESD and justify them with an example for your lessons. Refer to the relevant literature on mathematical modelling and ESD.

Four pages had to be written for this part of the report. A total of 56 pages from each of 14 pre-service mathematics teachers formed the data basis for evaluating the anonymised content. According to Heinze (2016), these are '[…] scientific descriptions of a social object. They are neither "pre-knowledgeable", like everyday descriptions, nor scientific-quantitative, i.e. not in the form of frequencies, quantities, series of numbers or indices that have to be explained or interpreted by the researcher. Rather, they are meaningful in themselves' (Heinze, 2016, p. 13).

3.4 Data analysis

The data were analysed using type-forming qualitative content analysis, according to Kuckartz (2016), which is a special form of qualitative content analysis (Mayring, 2022). This method aims to meet the requirements of methodological control and transparency.

In this method, the data are structured in terms of content so that categories are formed based on the research question and all material is segmented and coded. More specifically, Kuckartz (2016, p. 48) described type-forming in eight steps (Table 2).

Regarding the research question presented here, type-forming plays a major role. The purpose of type-forming according to Step 1, is to contrast the views of the pre-service mathematics teachers regarding an integrative teaching-learning approach to ESD through modelling activities in a case-based manner while carrying out a grouping in the sense of type-forming in a methodologically controlled manner.

Regarding Step 2, the selection of the two relevant dimensions for the typification in the study arose from the theoretical background described in Sect. 2.3, which formed the basis for our model in Fig. 1: Mathematical modelling (MM) in the context of ESD from an interdisciplinary perspective and the multilevel process of ESD with the help of mathematical modelling. The feature space was determined first theoretically and thus deductively by using the dimensions as theoretical glasses and then inductively through a detailed analysis of the data (Mayring, 2022) by successively identifying the characteristics for the coding system.

In order to make the results presented later—the three teacher types—more transparent, the characteristics in Table 1 are briefly explained below.

I. *ESD for mathematical modelling is contextual and meaningful*.
ESD provides a content framework in which learners learn to deal with mathematical modelling in a problem-oriented way. The teaching of a holistic view is done by applying mathematical modelling to the topics of, for example, socially relevant problems and is thus in the focus in the foreground of a teaching unit.
II. *ESD topics to promote mathematical terms/concepts*.
Mathematical ways of thinking and working are the focus when it comes to using ESD as an ideal context for the application of mathematical modelling. Through multiple possibilities of linking mathematical content with real ESD topics that are relevant for learners, it is possible to make mathematical modelling tasks even more attractive and motivating.
III. *Mathematical modelling as a tool for achieving ESD goals in the classroom*.

Mathematical modelling is a tool for achieving the target competences of ESD in superficial engagement with ESD topics. Mathematical modelling is a suitable method and core competence for ESD promotion in mathematics. The high value of interconnected learning in ESD provides the basis for sustainable action orientation as the main goal of the ESD-modelling activity.

We argue that for characteristics I through III, competencies for appropriate behaviour and self-organised action need to be increasingly promoted via redefined teacher role, away from that of an instructor and towards being a supporter of learning processes.

The multilevel goals of ESD and MM are represented and overlap in characteristics (1) to (3). Using a modelling approach in the integrated ESD/STEM context allows teachers to (1) focus on broad social problems and address the ultimate goal of ESD, which is to shape society using principles of sustainable development. However, this approach also requires development of new pedagogical repertoires for implementing interdisciplinary and project-based teaching, thus (2) further developing the whole education system. At the level of the mathematics lesson, (3) teaching mathematical content and modelling competencies entails mutual interactions between models, people, and reality. According to Kuckartz (2016), in the Step 3, the data were independently and multiply coded by the authors based on the above characteristics. Particular attention was paid to how the pre-service mathematics teachers argumentatively linked the contexts of ESD with the theoretical background of SDGs and ESD through modelling. The validation of the codes, which, in turn, led to the discovery of patterns and groupings into a typology (Step 4), was done through validation or member checks (Flick, et al., 2010). The following examples show how the coded passages were assigned (Step 5) to two central characteristics of the feature space, which resulted in type-forming.

III and (1): 'Mathematical modelling can be used to raise students' awareness of the SDGs […] The importance of mathematical modelling is increasing. In doing so, ecological, economic, social and culture areas can also be covered by promoting ESD precisely through modelling.'

I and (2): 'While I think such ESD-related modelling tasks are great, I will definitely do this interdisciplinary in the future, as knowledge of global connections is a significant learning goal in school in general.'

II and (3): 'The goals of ESD pose a real problem that gives rise to a mathematical approach. Not only are the competences of mathematical modelling touched upon here, but the problems provide a basis for tasks for modelling exercises that move learners to complete a modelling cycle.'

4 Results of the study

In this section, the research question is answered and thus the results regarding the typology are described (Step 6), as are the relationships between types (Step 7) are also presented with further possible types (Step 8) become apparent.

4.1 Ideal teacher types for handling ESD using mathematical modelling

The realisation of the close linkage of mathematics and mathematical modelling with ESD topics and their mutual promotion of competences was emphasised by all pre-service mathematics teachers. However, pre-service mathematics teachers chose different approaches to developing modelling tasks in the context of ESD. Furthermore, they placed different emphases on the implementation of the teaching idea. Through the type-forming qualitative content analysis, three teacher types, based on the dimensions and characteristics in Table 2, were empirically generated, as seen in Table 3. It is obvious that then some of the typology's cells should be empty. However, the coding of the data showed that not enough robust findings for further types emerged from our current database. Nevertheless, we provide an outlook on possible types (in brackets in Table 3) and their descriptions in Section 4.3.

Five people were assigned 'The reformer' type and four people were assigned to each of 'The mathematician' and

Table 3 Teacher types in dealing with ESD through mathematical modelling (MM)

Dimensions		*The interdisciplinary nature of MM in ESD contexts*		
	Characteristics	ESD for MM contextual and meaningful	ESD topics to promote mathematical terms/concepts	MM as a tool for achieving ESD goals in the classroom
The multilevel goals of ESD and MM	Focus on social problems through STEAM/ESD	(The bridge builder)	(The user)	The do-gooder
	Further development of the education system	The reformer	(The traditional)	(The networker)
	Teaching mathematical content/ modelling competencies	(The pragmatist)	The mathematician	(The project manager)

'The do-gooder' types. The three types are described below, each illustrated with prototypes.

4.1.1 Type 1: the reformer

According to 'The reformers', ESD and mathematical modelling contain an educational claim that will play a central role in the further development of our education system.

In ESD, 'The reformers' see an opportunity to reform the school institution towards a self-responsible system. The focus is on a school development process intended to ensure educational quality in which pupils would be trained in schools regarding the changes in the world and the accompanying problems in terms of content and pedagogy. The teaching of a holistic view is promoted through the application of mathematical modelling to socially relevant problems of sustainable development and is thus in the foreground of a teaching unit. The importance of mathematics in society is also emphasised regarding the role that mathematics can play in the elucidation of social phenomena, environmental issues or economic contexts. This interplay of common interests could cause strong cooperation and the joint knowledge transfer of mathematical modelling together with ESD. ESD was seen as contextual for mathematical modelling, providing the content framework in which the learners dealt with mathematical modelling in a problem-oriented way. Central quotes from the participants are as follows:

ESD contains an educational claim that will play a central role in the further development of our education system. Teachers are learning facilitators rather than knowledge transmitters and design self-organised teaching and learning processes.

As a tool for sustainable development, ESD should be anchored in as many subjects as possible. The implementation of ESD in schools should be newly recorded in the core curricula, so that one is obliged to implement a promotion of ESD in the lessons.

4.1.2 Type 2: the mathematician

For 'The mathematician', the focus is on teaching the subject content of school mathematics, as well as learning mathematical modelling in the context of ESD-oriented mathematics lessons. Mathematics provides the data and facts for describing real problems from all perspectives of sustainability and contributes to structuring and representing them. Thus, the topics of ESD provide an ideal context and content framework for mathematical modelling. Because of the variety of possibilities for linking mathematical content to real ESD topics that are relevant to pupils, it is possible to make mathematical modelling tasks even more attractive and motivating. The connection to ESD topics can also motivate the learning and application of mathematical concepts and methods, contributing to a better understanding of mathematics. With the practical application of mathematical modelling, on the one hand, modelling competences are promoted via the modelling cycle, and on the other hand, they are linked to ESD competences. 'The mathematicians' are aware of the possibility of communicating mathematical content with topics in the environment. Central quotes from the participants are as follows:

'ESD is meant to make you think about your own consumption. In math, this works very well with modelling. Math provides concrete figures on societal problems which visualise the whole subject better and make the learner think.'

Mathematics as a socially accepted scientific discipline can provide knowledge within the framework of ESD. Mathematical modelling is in cooperation with ESD in the classroom and causes good cooperation and collaborative knowledge transfer.

4.1.3 Type 3: the do-gooder

For 'The do-gooder', ESD will take a high priority in future school lessons, which means that concrete applications and the targeted discussion of ESD topics in general will be in the foreground. According to 'The do-gooders', social problems can be addressed through mathematics lessons because working with concrete numbers confronts the learner with reality, contributes to a better visualisation of the whole matter and stimulates the learner to think. Modelling problems are developed based on the teacher's motivation and are designed in such a way that the teacher contributes to the students' awareness, promotes their social development and motivates them to actively participate in sustainable development. Thus, mathematical modelling is a tool for achieving the target competencies of ESD and, as an appropriate method and core competence in mathematics, contributes to ESD promotion in schools. The interplay of the different sciences and cooperative work within the framework of ESD includes, in addition to the STEAM subjects, the assessment of justice in the sense of ethical education in the social sciences. The task contexts used are interesting for pupils, fit their life situations, encourage them to reflect on their own experiences and develop sustainable thinking in the sense of a future-oriented life. Central quotes from the participants are as follows:

'The acquisition of ESD skills should always be a weighty part of today's teaching. The ESD sees mathematics as the basis for many topics in society. Mathematics provides sound data and figures that can also serve as a basis for processing in other subjects.'

Qualitative mathematics teaching can help to empower students to think and act conscientiously and sustainably.

4.2 Possible teacher types of teachers in handling ESD within mathematical modelling

An intensive further examination based on the theory and the existing types so far leads to additional possible teacher types, which are in brackets in Table 3.

4.2.1 Type: the bridge builder

'The bridge builder' has differences in the world in mind and uses the data and facts of mathematical modelling to show the different perspectives and opinions on a topic in the local environment as well as in the global world. He/she/they sees mathematical education as the foundation for reforming society with a focus on just coexistence in the sense of inter- and intragenerational justice because mathematical modelling clarifies injustices and acts as a bridge builder with 'knowledge about' and 'understanding for' others, locally and globally.

4.2.2 Type: the pragmatist

'The pragmatist' takes different models of an ESD issue as the central point of discussion to make learners aware of the key role of mathematical modelling as a basis for social and political decision-making. In this way, the pragmatist provides a firm mathematical foundation and a new quality for individual visions of the future.

4.2.3 Type: the user

'The user' is 'The mathematician's' big brother. For this teacher type, the application of the subject content of school mathematics and the learning of mathematical modelling in the context of ESD topics are important. This type uses examples of development processes that are close to reality to focus, analyse, understand and further develop the real problems of sustainability in society and open up perspectives for action by looking beyond the horizon.

4.2.4 Type: the traditionalist

'The traditionalist' sees other school subjects as being obliged to integrate mathematics as an auxiliary and structural science in their teaching. They stick to their sole task of teaching the mathematical ways of thinking and working necessary for this through traditionally structured mathematics lessons. Thus, a fundamental change in mathematics teaching within the framework of ESD is rejected but is offered as a support for the integration of mathematics into other subjects. In this way, this type avoids a dilemma between the importance of ESD-related modelling, cooperative work within the framework of ESD and the fulfilment of the mathematics curriculum.

4.2.5 Type: the networker

'The networker' recognises the fundamental role of the mathematical perspective on ESD topics and content. However, this type also sees that this requires knowledge and competences that he/she/they, as a mathematician, does not have in sufficient form and therefore pleads for a structured opening and cooperation of the school to facilitate extracurricular places of learning, organisations and experts. Mathematics provides data and facts as a basis for this interdisciplinary exchange.

4.2.6 Type: the project manager

'The project manager' incorporates his/her/their task first of all in taking up the common educational claim of ESD and mathematical modelling in the development of his/her/their teaching. This type sees ESD as an opportunity to reform his own teaching, both in terms of content and methodological-didactic aspects, and to move away from a 'textbook-task-dominated' mathematics lesson towards a realistic, pupil-oriented lesson design. This type focuses more on ESD-modelling problems as 'co-designers' of lessons in order to support individual learning processes with regard to ESD design competences.

5 Reflections and perspectives

Research evidence on teacher professionalisation in STEAM, especially on an integrative teaching-learning approach to ESD through mathematical modelling, is scarce. How the STEAM disciplines and the SDG's dimensions of sustainability can be united in a model in such a way that mathematical modelling activities can become a tool for implementing ESD was theoretically discussed and resulted in the model presented in Fig. 1. The results of the research regarding how the developed theoretical model (Fig. 1) can be used to support pre-service mathematics teachers in developing an integrative approach to STEAM education and ESD through mathematical modelling are original and provide new insight.

First, an ESD-modelling seminar could be developed on the basis of this model, which takes all components into account and focuses, in particular, on teacher education.

Furthermore, through intensive engagement with mathematical modelling, STEAM, SDGs and ESD in the seminar, the knowledge of the pre-service mathematics teachers changed. The pre-service mathematics teachers' examples of modelling tasks in the context of ESD and producing ideas for teaching showed the beginnings of their integrative ESD understanding. The analysis of the data through type-building qualitative content analysis proved to be a successful method, providing three teacher types based on mathematical modelling that deal with ESD and further possible types for the remaining empty cells could be described.

For the first time, the identification of ideal types of teacher action provides insight into which emphases are required in the teaching of ESD through pre-service mathematics teachers' modelling tasks.

The limitations of the current study result from the small number of pre-service mathematics teachers. This requires a generalisation of the results, which involves a consensus in qualitative studies (Flick, et al., 2010) and was not possible in this case. Furthermore, only pre-service secondary school mathematics teachers were examined in the study—no teachers were trained for primary or high school.

The results of the study, as well as the limitations mentioned, open up new possibilities for further research in this field. We consider the presented typology of teachers' indicative, but we see further potential for empirical validation for the possible types. Another limitation is that the teachers in the cohort described were unable to teach the ESD-modelling task because of the pandemic. The pre-service mathematics teachers' reflections will, accordingly, be significantly expanded in the following semesters through the teaching experience. In concrete terms, this means that we will investigate this subject in further studies to continually validate the existing typology. Even with this being the case, the typology now makes it possible to further optimise the ESD-modelling seminar. Overall, the discussions about the importance of ESD, STEAM and 21st -century skills for life on earth present an innovative area of research. The associated challenges for teachers are to motivate and inspire learners on both the subject and soft-skill levels regarding current and future topics of the 21st century and to contribute to the development of competencies for action towards sustainable development.

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