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Developing Problem-Solving Skills to Support Sustainability in STEM Education Using Generative AI Tools

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Abstract

This paper presents a novel, multi-stage modelling approach for integrating Generative AI (GenAI) tools into design-based STEM education, promoting sustainability and 21st-century problem-solving skills. The proposed methodology includes (i) a conceptual model that defines structural aspects of the domain at a high abstraction level; (ii) a contextual model for defining the internal context; (iii) a GenAI-based model for solving the STEM task, which consists of a generic model for integrating GenAI tools into STEM-driven education and a process model, presenting learning/design processes using those tools. A case study involving the design of an autonomous folkrace robot illustrates the implementation of the approach. Based on Likert-scale evaluations, quantitative results demonstrate a significant impact of GenAI tools in enhancing critical thinking, conceptual understanding, creativity, and engineering practices, particularly during the prototyping and testing phases. This paper concludes that the structured integration of GenAI tools supports personalized, inquiry-based, and sustainable STEM education, while also raising new challenges in prompt engineering and ethical use. This approach provides educators with a systematic pathway for leveraging AI to develop STEM-based skills essential for future sustainable development.

Keywords: design-based STEM education; STEM skills; multi-stage modelling; Generative AI tools; prompt engineering

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1. Introduction

STEM (readable as Science, Technology, Engineering, and Mathematics) is an educational paradigm that plays an extremely important role in the 21st century for the following reasons. STEM supports Education for Sustainable Development (ESD), a global challenge of society [1–3]. STEM brings together various interdisciplinary knowledge to prepare learners to fluently enter highly technologized workplaces [4]. STEM relies on the solution of authentic real-world tasks to obtain problem-solving skills, which are the most important skills in the 21st century [5]. Typically, a large body of real-world tasks comprises complex tasks. One important feature of those tasks is that they are more interesting and engaging, making it easier to motivate students to learn. However, human efforts to find effective ways of solving those tasks are often not enough, and researchers have focused on applying AI approaches and tools [6,7], providing additional benefits. Learners can learn not only from the task-solving process but also from the approaches and tools used. Considering the complexity of problem solving with the help of AI is one way of introducing new technologies in education in general and in STEM, in particular. This is so because of the close relationship between AI approaches and other modern technologies, such as the educational Internet of Things, big data, and robotics [8], which are highly valued in the 21st century. On the other hand, the most significant role of problem solving is that it stands as a vehicle or source to produce and deliver other highly important skills (such as computational thinking [9], design thinking [10], data-driven thinking [11], system thinking [12], and analytical thinking [13], among practically all kinds of skills needed for the 21st century).

Currently, STEM educational research and practice are evolving extremely rapidly towards a higher degree of integration. There have been broad discussions and different views on integrated STEM [14,15]. The integrated STEM framework [16], for example, indicates seven key characteristics of the approach: (a) focus on real-world problems, (b) centrality of engineering, (c) context integration, (d) content integration, (e) STEM practices, (f) 21st century skills, and (g) informing students about STEM careers. Among other trends, the evolution of integrated STEM includes an enhanced focus on engineering and design [17,18]. Design is an interdisciplinary domain that uses approaches, tools, and thinking skills that help designers to devise more and better ideas with the aim of creating solutions [19]. From an engineer's point of view, design is a process of generating abstract ideas, then moving to concrete ones, seeking out design patterns, experimenting, testing, and rethinking to find the needed solution. Design promotes creativity and design thinking through task solving. Design thinking is "an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign" [20]. The authors of [21] argue that design and design thinking are important to creativity and innovation not only in engineering and technology and in the current movement of developing and implementing integrated STEM education but also for everyone (similarly to computational thinking, the far-reaching concept proposed by Wing). According to this paper, design thinking can and should be viewed from a broader perspective, that is, as a model of thinking in scholarly education to help nurture and develop creativity and innovation among every student in the 21st century. Integrated STEM, with its various versions, such as design-based STEM, is a highly influential and valuable approach to supporting Education for Sustainable Development (ESD). UNESCO provides a comprehensive definition of this term: "ESD allows every human being to acquire the knowledge, skills, attitudes and values necessary to shape a sustainable future. ESD empowers learners to take informed decisions and responsible actions for environmental integrity, economic viability and a just society, for present and future generations, while respecting cultural diversity" [22]. As a response to this challenge, there have been many discussions on the relationship between STEM and sustainability, as the analysis of the related work shows.

On this basis, it is possible to admit that solving design-based tasks has great potential to contribute to sustainability in STEM education through the variety of skills obtained (e.g., "thinking paradigm") and modern technologies applied (e.g., AI).

Therefore, in this paper, we focus on design-related tasks and the skills obtained through their solution in the context of sustainable STEM education. The aim is to discuss an approach to enforce design-based task solving using Generative AI (GenAI) tools and to evaluate and measure the obtained problem-solving skills. This paper presents a novel multi-stage modelling approach to deal with problem solving from the perspective of sustainability in STEM education. The approach covers the development of (i) a conceptual model to explain the basic idea; (ii) a context model to provide contextual information; (iii) a model for integrating GenAI tools; (iv) a model of the relationships among design-based processes, learning processes, and GenAI tools to define the interaction between the design/learning outcomes and skills; and (v) a model for evaluating learning outcomes by measuring the obtained skills. The contribution of this paper includes (i) the proposed multi-stage modelling methodology for the systematization and better understanding of the role of GenAI tools and processes with respect to the development of problem-solving skills for the 21st century aiming to enforce sustainability in STEM education and (ii) the introduction of an evaluation model for STEM skills within a methodology for empirically defining sustainability aspects. The structure of this paper is described as follows. Section 2 analyses the related work. Section 3 presents the basic idea of this research, as well as background and research questions. Section 4 focuses on a multi-stage modelling methodology. Section 5 discusses the case study on the design of a robot for a folkrace contest. Section 6 discusses the results and evaluates the proposed approach. Section 7 presents our conclusions.

2. Related Work

Stream 1: *Sustainability and Integrated STEM*. The reviewed research on STEM education consistently emphasizes its pivotal role in fostering critical 21st-century skills, particularly problem-solving, creativity, and awareness of sustainable development. Recent scholarly contributions address various pedagogical strategies and interdisciplinary frameworks to support the goals of sustainable education. For example, the paper [1] examines the effectiveness of STEM-based teaching in achieving the Sustainable Development Goals (SDGs), highlighting that STEM pedagogy significantly supports inclusive and equitable education, particularly when adapted to national educational frameworks, such as Saudi Arabia's Vision 2030. Similarly, a systematic literature review [23] confirms that integrating STEM with Education for ESD not only enhances student engagement and systems thinking but also increases their environmental awareness and literacy. Another literature review [24] demonstrates that STEM education effectively enhances students' problem-solving abilities, particularly in physics and science contexts. This analysis supports the incorporation of STEM methods in curricula to foster critical and logical thinking skills. This is echoed by Hebebci and Usta [25], who empirically validated that integrated STEM education has a positive impact on problem-solving, scientific creativity, and critical thinking dispositions in middle school learners. The paper [26] highlights the value of place-based STEM education in creating socio-ecological resilience through collaborative, transdisciplinary projects. The ethnographic findings indicate that engaging students in real-world tasks and sustainability-related challenges fosters attitude and behavioral change towards environmental issues. The paper [27] introduces the IGNITE model, a scalable STEM curriculum grounded in design thinking, which empowers students, particularly in under-resourced regions, to address local sustainability issues using engineering solutions.

The study [28] presents a transdisciplinary STEM model that merges science, art, and community interaction to deepen understanding of sustainability. The model demonstrates the effectiveness of mutual learning in fostering a holistic grasp of human–nature relationships. Additionally, Habibaturrohmah et al. present a systematic review [29] indicating five effective strategies for integrating ESD into STEM: (i) incorporating SDG concepts, (ii) project-based learning, (iii) real-world problem solving, (iv) community collaboration, and (v) teacher training. These strategies collectively support sustainable development through education.

The study [3] on the perceptions of pre-service teachers concludes that STEM education is an essential strategy for promoting awareness of sustainable development among future educators. This study highlights the importance of integrating sustainability into teacher education to create a lasting impact in future classrooms. Research in recent years has shown an increasing attention to the intersection of integrated STEM education, sustainability, and the cultivation of problem-solving skills across diverse educational settings and levels, as follows. The paper [30] analyses how integrated STEM teaching persists in secondary schools after external funding ended. The study on the TRAILS program indicates sustained implementation and consistent student achievement, highlighting the value of collaborative communities of practice among science and engineering teachers for building sustainable STEM programs. Kennedy and Odell [31] contribute to the discourse by framing STEM education as a "meta-discipline." Their work emphasizes the need to rethink curricula, pedagogy, and assessment in ways that align with sustainability goals and 21st-century skills, providing a comprehensive philosophical and structural basis for interdisciplinary integration. Ling et al. [32] focus on planning integrated STEM lessons that explicitly align with national curriculum standards and the SDGs. They propose contextual problem solving as a pedagogical bridge to connect students' real-world challenges with STEM competencies, offering a replicable model for contextualized STEM teaching. Manasikana et al. [33] present a bibliometric review on trends in teaching problem solving in STEM education. Their analysis identifies project-based learning and mobile-assisted instruction as the most impactful strategies, confirming the centrality of real-world contexts and interdisciplinary methods in fostering problem-solving skills. Maass et al. [34] underscore the critical but often understated role of mathematics in interdisciplinary STEM education. They advocate for mathematical modelling as a key strategy to equip learners with the responsible citizenship and problem-solving capabilities necessary in sustainability-related contexts. Nesterenko et al. [35] address the barriers to STEM-ESD integration in higher education. Their study reveals that institutional resistance can be constructively navigated through targeted training, leadership involvement, and gradual integration, positioning higher education institutions as key agents in sustainability transformation. Nguyen et al. [36] explore STEM education in Vietnamese secondary schools, analyzing 77 STEM teaching projects. Their study emphasizes that real-world, constructivist approaches are most effective in promoting sustainability-oriented mindsets and problem solving among students and educators. Pagkratis [37] presents insights from the German perspective on how STEM education and vocational education training promote green skills and innovation. This study stresses the role of policy alignment and industry collaboration in ensuring that problem-solving skills developed through STEM education meet labor market and sustainability demands. Rogers et al. [38] propose a multidisciplinary framework that incorporates sustainability-themed modules across various university departments. Their findings support the use of asynchronous and discipline-bridging learning formats to improve students' ability to collaborate on complex sustainability challenges. Vilmala et al. [39] study the literature on ESD in science education. Their work proposes inquiry-based learning and socio-scientific issues as central to ESD integration in STEM, reinforcing its capacity to cultivate reflective and analytical problem-solving skills.

Velázquez and Rivas [2] suggest that technical drawing classes can serve as a platform for ESD through eco-urban projects. Their work aligns the design and implementation of 3D space planning with UNESCO's learning objectives and SDG 11 (Sustainable Development Goal 11: Sustainable Cities and Communities). Their method integrates socio-emotional, behavioral, and cognitive competencies, making technical STEM skills instrumental in promoting urban sustainability awareness. Zeeshan et al. [40] focus on STEM pedagogies in early education and their impact on the development of problem-solving skills. Their mixed-methods study applies both design-based and scientific-inquiry-based learning activities with primary school students. The results confirm that these methodologies significantly enhance learners' critical thinking, creativity, teamwork, and eco-consciousness. These findings underscore the importance of early STEM intervention in equipping young minds with the skills necessary to address global sustainability challenges.

Thus, the reviewed literature consistently demonstrates that integrated STEM education, particularly when aligned with sustainability goals, cultivates essential problem-solving competencies in learners across various age groups and contexts. A common thread among these studies is the emphasis on interdisciplinary, real-world, and project-based learning as central instruments for developing critical thinking, creativity, collaboration, and ethical reasoning.

Stream 2: *The AI Use and Prompt Engineering*. This review integrates insights from six primary papers and additional scholarly materials to contextualize the emerging discourse around prompt engineering, AI literacy, and student engagement in higher education. The general conclusion is that GenAI tools such as ChatGPT, Copilot, and MidJourney are reshaping educational practice by facilitating personalized, creative, and multimodal learning. Zahirah et al. [41] propose the "AI Immersion" model at Universitas Ciputra to cultivate "AI super users" across disciplines. Students demonstrate growth in technical proficiency and ethical awareness, supported by faculty mentorship and access to free GenAI tools. Walter [42] argues that the presence of GenAI tools in university classrooms shifts the educator's role towards facilitating metacognitive and ethical reflection, not just content delivery. A broader literature also supports these findings.

Prompt engineering is emerging not only as a technical skill, but as a new form of literacy required for meaningful human–AI interaction. Choi & Chang [43] survey educational strategies and student perceptions regarding prompt engineering. They proposed a framework with ten core strategies, including task segmentation, role-based prompting, and counterfactual exploration, that enhance metacognitive engagement. Hwang et al. [44] define "prompt literacy" as learners' ability to craft, refine, and evaluate prompts to generate desired AI outputs. Their study shows that language learners who use visual AI tools improve their vocabulary acquisition and digital expression. Additional sources emphasize that prompt engineering skills empower students to engage critically with AI content, fostering awareness of bias, clarity in instruction, and domain-specific articulation. Important factors are AI literacy and student engagement. AI literacy extends beyond the use of AI tools. It includes understanding their capabilities, limitations, and societal implications. Findings [45] indicate that AI literacy development is correlated with improvements in digital fluency, critical reasoning, and collaborative learning outcomes. However, without guidance, students often either misuse tools or underutilize them due to uncertainty or ethical fears. Structured curricula that include GenAI literacy, such as those developed at Arizona State and Colorado State, address these gaps with policy and practice. However, the integration of GenAI in academic contexts raises complex ethical questions surrounding bias, authorship, integrity, and digital equity. Learners' perceptions of GenAI play a significant role in their adoption and use patterns too. Hamerman et al. [46] indicate that students are more likely to engage with GenAI tools when social norms support their use and when academic policies clearly define ethical boundaries. Cultural context also affects adoption. While the U.S. and Japan emphasize ethics, China focuses on scaling infrastructure, and Indonesia provides regulatory clarity through national guidelines [47]. This brief analysis allows us to draw the following conclusions.

- GenAI tools, when integrated with intention and scaffolding, enhance creativity, digital literacy, and interdisciplinary learning.
- Prompt engineering and AI literacy are core competencies that should be embedded into curricula across domains.
- Student perceptions and cultural contexts must be factored into institutional strategy.
- Ongoing concerns around bias, privacy, and integrity highlight the need for adaptive, ethically grounded frameworks.

- Researchers warn that GenAI tools, due to their training on biased datasets, can inadvertently perpetuate stereotypes unless used critically. Therefore, institutions vary in their policies—some embrace GenAI for instructional innovation, while others restrict it over concerns about academic integrity and learning quality.
- Many studies are still exploratory and do not cover all diverse aspects of using GenAI in learning.

In summary, STEM task solving using GenAI tools is an interesting and intensively researched topic; however, little effort is being made to find new, effective approaches to support sustainability in STEM education when design-based task solving is the focus. This encourages and motivates the research we present in this paper.

3. Basic Idea, Background and Research Questions

The domain this paper focuses on is STEM skills development through design-based problem solving to support sustainable education. The first step in understanding this domain is its analysis; this, to some extent, has already been done in Section 2 by examining the related work. The next step is a deeper analysis and better understanding of the domain. It is a common research practice to use modelling as a vehicle for a deeper understanding. Here, by modelling we mean the development of the relevant models at the given abstraction level and analysis of their properties. This understanding, however, comes not only through modelling of the domain itself but also from its context. Context is an essential attribute in discovery models and modelling. Context is a multidimensional category that, in general, may include entities such as physical conditions, computing resources, users, activities, and social entities [48]. There are a variety of models and modelling approaches. Typically, we need to start using conceptual models and conceptual modelling as the most general ones [49]. The basic idea we rely on is therefore the development of the conceptual model as a primary step that defines relationships among the basic concepts to outline further actions within the proposed approach. Note that the motivating concepts of design-based problem solving were discussed in Section 1. More details on these concepts will be given in Section 4. Next, we focus on a gradual refinement of the conceptual model by introducing lower-level models, such as a context model, a GAI tools integration model, the model defining the interaction among GAI tools, learning and design-based problem-solving processes, the model outlining the interaction in the chain tools, processes, and skills, and the assessment model of outcomes. Thus, the background of this research is modelling. All models are combined into a coherence methodology identified as multi-stage modelling. To discuss the methodology and approach systematically, the following research questions (RQs) are under consideration.

RQ1: What is a conceptual model (CM) to explain the basic idea on how to integrate Generative AI tools into STEM in the context of sustainable education regarding the formulated aim, i.e., *the enforcement of STEM skills development through problem solving?*

RQ2: How to develop and organize the relevant activities for the gradual refining implementation of the proposed CM?

RQ3: How to evaluate the outcomes of the approach by measuring the STEM skills obtained?

4. Methodology: Multi-Stage Modelling

Relying on the basic idea, we propose a methodology for solving the formulated RQs. The methodology includes multiple stages. Their implementation can be interpreted as using a top-down approach with a gradual decrease in the abstraction level by adding new aspects. At the top level, i.e., stage 1, we consider RQ1. It explains the basic idea and provides a general understanding of the approach's essence. The remaining stages, from 2 to 5, are responsible for explaining how we address RQ2, providing more details of the approach by gradually investigating the adequate models and relationships among their constituents at each indicated stage to facilitate the practical implementation of the proposed conceptual model at stage 5 (RQ3). Finally, we present a case study aimed at extending RQ3 to address a complex problem-solving task, confirming the practicality and evaluating the outcomes of the proposed approach by introducing a skills measurement model.

Stage 1: The development of the CM. To develop this model, we have drawn inspiration from the TPACK framework [50]. This framework defines any educational domain in large through the following components: T (technology), P (pedagogy), and CK (content knowledge). We have adapted and extended this framework to our context through (i) adding new components (i.e., STEM skills development through task-solving processes, and design-based learning processes), (ii) separating outcomes from the remaining components, (iii) splitting technology (i.e., tools) into parts to focus on GenAI as a separate component, and (iv) introducing the external context (e.g., space of STEM tasks and SLE). Therefore, the indicated actions resulted in the development of the CM (see Figure 1). This model comprises six significant components. The original TPACK components [50] are presented in italics, but their interpretation differs significantly here. At the center of CM are the student and STEM skills development processes. This component has links with all the remaining components, representing the interaction among them using bi-directional arrows. Due to the aim of this paper, the use of GenAI tools is highlighted. CM defines the structural aspects of the domain under consideration at a high abstraction level; however, the functional and behavioral aspects are given only schematically. Therefore, for a deeper understanding, this CM is to be refined in the following stages.

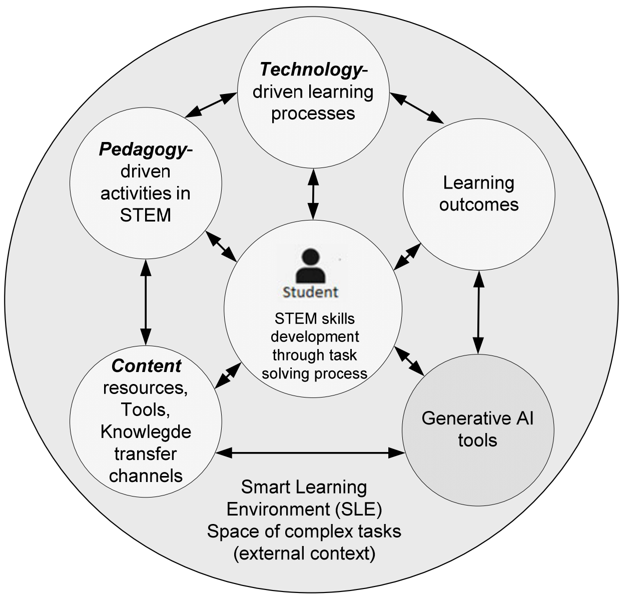

Figure 1. A conceptual model to explain STEM learning on a large scale through a sustainability perspective.

Stage 2: Context model development. Here, we will not discuss the external context, as outlined in CM, but rather the internal context. The latter includes the description of the learner's profile, possible types of technology (e.g., hardware and software tools needed to support task solving), possible pedagogical approaches to be used, and the types of content needed. Note that the internal context is influential in determining the adequate CM components, as reflected in their names. To represent these contextual items semi-formally, we use feature diagrams [51]. For clarity, we present a comprehensive body ofontextual information in Figure 2, utilizing the TPACK framework.

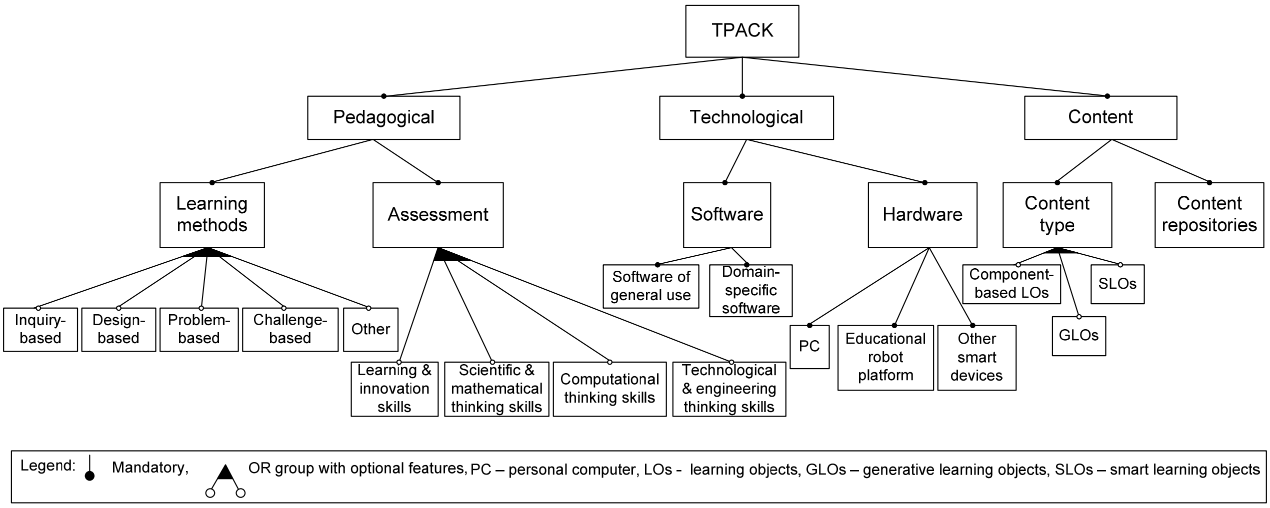

Figure 2. TPACK-based contextual information as a part of the context model.

Stage 3: Development of GenAI-based model for solving STEM task. This model consists of two parts, i.e., requirements statement (Table 1), and structural and functional aspects of the model itself (see Figure 3). Requirements (R.) are grouped into four categories: (i) Pedagogical R. to define how the relationship "Student–GenAI tool" should be organized and what consequences of that should be. (ii) Functional R. to define specific aspects of STEM education, when CS, robotics, etc., are the focus [8]. (iii) Learning processes R. to indicate the basic constraints regarding the learner's interaction with the AI tool. (iv) Ethical R. to define ethical aspects of AI usage in education. Requirements were formulated based on an analysis of related works [43–45] and our experiences with using AI tools.

Table 1. Requirements for the integration of GenAI tools into the Smart Learning Environment.

Requirements' Group	Requirement
Pedagogical	1. GenAI should develop students' critical thinking. 2. GenAI should be used in problem solving, not just for the answer. 3. The student must be able to explain the solution presented by the GenAI in their own words. 4. Using GenAI as a tool that supports inquiry-based learning.
Functional	1. GenAI should help generate program code with comments. 2. GenAI must be able to analyze errors and provide suggested corrections. 3. GenAI should help create schemes and/or explain how to connect sensors, actuators, and other devices.
Learning processes	1. Students should use prompt templates to learn to ask questions correctly. 2. Students should use GenAI not as a decision-maker or problem-solver, but as an assistant and collaborator.
Ethical	1. Interaction with GenAI must be transparent—the student knows that AI is not a human. 2. The student must be able to distinguish their own decisions from AI suggestions. 3. The student must properly define the assessment criteria, including the use of GenAI.

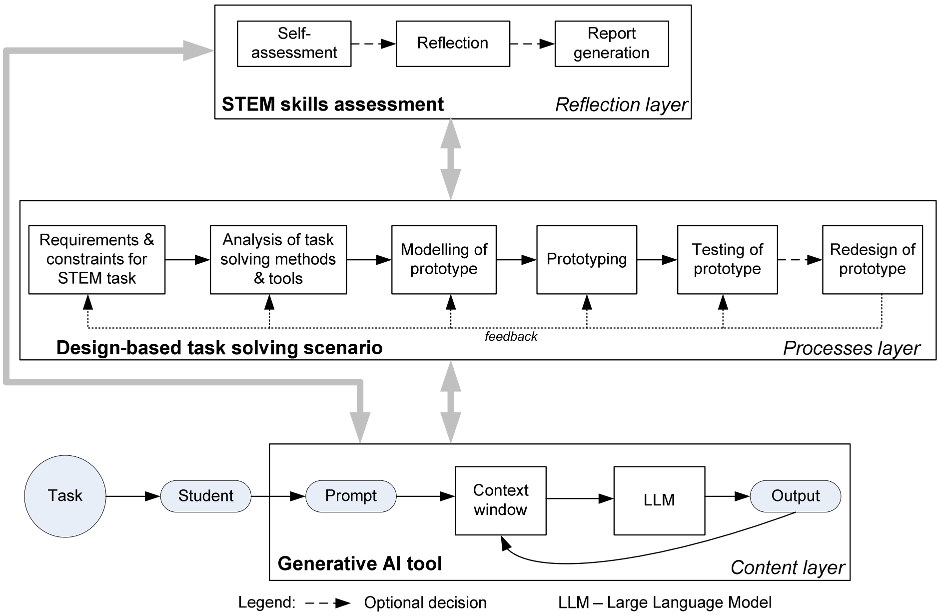

Figure 3. Generic model for integrating GenAI tools into STEM-driven education.

The second part of this model (Figure 3) consists of three layers: (i) the *content layer*, (ii) the *process layer* and (iii) the *reflection layer*. The content layer presents a generic scheme to define the student's interaction with a GenAI tool. The interaction includes the prompt (formulated by student regarding the requirements of the prompt engineering [43] including the task specificity and anticipated/desirable goal to form an output), context window (it stands for the interface to accept the prompt, and then send it to the tool) and the interaction cycle (it includes the LLM, i.e., the other name of the GAI tool, output from the LLM and feedback). During the interaction cycle, the LLM tools refine the prompt content until the user is satisfied with the output provided by the tool. The duration of the interaction highly depends on how precisely the learner formulated the prompt's initial content. It is the most crucial issue that we omit in this paper, as it requires a separate discussion.

At stage 3, a student accepts the STEM task, initiating the process. To do so, the following conditions should be met: (i) student needs to have previous knowledge regarding the task (in this case, the knowledge about robotics); (ii) student needs to have a primary understanding of how the GenAI tool is to be used, keeping in mind the requirements given in Table 1. Stage 3 describes schematically the capabilities for students to communicate with the GenAI tool and navigate among its internal components, but not the process itself (this occurs at the next stage). The presented model is central to this approach due to the specificity of design-based problem solving and the interaction between the "Student–Gen AI tool". The STEM task relates to using robotics in our research, which requires anticipating how the robot should be constructed, including the selection of constituent parts such as sensors and their programming. Therefore, the task-solving scenario includes many phases or subtasks. They begin with a requirements statement, including the selection of tools and methods, prototyping, and testing. Note that these phases also appear in other complex tasks. Possibilities for the intensive interaction "Student–Gen AI tool" are vast. The interaction can take place at all layers when the model is enacted. There are three layers. In the content layer, a GenAI tool provides explanation, code and questions. In the process layer, this tool is treated as an assistant in problem solving. The interaction in this layer is extremely intensive because, at any phase, the student has several options, as follows. (a) Move from phase i (i = 1 . . . 5) of the process layer to the reflection layer. (b) Return to phase i of the content layer after the self-assessment. (c) Move from the reflection layer to the content layer to clarify the assessment. (d) Move from phase i (i = 1 . . . 5) of the process layer to the content layer. Bearing in mind that the options may be cyclic, it is easy to understand the intensiveness of the interaction. On the other hand, each interaction is unique in its content and outcomes, in terms of the skills gained. Note that the actions of the GenAI tool may be optional in the reflection layer; for example, learners may only ask for help in preparing the report. Therefore, the model, when enacted and executed, serves as a generator of a variety of STEM skills. However, this model is a scenario or plan only to define the possible paths in communicating and navigating with the GenAI tool in the task-solving process.

Stage 4: Refinement of the model of Stage 3 to define relationships among AI tools, the learning and design processes. Figure 4 presents the model of Stage 4. It consists of four sections: (1) A set of GenAI tools for a more effective use, since tasks are dependent on tools. (2) Learning processes initiated by students using the possible pedagogical approaches (they are introduced from the context model of Stage 2). (3) Design processes refined from the process layer of Stage 3. (4) Design results obtained from each design phase *i* (*i* = 1 . . . 5). Design results are a matter for the assessment according to the STEM skills model (see Chapter 2, pp. 41–80 [8]).

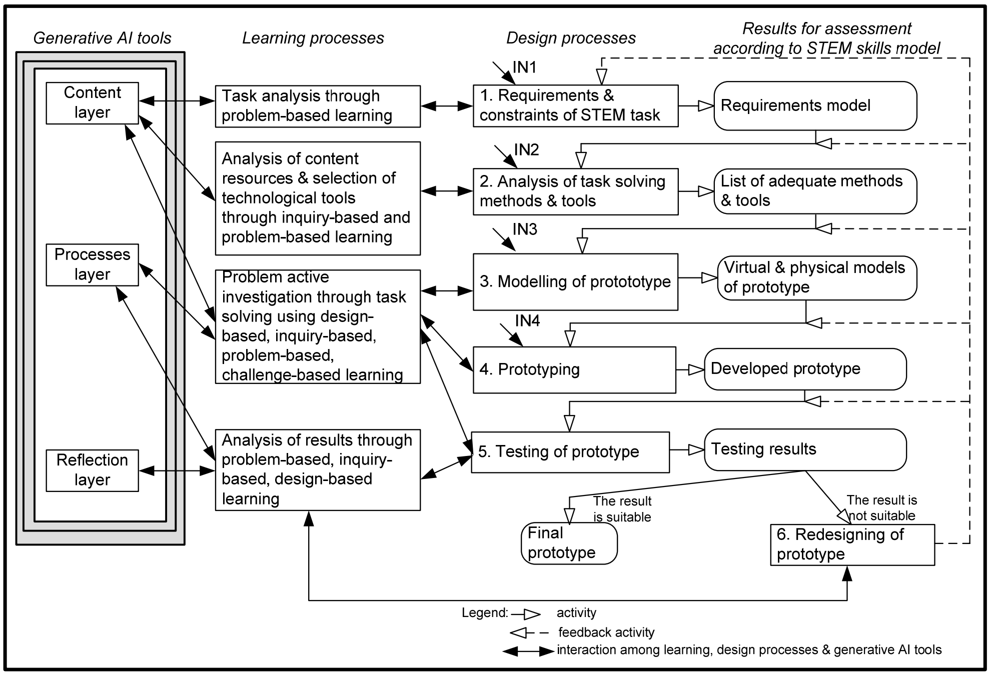

Figure 4. Model for refining the model of Stage 3: the focus on learning/design processes and GenAI tools.

Design is conducted using input data (IN1, IN2, IN3, and IN4) obtained from the context. IN1 originates from the curriculum and includes descriptions of task objectives, timing constraints, and other relevant details. IN2 specifies the needed methods and possible tools to select adequate ones for task solving. IN3 specifies modelling tools and their use instructions. IN4 gives facilities and information for prototyping. The other inputs are derived from the other internal design phases or potential feedback. On one side, refinement represents input–process–output relationships among the core design processes. On the other hand, the refinement specifies the relationship between design processes and learning processes, as well as activities related to the use of the selected GenAI tool. The refined model is generic and oriented to complex tasks.

Stage 5: Skills assessment model to evaluate the contribution of GenAI tools for outcomes in design-based learning. The aim is to provide empirical research based on the observation and evaluation of outcomes, using a five-point Likert scale as follows: 1. no impact, GenAI has no contribution; 2. low impact, GenAI has little or indirect contribution. 3. moderate impact, GenAI can assist, depending on use. 4. strong impact, GenAI meaningfully enhances the skill. 5. very strong impact, GenAI tools are critical enablers. Table 2 presents the impact of GenAI tools on the development of STEM skills. The values of the obtained skills are in parentheses. More details on the STEM skills model can be found in (Chapter 2, pp. 41–80 [8]).

Table 2. Impact of GenAI tools for STEM skills formation.

STEM Skills	Impact of GenAI Tools in
Learning and innovation skills	
Critical thinking and problem solving (LI1)	GenAI supports the evaluation idea and troubleshooting (4–5).
Creativity and innovation (LI2)	GenAI tools aid in generating novel ideas, particularly in prototyping (3–5).
Communication (LI3)	GenAI assists moderately (e.g., summarizing, explaining), but not as much in dynamic interpersonal communication (2–4).
Collaboration (LI4)	Slight enhancement when teams use AI for shared tasks or co-writing (3–4).
Scientific and mathematical thinking	
Forming and refining hypotheses (SM1)	GenAI helps in early stages by suggesting hypotheses or modelling scenarios (3–5).
Investigation skills (SM2)	Strongly enhanced by GenAI's data interpretation and simulation tools (4–5).
Evaluating evidence (SM3)	High utility in analyzing large datasets or identifying trends (4–5).
Computational thinking	
Abstraction (CT1)	Moderate support in simplifying problems (3–4).
Decomposition (CT2)	AI helps break complex tasks into manageable parts (3–5).
Generalization (CT3)	Less direct support; depends on user prompting (2–4).
Data representation (CT4)	Strong support through charts, graphs, and visual AI tools (3–5).
Algorithm (CT5)	GenAI tools can write, explain, and optimize algorithms—especially useful during testing and refinement (2–5).
Technological and Engineering thinking	
Knowledge	
Core concepts (TE1)	GenAI can explain design principles, aiding foundational understanding (4–5).
Designing (TE2)	Helpful in idea iteration and simulation before physical modelling (3–5).
Applying, maintaining, and assessing technological products and systems (TE3)	Substantial impact in later stages, where troubleshooting or optimization is needed (3–5).
Practices	
Systems thinking (TE4)	Enhanced through AI modelling of system interactions (4–5).
Creativity (TE5)	Similarly to "Creativity and innovation," particularly valuable in early design and final product (3–5).
Making and doing (TE6)	Enhanced when AI supports prototyping instructions or testing scenarios (3–5).
Critical thinking (TE7)	Strong role in analyzing engineering decisions (4–5).
Collaboration (TE8)	Mild to moderate—AI is more of a tool than a team member (3–4).
Attention to ethics (TE9)	Increasing importance—AI can prompt ethical considerations, but must be guided (2–5).

5. Case Study: Robot Designing for Folkrace Contest

The aim is to demonstrate the implementation aspects of the proposed approach. For this, we have selected one of the most engaging and motivating projects for students, in which they design a robot to participate in the folkrace competition. It is an autonomous robot racing event aiming to emulate the exhilarating nature of rallycross, where robot designers (in our case, students) turn the robot on to start only. Up to five robots are allowed on the track at a time, competing against each other in speed and skill. The main requirements for robots and the competition field are as follows. (i) The robot must be autonomous. (ii) The race aims to complete as many laps as possible in the correct direction. Each lap in the right direction scores 1 point. (iii) The robot's maximum dimensions are 15×20 cm, and its maximum weight is 1 kg. (iv) A green and red band (10 cm wide) will be visible on the field to identify the correct direction. (v) The width of the track varies between 100 and 120 cm. (vi) The course has obstacles, such as hills, holes, loose material, obstructing walls or poles and uneven surfaces. All these are the concrete representations of abstract requirements given in (Figure 4, Phase 1).

The 48 students (15–16 years old, 9th grade) of the Robotics module participated in the folkrace robot design task. The teacher's role was to collect data through observation anonymously.

In developing the requirements model and selecting suitable methods and tools, ChatGPT-4o and Gemini 2.0 Flash were utilized to compare different distance sensors, including ultrasonic (HC-SR04), Sharp IR (GP2Y0A21YK), and VLX (VL53L0X Time-of-Flight). In creating prototype models, ChatGPT and Gemini helped with coding the functionality of different distance sensors. Gemini and ChatGPT provided actionable solutions during testing phases when students encountered erratic sensor readings or lag in obstacle detection. Table 3 presents a comparison of executing a design phase without and with the use of GenAI.

Table 3. Comparison of conventional vs. GenAI-augmented design processes.

Design Phase/Task	Without Generative AI	With ChatGPT/Gemini
Sensor selection (covers Phases 1–3 in Figure 4)	Relied on static datasheets and manual internet research; time-consuming comparison.	AI provided comparative pros/cons of ultrasonic, IR, and LIDAR based on real-time prompts.
Code writing for sensor integration (covers Phases 3, 4 in Figure 4)	Manually written; syntax errors and logic issues are common.	AI auto-generated sensor integration code; reduced debugging time.
Troubleshooting faulty sensor readings (covers Phase 5 in Figure 4)	Required trial and error or mentor input.	AI suggested probable causes and calibration tips based on scenario descriptions.
Obstacle avoidance algorithm design (covers Phases 3, 4 in Figure 4)	Based on fixed patterns and predefined logic.	AI proposed variations (e.g., PID-based adjustments and dynamic thresholding).
Understanding sensor limitations (covers Phases 2–4 in Figure 4)	Surface-level understanding of reflectivity, timing, and range.	AI explained how environmental factors affect sensor accuracy, enriching conceptual depth.
Design exploration (What-If scenarios) (covers Phases 1–6 in Figure 4)	Limited due to time constraints.	AI-enabled fast exploration of alternative designs and algorithms based on prompt changes.

Table 4 presents the average impact values of the empirically obtained GenAI tools for each STEM skill, along with the design results for each phase. Thus, Table 4 concretizes the content of Tables 2 and 3.

Table 4. GenAI tools impact values in a five-point Likert scale as related to the task design phases and STEM skills.

	Task Design Phases					
STEM Skills	**Requirements Model**	**List of Adequate Methods and Tools**	**Virtual and Physical Models of the Prototype**	**Testing Results**	**Final Prototype**	**Sum of Assessments**
			Learning and innovation skills			
LI1	4	4	5	4	5	22
LI2	3	4	5	4	5	21
LI3	2	3	4	4	4	17
LI4	3	3	4	4	4	18
			Scientific and mathematical thinking			
SM1	4	5	4	3	4	20
SM2	4	5	4	4	5	22
SM3	3	4	4	5	5	21
			Computational thinking			
CT1	3	4	4	4	4	19
CT2	3	5	4	4	4	20
CT3	2	4	3	3	4	16
CT4	3	4	5	5	5	22
CT5	2	4	4	5	5	20
			Technological and engineering thinking			
TE1	4	5	5	4	5	23
TE2	3	4	5	4	5	21
TE3	3	4	5	4	5	21
TE4	4	4	4	4	5	21
TE5	3	4	5	4	5	21
TE6	3	4	5	5	5	22
TE7	4	5	4	5	5	23
TE8	3	3	4	4	4	18
TE9	2	3	4	4	5	18
Sum of assessments	65	85	91	87	98	

As a conclusion, the empirical research showed that (i) the highest impact of GenAI tools is in final prototyping (98 sum of assessments in Likert's scale), virtual and physical modelling (91), testing (87), and selecting tools and methods (85) and design phases; (ii) for STEM skills, the highest impact appears in critical thinking (23) and core concepts (23). What distinguishes this project is the strategic use of Generative AI tools—specifically ChatGPT and Gemini—to enhance engineering decisions, streamline coding, and deepen conceptual understanding.

6. Results Analysis and Evaluation

Integrated STEM education promotes innovation and creativity, providing learners with the opportunity to develop critical thinking, problem solving, and analytical skills, all of which are essential for sustainable education. It is especially true when these skills are applied to real-world contexts, helping to address economic, social and environmental challenges. In addition, integrated STEM can foster the development of new solutions and technologies that contribute to ESD. Integrating GenAI tools into STEM education provides additional opportunities to promote sustainable development by tackling more complex tasks. Complex tasks, such as design-based ones, when interpreted, are decomposed into a sequence of separate phases, thereby allowing the application of GenAI tools at each phase. This opens the door for extremely intensive interaction among learners and GenAI tools.

In this paper, in response to the current trends in the evolution of integrated STEM research and practice discussed in Section 2 [12,14,17], we have focused solely on design-based STEM task solving. We have presented a novel approach based on multi-stage modelling when GenAI tools are integrated into SLE to promote task solving through design. By multi-stage modelling, we mean the development of a set of models represented at different abstraction levels and then refining each model at the next stage to lower the level of abstraction until the desired result is achieved. The set of models includes (i) the conceptual model (CM) in Stage 1 to give a general understanding of the approach, (ii) the contextual model in Stage 2 to enrich the CM with the additional contextual information, (iii) the model for integrating the GenAI tools into the learning scenario for highlighting the interaction Learner-GenAI tools, (iv) the Design Process Model to implement the learning scenario through outcomes obtained, and (v) the model for assessing the GenAI tools impact on STEM skills gained. The proposed approach possesses *methodological*, *scientific*, and *pedagogical value*. From a methodological perspective, the approach introduces systematization due to the inherent dependencies among stages and the appropriate relationships between models. The proposed conceptual model is general enough to be applied in other educational contexts by adapting TPACK components [50] according to the given subject specificity. It is therefore helpful for policymakers, developers of educational software systems, and teachers. It was outlined in Sections 1 and 2 that sustainability in integrated STEM education is highly valuable and the most valuable attribute of the 21st-century [1,2,22,23,39]. The proposed approach promotes sustainability in education in this way: (i) due to STEM skills development and (ii) design-based problem solving using GenAI tools. *Scientific value* includes (i) formalization of complex learning processes through multi-stage modelling, (ii) bridging educational modelling with engineering design research introducing an interdisciplinary framework that combines educational sciences, AI interaction, and STEM (especially engineering) education under a cohesive pedagogical model, (iii) creating theoretical and empirical links between AI tools usage and cognitive skills development, enabling a foundation for AI-integrated instructional design models, (iv) deepening the theoretical understanding of how design-based task decomposition, supported by AI, can scaffold higher-order thinking and systems understanding skills.

Methodological value includes: (i) development of an empirical skill-assessment model that advances to empirical methods in educational assessment by linking cognitive outcomes to AI-mediated interventions directly, and (ii) enabling hypothesis testing through design scenarios to provide a basis for experimentation on the pedagogical efficacy of AI in STEM problem solving and sustainability education.

Pedagogical value includes: (i) applying multiple pedagogical approaches at once, (ii) high orientation to personalized learning through design, and (iii) approach supports design-based, project-based learning and in case of complex tasks, providing a collaborative or mixed learning.

Our approach supports some Sustainable Development Goals [22]: SDG 4 (Quality Education) by enhancing inclusive, personalized and skill-oriented education using AI-mediated learning, SDG 9 (Industry, Innovation, and Infrastructure) by AI-supported modelling, prototyping and engineering design, SDG 11 (Sustainable Cities and Communities) by adapting the folkrace robot design task to urban mobility, SDG 13 (Climate Action) by the possibility engaging students to deal with real-world environmental issues using AI-supported simulations and data analysis.

At the same time, the approach has some difficulties and drawbacks. For some users (teachers and students), the approach requires additional effort in assessment, evaluating the impact of GenAI tools on skill acquisition due to other factors (motivation, prior knowledge, etc.). There is a high risk that students will use GenAI tools as an "answer machine" instead of collaborative tools. Another crucial aspect is how precisely or efficiently learners should formulate prompts. Our experiments have shown that preparing in advance prompts' templates is very helpful in enabling the formulation of structured prompts and decreasing the risk of unethical use of Gen AI tools. Future work will focus on developing the relevant methodology for designing prompt templates.

7. Conclusions

The more complex the design task, the more interesting and engaging STEM learning becomes, and therefore, the demand for integrating GenAI tools in Smart Learning Environments increases to a larger extent. Design-based task solving undergoes multiple phases, each representing a set of separate subtasks that typically differ in functionality. Consequently, the skills obtained are highly diverse and rich, even when GenAI tools are not used. However, the use of these tools highly amplifies the diversity and richness of skills gained through design-based STEM sub-task solving, due to the multiple interactions between learners and GenAI tools (see Table 3). The primary concern regarding the outlined actions and properties is how to understand better and manage these complex processes more flexibly and efficiently. The solution proposed in this paper is a systematic approach based on multi-stage modelling and the use of GenAI tools. The approach presents a gradual refinement of the whole design task-solving process, providing more details in each subsequent stage as it progresses from conceptual understanding to the acquisition and measurement of STEM skills. The presented case study, specifically the design of the robot for the folkrace contest, confirmed the accepted assumptions and theoretical reasoning underlying the proposed approach. This research has shown that the use of GenAI tools significantly improves the capabilities of design task solving and skill acquisition, while also posing new challenges. The most crucial aspect is how to formulate prompts (input to GenAI tools) more efficiently and accurately to optimize the learner's interaction cycle with the tools. The empirical research showed that the highest impact of GenAI tools is in final prototyping, virtual and physical modelling, testing and selecting tools and methods within design phases. Additionally, for STEM skills, the highest impact appears in critical thinking and core concepts.

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