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Synergizing Systems Thinking and Technology-Enhanced Learning for Sustainable Education Using the Flow Theory Framework

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Abstract: In an era where digital technologies are integral to daily life and sustainable education is increasingly critical, developing higher-order thinking skills with appropriate information and communication technology (ICT) support is crucial for achieving Sustainable Development Goals (SDGs). The purpose of this study was to examine synergies of systems thinking and technology-enhanced learning from the perspective of flow theory within the context of sustainable education. We surveyed more than 65 pre-service preschool teachers engaged in a design, technology, and engineering (DTE) course at the University of Ljubljana. Mapping of systems thinking revealed that pre-service preschool teachers needed support regarding feedback and understanding the interrelationship dimension of systems thinking—essential components of sustainable education. Predictive and mediation analyses yielded noteworthy results. Participants in the ICT-enhanced DTE course rated their cognitive and social engagement above the mid-point of the scale, with this higher engagement correlating with higher systems thinking crucial for sustainable education. In contrast, their aesthetic engagement was below the mid-point of the scale. Experiencing a flow state during ICT activities positively influenced systems thinking, particularly in terms of clear goals and autotelic experiences. Flow theory thus emerges as a solid and appropriate framework to use for studying synergies in technology-enhanced systems thinking for sustainable education. These findings underscore the importance of integrating systems thinking into curricula to enhance learning outcomes and prepare students for future challenges, thereby contributing to the achievement of SDGs through sustainable education.

Keywords: systems thinking; higher-order thinking; student engagement; technology-enhanced learning; flow; optimal experience; sustainable education

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1. Introduction

In today's rapidly changing technological world, the ability to solve problems has become one of the most important skills individuals need in order to live and work successfully [1]. However, along with technological progress, many challenges arise that require innovative approaches and critical thinking. Therefore, it is important to start developing higher-order thinking skills at a young age, which will enable us to effectively deal with complex situations. Higher-order thinking skills such as analysis, synthesis, and creativity enable individuals to adapt to change, critically evaluate information, and find new solutions. In the educational process, it is therefore crucial to give students the opportunity to develop these skills by using appropriate teaching methods [2].

One of the promising approaches to nurturing higher-order thinking skills is systems thinking. Systems thinking takes a holistic view of problem solving and therefore has the potential, as a new learning approach, to contribute in some way to the transfer of knowledge and skills for a sustainable future [3,4]. It has also been recognized by the OECD to be an important approach for understanding the world we live in and the policies we live under [5]. Additionally, systems thinking offers a process, a set of "technologies" and thinking skills that can improve the understanding required for sustainability education [6]. For educators, mastering systems thinking is crucial, as it equips them to teach these essential skills to future generations.

When using different, novel approaches, student engagement is necessary for a successful process, which depends on many factors, including the use of ICT and digital tools. Digital technologies and ICT have become an important part of the learning process, although both teachers (pre-/in-service) and parents have mixed attitudes towards their use in education [7–11]. With regard to the use of digital technology in early childhood, Bredekamp [12] states that there is a need to address how to introduce it into the child's environment in a quality way, rather than whether to include it. Digital tools and ICT not only provide means of entertainment but enable many processes to be improved, such as facilitating visualization, preparing materials, watching videos, programming, taking and editing pictures, storing data, and many others [13]. Digital tools create interactive learning environments that facilitate experiential learning and help simulate complex systems.

Transitioning from viewing digital technology as an escape for children (and adults) to recognizing it as a tool for collaborative learning is crucial. For this reason, professional support both from and for teachers is essential. Achieving a state of deep immersion and focused engagement in an activity, known as a flow state [14], could significantly enhance the learning experience when using digital tools [15]. When students experience a flow state, they are more likely to engage deeply with the content, persevere through challenges and attain higher levels of understanding. To optimize learning outcomes and promote a deeper understanding of complex systems, digital tools should be used strategically in education. Furthermore, effectively integrating these tools into the classroom will help students develop important digital skills [16]. Many models for integrating ICT and digital tools have already been proposed in the literature, such as SAMR, TPACK, the pedagogical wheel, etc., but despite the potential benefits, the applications and outcomes are questionable [17,18]. Both positive and negative effects have been shown, so a clear articulation of the use of ICT and digital tools requires further research. The optimal use of digital technology in the classroom requires an appropriate learning environment that fosters the development of higher-order thinking skills [19]. This means creating a stimulating environment in which students can explore, experiment, and work collaboratively to solve problems. Teachers play a key role, as they need to be able to guide and support students in the use of digital tools [20–22]. In addition, choosing the proper digital environment from among all digital applications (e.g., for coding lessons) can be a challenge for both teachers and parents [23].

In an era where global challenges such as climate change, resource depletion and social inequalities are intensifying, the importance of sustainable education has never been more pronounced. This study aligns with the global education goals, particularly Sustainable Development Goal (SDG) 4 [24], which emphasizes the need for inclusive and quality education that promotes lifelong learning for all. The development of higher-order thinking skills in pre-service teachers, such as systems thinking, creativity and critical thinking, is essential for tackling the complexity of sustainable development. Systems thinking in particular enables learners to approach problems holistically and understand the interconnectedness of environmental, economic and social systems [4]. Goal 4 of the Sustainable Development Agenda [4,24], which focuses on quality education for all, is key to realizing a sustainable future. Surveys such as PISA [25] allow us to monitor progress toward this goal and identify where improvements are needed. In Slovenia, the results for mathematics and science were above the average for OECD countries, but the results for reading literacy were below the average. However, the results show a decline in all areas of literacy among young people examined, indicating the need for change [26]. Based on the results, measures are being taken to improve the situation as part of the ongoing curriculum renewal. In the area of reading literacy, action plans for implementing the National Strategy for the Development of Reading Literacy are already in progress, while there are no specific educational strategies for science, technology, engineering, arts, and mathematics (STEAM) subjects. On the other hand, these areas are included in the Action Plan for Digital Education until 2027 (ANDI), the National Program for the Development of Artificial Intelligence 2025, and the Digital Slovenia 2030 Strategy [26]. All of these strategies at the national level, as well as in a broader sense, show that it is still necessary to search for new approaches and methods for teaching and ultimately working in today's world. The importance of exploring modern approaches and stakeholders on the path to literacy is recognized at a higher level. The University of Ljubljana has been heavily involved for quite a long time in many projects to improve learning processes and integrate ICT into educational processes for a digital future and sustainability [27,28].

However, there is still no clear understanding about how to complement implementing the systems thinking approach through the lens of flow theory with ICT and students' engagement in activities. Even though there has been research on systems thinking [29–32], to date, there is no study that has contextualized and conceptualized synergies of systems thinking and technology for an optimal experience as reflected by flow theory. Against this background, the purpose of this study was to investigate the state of the art of systems thinking among pre-service teachers, their perceptions about stimulating higher-order thinking skills, how they engage in design, technology, and engineering (DTE) activities, and how they experience technology-enhanced DTE through the lens of flow theory. To our knowledge, this is the first study of systems dynamics from the perspective of flow theory, but we still assume with caution that flow might affect systems thinking, especially through collaboration and engagement in DTE activities where ICT is carefully selected for target use and learning goals are clearly defined. This study contributes to the growing field of sustainable education by exploring the integration of systems thinking with technology-enhanced learning in teacher education study programs. The focus on pre-service preschool teachers is particularly important as they are at the forefront of shaping young learners' attitudes and behaviors towards sustainability from an early age.

The theoretical background for understanding our research is presented in two sections. Section 1.1 addresses theory in systems thinking and higher-order thinking skills and their importance, particularly for successful action in the 21st century and as key competencies acquired in education for sustainable development. The importance of the concepts is reflected in the awareness that they need to be developed at all levels of education, starting in early childhood. The section provides information to understand the connections between systems thinking and the relationship to higher-order thinking skills, and its categorization as higher-order thinking skills. Section 1.2. introduces flow theory in detail, which provides the reader with a comprehensive overview of the concept of flow state and the findings related to flow state and the use of digital technology which are relevant in this research for better understanding of effective technology integration from the perspective of systems thinking. Various insights and influences are discussed in this section, including rapid feedback, visualizations, creativity, and design thinking, etc. The chapter also refers to activity theory, which serves as the theoretical basis for the DTE course. By examining these studies, one can gain a deeper understanding of how ICT tools foster the flow state in the DTE course and what impact this has on systems thinking, which forms the basis for the present study.

1.1. Systems Thinking and HOTS

Systems thinking, an approach that is used to understand today's increasingly complex world, refers to interrelationships and dependencies, to the interactions of a system with other systems or subsystems [30]. Different authors define systems thinking differently, including as a discipline to see the whole [33], an important interdisciplinary skill for collaborative work in solving problems [31], and a 21st-century competency for sustainable development and a sustainable society [4]. The importance of systems thinking is also recognized by the International Association for Technical and Engineering Education (ITEEA) [1], which defines it as an important practice of technological and engineering literacy. The general understanding of systems thinking as taking a holistic view is somewhat narrow, as both a holistic and a reductionist view of system dynamics are important [3]. After reviewing several definitions, Arnold and Wade [34] defined systems thinking as "... a set of synergistic analytical skills used to improve the ability to recognize and understand systems, predict their behavior, and design their changes to achieve desired effects." ([34], p. 675).

Moore et al. [35] recognized systems thinking and measured it in individuals using dimensions such as sequence (specifically sequence of events, causal sequence), diversity of causes and variations (specifically multiple possible causes, variations of different kinds (random/special)), and relations and feedback (specifically interrelationships of factors, patterns of relationships, feedback). In their work, they also suggested adding further dimensions and extending the measurement to include elements related to strategic approach orientation, such as personal effort, reliance on authority, and strategic thinking [35]. Several models of systems thinking have been developed from simple models with three components [29] or four domains or dimensions [36,37] to those with more complex and hierarchical levels [38]. A model for DSRP (distinctions, systems, relationships and perspectives) rules was defined by Cabrera [3] when he was looking for common features of the many definitions of systems thinking. In the model, the author addresses four so-called simple rules that can be applied to any system to distinguish between elements/systems/ideas in terms of what they are/are not, identify systems (wholes) and elements (parts), identify mutual relationships between elements and the system, and view the system from different perspectives. To support systems thinking, temporal behavior diagrams, causal loops, connecting circles, concept maps, flow state maps, and computer programs, including simulated models for education, have been proposed in the literature [32,39,40]. Other studies [41,42] have shown the positive effects that systems thinking has on the development and improvement of skills in various engineering fields and emphasized the importance of systems thinking as a complement to traditional teaching methods [39]. Systems thinking is an appropriate approach for solving complex problems [32,37,42,43], and therefore its integration into learning programs for current and future teachers is strongly recommended [44].

In his study, Frank [45] found that the systems thinking approach combined with project-based learning effectively promoted the understanding of engineering issues among pre-service teachers who did not have much prior knowledge of technical and technological content. Engström et al. [37] also noted that systems thinking is an appropriate approach for technological and engineering education, as it encourages learners to view technological systems as interconnected parts and to understand relationships, inputs, outputs, processes, etc., holistically. Because systems thinking involves understanding relationships and using multiple perspectives, it promotes interdisciplinary learning and enables a focus on real-world problems. It promotes cooperation, collaborative learning, and the development of higher-order thinking skills (HOTS), such as problem solving and analytical thinking, through modeling, predicting, and searching for improvement—all of which are linked to a technology education that emphasizes practical applications and real-world problem solving [37].

The importance of HOTS is widely recognized around the world, and systems thinking is among the approaches with a high potential to foster them. Some authors [46] even include systems thinking among these skills. HOTS generally refers to more complex cognitive processes that go beyond memorization and other lower-level thinking. One of the best-known models is Bloom's cognitive taxonomy, revised in 2001 [47], which divides cognitive processes into higher and lower levels. The latter include memorizing, understanding, and applying knowledge, and the former include analyzing, evaluating, and creating [47]. HOTS enable critical thinking, decision making, and creativity. They require the use of prior knowledge for reasoning, evaluating, analyzing, synthesizing, and solving problems [2]. Preschool educators use developmental strategies such as comparing, differentiating, identifying, evaluating, classifying, disassembling/assembling, fantasizing, building, planning, and drawing conclusions to promote HOTS in children [48]. After reviewing the work of other authors and the definition of HOTS, Liu et al. [49] proposed five categories: skills in problem solving, metacognition, critical thinking, teamwork, and innovation development. HOTS can also be found among the 21st-century skills that individuals need to be successful in society and play an important role in global education [50].

As there is a relationship between learning ability and HOTS, it is important to use appropriate approaches and learning methods. Classroom activities that motivate active participation help students develop HOTS [51]. In their study, Lu et al. [52] investigated the relationships between smart classroom preferences, learning motivations, learning strategies, peer interactions, and HOTS. They confirmed that peer interactions and learning motivations in the learning environment have a positive influence on the ability to learn knowledge and skills. They focused on the smart classroom learning environment, which includes technology-enriched classrooms with physical and virtual spaces. The results show that in their work to develop HOTS, teachers must take into account learning motivations and peer interactions, as well as learning strategies and smart class preferences, as the latter also have an influence on HOTS, albeit indirectly [52]. In addition, graphic organizers and concept maps have been found to be a good support for learning strategies to promote HOTS, as they promote reasoning, contrasting ideas, and making connections [53].

Alammary's research [54] found that in order to increase engagement and promote HOTS, the most effective type of blending learning among the different types (instructor-led face-to-face learning, instructor-led online learning, collaborative face-to-face learning, collaborative online learning, and self-directed online learning) was collaborative face-to-face learning, which was otherwise described as challenging by students. The effect, of course, depends on the size of the group, which in this case must be manageable [54]. For larger groups, online collaboration with greater support from online resources is more suitable. On the other hand, Alammary [54] noted that self-directed online learning is more suitable for lower levels of thinking skills.

In addition to global guidelines for sustainable development [4,50], the importance of developing HOTS can also be seen in educational curricula, even for the preschool years [55]. Modern learning paradigms emphasize the importance of constructivism [56] and social constructivism [57] and aim to create a stimulating environment and provide attentive care, especially for preschool children [58]. According to Piaget [56] and Vygotsky [57], knowledge is built by interactions with the environment and the social context. Piaget focused on existing abilities, while Vygotsky emphasized potential abilities realized with the right support. Interactions between students encourage discussion and critical thinking and support adaptation and problem solving.

In their research, Kumar and Mohamed [59] showed that preschool teachers had high levels of readiness with regard to their knowledge, understanding, and implementation of HOTS. On the other hand, some authors [60] have shown that preschool teachers in rural areas are somewhat less willing to include HOTS in terms of knowledge, skills, and application. As Slunjski [58] noted, the promotion of metacognitive skills among preschool children is influenced by the entire physical environment of the kindergarten. In particular, the positive effects are determined by the opportunities to use thoughtful learning materials that match interests, abilities, and prior knowledge. In addition, the quality of the kindergarten's social environment, the general atmosphere and democracy in individual groups, the encouragement of children to self-assess, the teachers' ability to listen to the children and to intervene, and their reflexivity also have a positive influence [58].

Integrating systems thinking and HOTS into education enhances problem solving and critical thinking and sets the stage for deeper engagement based on flow and activity theory. Systems thinking promotes a holistic understanding of interconnected elements, while HOTS empower learners to creatively address challenges [34,47]. This foundation transitions into flow and activity theory, in which individuals achieve optimal engagement by immersing themselves in tasks that match their abilities and interests [61]. By combining these concepts, educators can promote sustained engagement and meaningful learning experiences.

1.2. Using Flow and Activity Theory to Understand Human Engagement

The flow state, otherwise known as the optimal experience, is the state we experience when we are so immersed in a task that we no longer perceive our surroundings or time properly [62]. The flow state was originally described by the researcher Mihály Csíkszentmihályi [14] in the 1960s. Individuals in the flow state usually report being in a state of deep involvement and absorption [62]. People typically lose their sense of time, block out everyday problems, are highly concentrated, merge with the activity, and have a feeling of control over their actions. The activity is later perceived as if the end goal were an excuse for the process itself [16,61]. In a state of flow, the person's individuality is preserved while they are simultaneously cooperating with the surrounding environment. This cooperation involves changing the environment and, in turn, being changed by it through a complex system of transactions. The flow state is associated not only with pleasure but also with importance and engagement, meaning that the experience itself can be negative, yet a positive feeling often follows its completion [63]. For example, the pressure to finish a task or job can induce a flow state, as it presents a challenge for some individuals [64]. Flow can therefore occur in almost any activity, but this does not mean that the state is easy to achieve [63]. Clear, immediate goals, quick feedback, and an appropriate level of task difficulty are ideal conditions for achieving the state of optimal experience. If the ratio is not determined correctly, the person initially relaxes and then becomes bored (challenge too easy in relation to ability) or feels great anxiety (challenge too demanding in relation to ability) [16,61]. Achieving the flow state is an important strategic effort for novices and experts alike. Habits of attention are important in order to maintain self-confidence during times of uncertainty while conserving energy to effectively adapt to challenges and use one's skills [61].

Research over the past century, as noted by Whalen [61], has shown that fostering an environment in which an (otherwise complicated) combination of order and freedom is achieved can create a more effective learning context, compared to the classical approach of disciplined attention. In addition, people from environments where flow is encouraged tend to develop an openness to new experiences and the ability to focus and set realistic goals as part of self-regulation [14]. According to Palomäki et al. [15], the literature suggests that there is a connection between the flow state and task performance, but there are also empirical findings that suggest there could be another factor that moderates this link. Palomäki et al. [15] supported other research with their study, showing that when predicting the flow state, a deviation from the performance expectation is an even better predictor than the performance itself. Performance expectancy increases with new experiences in performing the task. They found that an additional factor or moderator associated with flow state and task performance is task experience [15].

The state of flow has been extensively studied in relation to the use of digital technology. By understanding how flow is facilitated by ICT, we can better understand its impact on users' cognitive processes and engagement and link it to improved systems thinking [65]. Pilke [64] has underscored research on flow and information technology in his work, emphasizing the potential of various interactions with digital devices to achieve flow (including gaming, commercial affairs, web surfing, etc.). Although Pilke's research [64] dates back to 2004, when there were fewer digital applications and tools, the presence of flow in this technology was evident. Pilke emphasized the importance of quick feedback, visual elements, and aesthetics in maintaining a state of flow. In contrast, common challenges include reducing the cognitive load and improving user interface skills [64]. He found that people often experience flow when using information technology, such as image editing, writing, and programming. This technology facilitates the flow state, allowing for an examination of the quality of the user experience. Regarding research on flow states and the use of ICT, there are numerous studies on flow while playing computer games [66,67], which found correlations between flow and motivation, engagement, and outcomes. Rutrecht et al. [66] reported that gamers had a better performance and sense of presence in the VR environment rather than in 2D. In education, the results of one study [68] showed that the factors influencing the flow state in the e-learning environment include the feeling of being in control of the virtual environment [69], attention and focus on the activity, and the feeling of being physically in the environment. Furthermore, the flow state was found to improve learners' academic performance in an e-learning environment.

A systematic review of flow experiences in game-based learning [70] also reported on individual factors of the flow state, as flow is a subjective experience. Factors that influence flow include interest in the topic, prior knowledge, etc. [70]. A literature review [62] summarized many influential connections of the flow state with cognition, personality, motivation, emotion, behavior, contextual factors, etc. A connection between the flow state and engagement, creative tasks, and creativity, which are important parts of design thinking, has been demonstrated. Furthermore, Yang and Hsu [71] noted that the flow experience could be improved with the help of design thinking. Primus and Sonnenburg [72] showed that this approach, which emphasizes creativity and problem solving, influences the flow experience at both the group and individual level. In addition, an influence was also demonstrated for so-called creative warm-ups and their interaction with design thinking tasks. Creative warm-up exercises have been found to improve individual flow in less stimulating tasks and in longer-lasting design thinking activities [72]. This link between design thinking and achieving a state of flow indicates the incorporating creative warm-up exercises could be advantageous. Design thinking, which is prevalent in engineering and technology, shares similarities with systems thinking. Both approaches require cognitive skills such as analogy, synthesis, and interpersonal skills, and are frequently applied in design and engineering. In some respects, engineering systems thinking serves as a specific complement to design thinking [73]. This overlap implies a potential link between systems thinking and flow. By merging these approaches, educators can create an environment that fosters deep engagement and innovative problem solving.

Flow theory focuses on the psychological state of the individual in terms of increasing engagement and performance. To provide a holistic overview of how to analyze and promote higher levels of satisfaction and engagement, we can complement flow theory with activity theory. The latter uses a broader sociocultural framework to understand human activity [16,74].

In examining developmental change, activity theory uses several perspectives: historical and situational, as well as individual and systemic. Activity theory was developed in the 1920s and is based on a sociocultural approach [57]. It is an approach to studying human interactions and relationships in specific situations, e.g., the use of digital tools and ICT in preschool. The theory considers the complexity of real-life activities, focuses on social practices, and is often used in the study of topics in teacher education. Key components of activity theory include the following [74,75]:

- Subjects, i.e., individuals or groups engaged in an activity/activity (e.g., preschool teachers);
- Objects of the activity, i.e., the goal/outcome of the activity (e.g., early robotics teaching);
- Tools or mediating artifacts, i.e., instruments or aids for carrying out activities (e.g., teaching materials, drawings, markers, robot sets);
- Community, referring to the context of or community involved in the activity (e.g., children in kindergarten);
- Rules, i.e., norms and regulations that govern the activity (e.g., curriculum for kindergartens, house rules, kindergarten requirements and rules, educational institutions, ministries);
- Division of labor, referring to the distribution of tasks among participants (e.g., which educator does what, preparation and purchase of materials, implementation, evaluation, reporting).

Engeström [76] summarized the main features of activity theory: the key unit of analysis (it is an object-oriented activity system that is multivocal and is related to other activity systems, including multiple views, perspectives, cultures), historicity (referring to the understanding of changes compared to the past), contradictions (representing the main source of change, the driving force of development), and the extension of information (referring to a newly conceptualized object or motive of activity) [76].

The two theories complement each other by emphasizing engagement in activities (social and psychological contexts of engagement) and the role of context, since despite the focus on psychological and internal factors, the environment in the state of flow must not be neglected. Understanding the role of context from both perspectives gives us guidelines for designing elements of the environment to provide engaging activities. In addition, both theories attach greater importance to feedback, which plays an important role in transforming activities from the activity theory perspective and in maintaining the flow state from the flow theory perspective, which is of great importance for improving the quality of activities. With a holistic view, it is therefore possible to create learning environments that meet the needs of individuals in several areas [16,63,74,75].

1.3. The Present Study (Aim, RQs, and Expectations)

The aim of the present study was twofold: (1) to explore the interplay between the systems thinking of pre-service teachers, their attitudes toward stimulating higher-order thinking, and their engagement in technology-enhanced learning from the perspective of flow theory, and (2) to reveal whether having an optimal experience with ICT has an impact on the performance of pre-service teachers in a design and technology course when mediated by systems thinking.

The present study addressed the following research questions (RQs):

- RQ1: What is the self-reported level of systems thinking among pre-service teachers, and to what extent are the dimensions of systems thinking evenly developed among them?
- RQ2: What are the attitudes of pre-service teachers toward teaching practices aimed at fostering higher-order thinking, and how do these attitudes influence their systems thinking abilities?
- RQ3: How do pre-service teachers engage with a design, technology, and engineering course enhanced by ICT and digital tools, and are there particular dimensions of engagement that influence ICT-enhanced systems thinking?
- RQ4: How do pre-service teachers perceive their engagement in a technology-enhanced design, technology, and engineering course through the lens of flow theory, and which components of flow impact their development of systems thinking skills?
- RQ5: What is the impact of flow on the performance of pre-service teachers when mediated by systems thinking?

Despite the number of project initiatives (both national and international), there is still growing interest in strengthening articulation of educational strategies due to rapid changes in different environments (social, cultural, technological etc.). The Agency of the Republic of Slovenia for Research and Innovation (ARIS) follows current trends. Together with European Union's NextGenerationEU [77], and the Ministry of Education of the Republic of Slovenia [78], ARIS supports educational innovations by funding this study, which is part of larger projects, specifically a pilot project, "5.02 Improving the digital skills and competencies of (future) educators for quality educational work with younger children"; a research project, "Developing the Twenty-First-Century Skills Needed for Sustainable Development and Quality Education in the Era of Rapid Technology-Enhanced Changes in the Economic, Social and Natural Environment"; and a program group, Strategies for Education for Sustainable Development Applying Innovative Student-Centred Educational Approaches [79]. The projects will identify the factors that influence the quality of education for future educators toward technologically driven sustainable development and 21st-century skills. They are based on studying the targeted integration of ICT across all levels of the educational system, from early childhood to higher education [78] and through the development of strategies or strategic approaches [79]. The research projects also aim to design, implement, and evaluate learning models and measure the impact on 21st-century skills [79]. In addition, the objectives of the project "5.02 Improving the digital skills and competencies of (future) educators for quality educational work with younger children" cover the increased use of digital tools and ICT by future educators, as it was found that no regular or elective courses in the preschool education degree program are designed to directly promote digital development. The goal will be achieved by revising existing or designing new study subjects with the didactic use of ICT to achieve a higher level of digital competency among the actors involved [78]. By evaluating current updated learning approaches, models, and curricula, it will be possible to gain insights into the strengths and weaknesses of modern approaches and their stakeholders in order to perfect a learning model focused on the use of ICT to develop sustainable competencies for the 21st century.

2. Materials and Methods

In the present study, the pedagogical focus was centered around technological and engineering literacy as the main outcome of a DTE course for pre-service teachers using ICT and digital tools. A set of practices proposed by ITEEA encompassing systems thinking, design thinking, making and doing, critical thinking, collaboration, communication, and attention to ethics [1] was used as the conceptual framework, reflecting the knowledge, skills, and attitudes toward DTE that pre-service teachers need in order to effectively implement DTE standards and achieve learning objectives defined by the curriculum.

The present study is a part of a bigger, multiannual research project conducted in recent years called "Developing the Twenty-First-Century Skills Needed for Sustainable Development and Quality Education in the Era of Rapid Technology-Enhanced Changes in the Economic, Social and Natural Environment" [79]. To test the feasibility of the main study, which will be carried out next year, a pre-experimental research design was employed as proposed by Creswell and Creswell [80]. This research design aimed to (1) explore the potential of utilizing various digital systems to support authentic pedagogical cases, and (2) identify potential relationships and generate hypotheses for further investigation. This study was conducted as a one-group experimental study with no control group. The study employed multiple instruments to map pre-service teachers' diverse characteristics, experiences, opinions, attitudes. However, no pre-posttest was utilized to determine the progress. Since the sample consisted of full-time students engaged in the subject of DTE, randomization was not applied. Nonetheless, we recognize that due to the higher risk of confounding variables and biases, the results of pre-experimental studies must be interpreted with caution, and any comparisons should be made with similar care and precision [81].

2.1. Course Format

The aim of the DTE course is to promote and understand the importance of creative transformation and processing of different materials for child development. Students are expected to incorporate design and technology into their work in various areas of the kindergarten education process. They are expected to develop creativity in their work, responsibility for working safely with children, and critical thinking skills, and to introduce digital technology meaningfully into their work through the knowledge gained in the course. The teaching and learning methods used in the lectures include explanations, demonstrations, and discussions, supported by ICT, interactive content, and virtual reality. Laboratory work takes the form of workshops with active student participation and focuses on projects and curriculum objectives. Both methods integrate technology to promote design and systems thinking and work with interactive content in a collaborative environment [82,83].

Table 1 shows the design of the modules during the semester. The colored parts indicate the periods in which lectures (90 min), laboratory work (90 min), kindergarten (KG) activities (approx. 60 min per group), and consultations with faculty (approx. 30 min per group) took place.

Table 1. DTE course design.

	October				**November**				**December**					**January**	
Week number	1	2	3	4	5	6	7	8	9	10	11	12		13	14
Lectures													Holidays		
Laboratory work															
Preparation for KG activities															
KG activities															

In the lectures, students discussed the content of the course according to the syllabus from a theoretical perspective. They discussed different approaches to learning, as well as the properties of materials and their processing, etc., which they later tried out in practice in the laboratory work. Students learned about different materials and their properties and processing, with safe use of working equipment in practice. The semester began with the processing of paper materials (paper, cardboard, corrugated cardboard), continued with artificial materials (EVA foam, PET bottles, plasticine and other artificial modeling materials, PLA filaments), and ended with the processing of wood. At the same time, other materials were also used in the products, such as cork (stoppers) and metal (staples, rivets, wires). At the end of the semester, the students produced individual products, for which they had to find the necessary materials and manufacturing techniques based on a drawing. They also familiarized themselves with construction collections, in which they produced constructions with different motion transmissions. With regard to kindergarten activities, groups of students prepared activities in which the main activity was the production and processing of materials. Each group was tasked with designing a suitable product to be made in the kindergarten with children. Before the actual activity, they had a consultation, discussed the appropriateness of the activity with the kindergarten teacher, wrote a lesson plan, produced the product, and prepared the required materials [82].

ICT and digital tools were used in the DTE course at all levels according to the substitution, augmentation, modification, redefinition (SAMR) model [18], which is commonly used to categorize educational practices with digital technologies. Examples of the use of ICT and digital tools at the level of enhancement (substitution and augmentation) include classic presentations, real-time review applications that provide immediate feedback, spreadsheets for faster data processing and chart drawing, and simulated applications. However, at the level of transformation (modification and redefinition), digital technology has enabled changes in tasks in terms of creating animation with digital tools, 3D modeling and printing, early programming, etc.

During the lectures, students used various mobile applications for consolidation and assessment (e.g., Plickers, Mentimeter, Kahoot) and collaborative learning environments for online lectures (e.g., Miro, Microsoft Teams). In the laboratory exercises, students made particular use of ICT and digital tools such as smartphones, tablets, and laptops to use spreadsheets and analyze data, draw diagrams, show simulations of a hand mechanism, create stop-motion animation, make technical drawings, perform initial programming and block coding, create 3D models and prints, simulate the transmission of movements via gears, etc. ICT and digital tools were also used for writing reports, monitoring the performance of colleagues through an online evaluation questionnaire, and, after their own activity in the kindergarten, creating a summary of the activities and experiences in an online collaborative environment (e.g., Miro), in which they could insert various graphics and graphical elements (Figure 1).

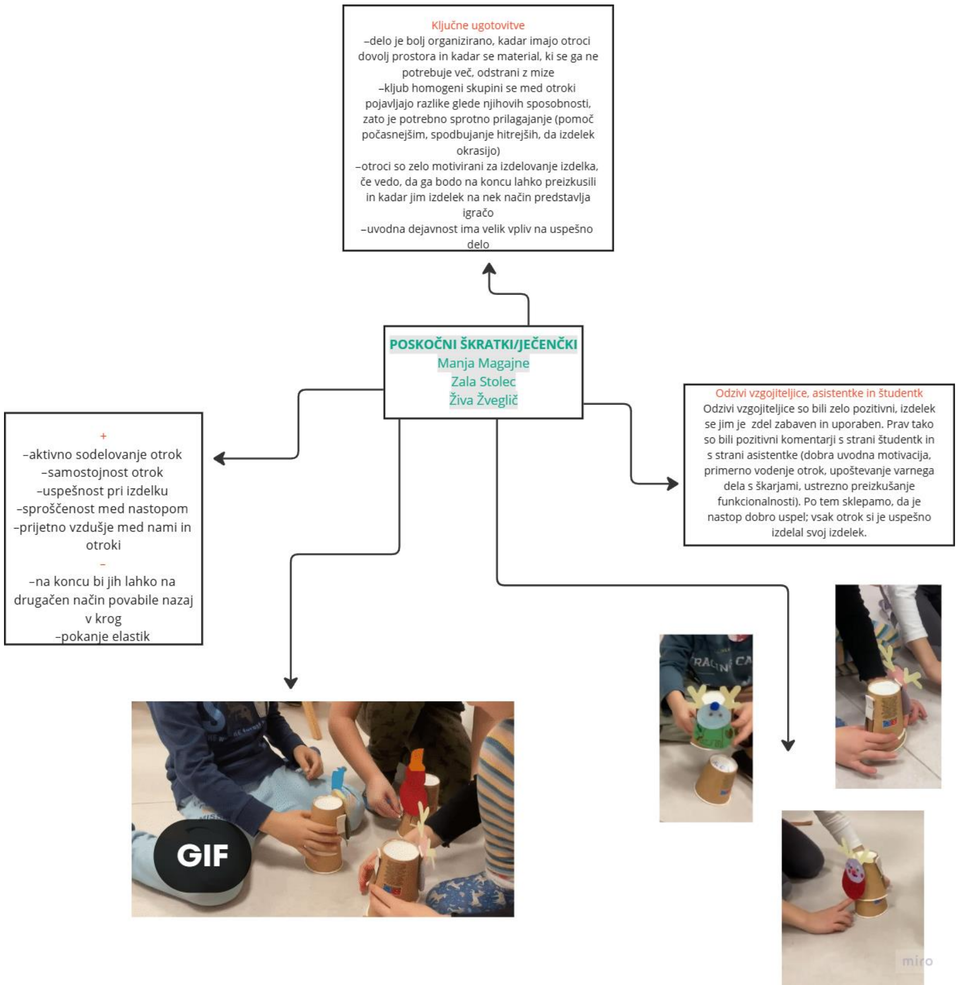

Figure 1. Example of a summary of a kindergarten activity at the University of Ljubljana.

Sustainability in the DTE Course

The goals and criteria of the 2030 Agenda are aimed at reducing poverty, protecting our planet, realizing human rights, and achieving gender equality in the dimensions of sustainable economic, social, and environmental development. The measures and incentives address five important areas [24]:

- People: poverty eradication, dignity, equality, healthy environment (SDGs 1–6);
- Planet: protection from degradation, sustainable consumption and production, resource management, action on climate change (SDGs 7–10);
- Prosperity: economic, social, and technological progress in harmony with nature, people enjoying a successful and fulfilling life (SDGs 11–15);
- Peace: promotion of peaceful, just, and inclusive societies free from violence and fear (SDG 16);
- Partnership: the mobilization of resources to implement the Agenda, global solidarity, focusing on the needs of the most vulnerable, cooperation among all countries (SDG 17).

The learning model applied in the DTE course primarily followed SDG 4, "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all", by integrating lectures and internships in kindergartens where students could apply their new knowledge. The subject specifically touches on achieving target 4.2: "By 2030, ensure that all girls and boys have access to quality early childhood development, care and pre-primary education so that they are ready for primary education". The course encompasses design, systems thinking, creativity, interdisciplinary integration, collaboration and communication, which are essential competences for sustainable development [4,24,84]. It aims to achieve SDG 9 and, overall, to promote equality, reduce inequality and advance gender equality, thereby addressing SDG 5 and 10 [24]. Furthermore, Slovenian educational institutions, including kindergartens, elementary schools, secondary schools, and universities, have participated in the Eco-School program [85] for many years, which has been active in Slovenia since 1996 (even prior to the adoption of the 2030 Agenda). The Eco-School Program is an internationally recognized initiative for integrated environmental education and training that seeks to promote and strengthen awareness of sustainable development among children, pupils, and students through their education and training program and active engagement in the local community and beyond. A responsible approach to the environment relies not only on the transfer and acquisition of knowledge, but also on actively changing behavioral culture and practices. Educational institutions promote sustainable practices through numerous events under the Eco-School program, focusing on climate change, circular economy, biodiversity, water conservation, local food production, recycling and more. To support this, the DTE course has been designed to enable students to design and create products suitable for use in kindergarten and to learn how to design these products so that their production is suitable for kindergarten children. The materials used in the kindergarten are usually reused waste materials, which is also supported by the course design, e.g., an octopus made from a waste bottle (Figure 2a) and materials reused for kindergarten activities (Figure 2b,c). This aligns with Sustainable Development Goal 12 ("Ensure sustainable patterns of consumption and production"). Simultaneously, students learn about sustainability, develop attitudes towards materials and the environment, etc., and strengthen mutual relationships. They develop critical thinking, cooperation, communication, and systems thinking as both an approach and an essential skill for sustainable development and achieving sustainable change. Through such activities, students not only reuse previously used materials, but also gain insight into closed systems, the impact of waste on the environment and habitats, pollution, and on the other hand, the benefits of recycling in reducing waste, etc. These are just a few examples of how sustainability and sustainable behavior are implemented within the DTE course [24].

(**a**) (**b**) (**c**)

Figure 2. Examples of learning in DTE by doing activities at the University of Ljubljana: (**a**) moving octopus made of a plastic bottle; (**b**) rocket made from paper cups and wastepaper; and (**c**) mill made from ice cream sticks, cotton buds, cardboard, and wood.

2.2. Sample

The study sample consisted of 65 pre-service teachers enrolled in a regular university course, technical education, during the third semester, conducted in blended learning form. A large majority of activities were carried out in face-to-face mode, and some of them through an online learning management system (synchronous and asynchronous) at the Department of Physics and Technology Education at the University of Ljubljana, the largest Slovenian state university. The 65 pre-service teachers (61 women and 4 men) were informed about the study at the beginning of the 2023–2024 academic year and agreed to participate without expecting any incentives. There were no dropouts, and only those who had incomplete data were excluded from the study (n = 7). The last time these teachers were exposed to any form of technical education or training was in primary school, and they did not attend any design, technology, or engineering courses in high school. Their age ranged from 20 to 22 years, and the mean score for age was calculated as 21.14 (*SD* = 0.39).

Since the sample reflected diversity in terms of demographics and socioeconomic status, the quality of the sample was assessed through power analysis using G*Power 3.1 (Heinrich Heine Universität, Düsseldorf, Germany) [86] to ensure that the sample size was adequate to provide statistically significant results. A power analysis with input parameters for a two-tailed test (α = 0.05, power(1-β) = 0.85) indicated that a total sample of 62 participants would be needed to detect a moderate effect size f^2 = 0.15 using the t-test with linear multiple regression and five predictors. The sample of 65 participants was adequate to test and answer the research questions. Participating pre-service teachers had limited practical experience, as the teacher training program included a 4-week school/kindergarten internship in the fourth and sixth semesters, whereas in the third semester, when this study was conducted, they had only 1 performance and 1 observation per methodical course (total of 10 courses). The sample was nationally representative, since it represented nearly 40% of all pre-service preschool teachers enrolled in the second year of the study in all three Slovenian universities where the study program was organized and is delivered [82].

2.3. Measures

This study examined the variables of students' systems thinking, their perception of stimulating HOTS, and the engagement and flow in the DTE course. Their grades on the final exam, expressed as percentages, were collected from the official information system at the Faculty of Education, University of Ljubljana. All 4 measures with the corresponding final instruments are attached in the Supplementary Materials, titled "Students' perceptions of and experiences with the DTE course".

2.3.1. Systems Thinking and Strategic Approach Orientation Scales

A systems thinking scale (STS), developed by Moore et al. [35] and adapted by Avsec et al. [87], and comprising 15 questions, was used as a data collection tool in the present study. A three-factor structure was confirmed using exploratory factor analysis (EFA) with the maximum likelihood estimation method:

- ST 1: Multiple causations possible, variation of different types (random/special) (6 items);
- ST 2: Interrelations of factors, patterns of relationships, feedback behavior (5 items);
- ST 3: Sequence of events and causal sequence (4 items).

As a complement to systems thinking, we added a scale to assess strategic approaches to study and changes proposed by Moore et al. [35]. Three subscales were revealed using EFA: personal effort (3 items), reliance on authority (3 items), and strategic thinking (5 items). Additionally, Velicer's MAP test [88] was used to determine the number of components, indicating an additional three factors.

Responses to the items of both scales ranged between 1 (never) and 6 (always) to assess individuals' perception of their systems thinking or strategic approach orientation. Mean (*M*) and standard deviation (*SD*) were calculated for all subjects. All items are ordinal, and the instrument was validated in a previous study [87], confirming the reliability of the scale. The total score for systems thinking was computed by summing up the responses to all items, and scores ranged from 15 to 90, with higher scores indicating better systems thinking ability.

2.3.2. Attitudes Toward Stimulating Higher-Order Thinking

Stimulating higher-order thinking (SHOT), a 7-point Likert-type scale was also used as a data collection instrument in the present study. Responses ranged from 1 (strongly disagree) to 7 (strongly agree). The original SHOT instrument was developed by Wijnen et al. [89] and comprised four factors; for the purposes of this study, we extended the original SHOT and adjusted it to our target group, resulting in a seven-factor solution instrument with 30 items, as also suggested by Wijnen et al. [89]. Since the original SHOT was aimed at measuring teachers' attitudes toward stimulating higher-order thinking in students, we adjusted several items to fit the context of this study. The main focus of the questionnaire was pre-service preschool teachers' perception of their attitude toward stimulating higher-order thinking in preschool children. Since preschool education is very sensitive, many preschool teachers tend not to see the relevance of stimulating students' higher-order thinking, or, even more, may not feel capable of engaging children in activities to enhance that type of thinking. On the other side, several European Union and national projects and government incentives are operating in the educational sector to boost higher-order thinking skills from kindergarten to university. Thus, new insights into how to effectively integrate ICT and other digital tools into the pedagogical process are necessary. Therefore, we extended the original SHOT with scales of enjoyment, anxiety, and perceived difficulty. The new factor solution structure of SHOT is as follows:

- Perceived relevance (PR, 4 items);
- Perceived student ability (PSA, 6 items);
- Self-efficacy (SE, 4 items);
- Context dependency (CD, 4 items);
- Enjoyment (ENJ, 4 items);
- Anxiety (ANX, 5 items);
- Perceived difficulty (PD, 3 items).

2.3.3. Student Engagement

Student engagement in DTE is a multifaceted issue that can be understood in several dimensions. For the purpose of this study, we used Avsec et al.'s [87] adapted survey, based on the original by Naibert and Barbera [90] and Diessner [91]. The instrument consists of 20 items, distributed into five dimensions. Conceptualizing student engagement involves understanding the interplay between behavioral, emotional, cognitive, and social/agentic dimensions. The dimensions used in the study were conceptualized as follows:

- Behavioral engagement (BE): participating, making an effort, and having persistence in academic tasks, facing challenges, investing time and energy in learning (4 items);
- Cognitive engagement (CE): investing in learning, self-regulating, and using deep learning strategies (4 items);
- Emotional engagement (EE): showing interest in the subject matter, having a positive attitude toward the pedagogical process itself, belonging to school or classroom community (5 items);
- Social engagement (SE): having a voice and owning the learning process by taking an active role (4 items);
- Aesthetic engagement (AE): using sensory perception, having emotional responses through personal connection and aesthetic appreciation, showing creative expression and critical reflection (3 items).

A 6-point Likert scale was used to assess student engagement, from 1 (never) to 6 (always). Negatively worded items were reverse coded before analysis.

2.3.4. Flow

To measure the optimal experience in technology-enhanced DET activities, we used an adapted flow state scale (FSS), originally developed by Jackson and Marsh [92]. The instrument consists of 36 items, and for assessment we used a 7-point Likert-type response format (1 = strongly disagree to 7 = strongly agree). A nine-factor solution of flow with four items per construct is as follows:

- Challenge–skill balance (CSB);
- Action–awareness merging (AAM);

- Clear goals (CG);
- Unambiguous feedback (UF);
- Concentration on task at hand (CTH);
- Paradox of control (PC);
- Loss of self-consciousness (LSC);
- Transformation of time (TT);
- Autotelic experience (AE).

The total score for flow ranged from 36 to 252 points, and the mean (*M*) and standard deviation (*SD*) were calculated for distinct components. It is possible that measuring individual components of flow offers a more robust foundation for evaluating the theoretical basis of the FSS than depending solely on an overall score, as argued by Jackson and Marsh [92], Šimleša et al. [93], and Palomäki et al. [15].

2.3.5. Student Performance

The final exam grade was used as a measure of student performance in the DTE course. The final exam was designed to measure students' technological and engineering literacy as the main outcome. It comprised 15 tasks or questions measuring knowledge and skill on different taxonomic levels. Each test task was worth 1 point, and the maximum score was 15 points (100%). The design of the final exam tasks followed a valid method for technological literacy testing [94], also relying on ITTEA guidelines and practices [1] and considering course syllabus learning objectives [82]. There were eight multiple-choice items (five options; 1 point for each correct choice), three fill-in-the-blank items (1 point for each correct blank), and four matching answers (1 point for each correct match). The test demonstrated moderate internal consistency (McDonald's ω = 0.82) [95]. The final exam was created and administered using the Exam.net portal, an official portal used for examinations at the University of Ljubljana. Students attended the examination in situ on the university premises.

2.4. Data Collection and Analysis

2.4.1. Data Collection

Prior to the beginning of the study, ethical approval was obtained by the corresponding university committee. All required information was presented to participants, including the purpose of the study, nature of data collection, analysis and record-keeping, benefits, and the possibility to withdraw from the study, and those who gave consent were given the survey. The data collection was carried out during the 2023–2024 academic year at the end of the winter semester, in January and February 2024, using 1KA (https://1ka.arnes.si/, accessed on 5 June 2024), a portal recommended by the University of Ljubljana for conducting surveys. The survey consisted of four questionnaires, which were delivered in two rounds two weeks apart. In the first round, two instruments were delivered to participants: the STS complemented with strategic approach constructs, and the SHOT. In the second round, when all activities in the DTE course were accomplished, participants were asked to rate their perception of engagement and rate their experience with the ICT and digital tools they used in the course (FSS). All four questionnaires were in digital form, and participants completed them as a part of an online course. For those who missed it the first time, we sent two reminders to complete the survey.

2.4.2. Data Analysis

Different software was used to analyze the data in this study descriptively and interpretively. The descriptive and inferential statistics, Shapiro–Wilk normality test, EFA, and reliability estimation were performed using IBM SPSS Statistics (version 25), while the variance-based mediation analysis was conducted using ADANCO 2.4 (https://www.utwente.nl/en/et/dpm/chair/pmr/ADANCO/; accessed on 1 May 2024).

As a measure of the effect size, Cohen's f^2 was used in mediation analysis for direct effects. The value of Cohen's f^2 can be interpreted as an unsubstantial effect ($f^2 < 0.02$), weak effect ($0.02 \leq f^2 < 0.15$), moderate effect ($0.15 \leq f^2 < 0.35$), or strong effect ($f^2 \geq 0.35$) [96]. For indirect effects, in this study, we used a mediation effect size measure, υ, developed by Lachowicz et al. [97]: the squared standardized υ is greater than 0.175 for a large effect, 0.075 for a medium effect, and 0.01 for a small effect [97,98].

The reliability of each scale and subscale was estimated using McDonald's ω. It accommodates varying factor loadings and does not require the stringent assumption of tau-equivalence, making it suitable for a wider range of scales, especially those that may not be strictly unidimensional. Using McDonald's omega can lead to better-informed decisions about the reliability of educational assessments, as argued by Dunn et al. [95].

3. Results

All participants in the study successfully completed all planned tasks in the DTE course, thereby meeting all requirements to qualify for the final exam. The average test score was $M = 69.84\%$ ($SD = 16.11\%$), and scores ranged from 40% (minimum) to 100% (maximum). The values of skewness = −0.41 (SE = 0.29) and kurtosis = −0.69 (SE = 0.58) were between −2 and +2, which is considered acceptable to prove a normal univariate distribution [99]. The assumption of univariate normality was confirmed with the Shapiro–Wilk test ($p > 0.05$).

Next, data collected in the survey were checked and cleaned until they were suitable for undergoing different analyses. In the next sections, the results are reported according to the research questions we created to guide this study.

3.1. Systems Thinking and Strategic Approach Orientation Among Pre-Service Teachers

We analyzed the systems thinking scale separately from the strategic approach factors. Before conducting our analyses, we first evaluated the items of both scales to develop some hypotheses regarding the factor structure already validated in previous studies [35,87].

3.1.1. Normality Tests and Validity Evidence

In this study, systems thinking is represented by three constructs, and the same for strategic thinking as a complement to systems thinking. The Shapiro–Wilk test results suggest that all six constructs follow a normal distribution ($p > 0.05$).

Next, we checked for possible multivariate outliers that might violate multivariate normality. For both systems thinking and strategic thinking constructs, the Mahalanobis distance of the cases did not exceed the critical value of 16.27 for three predictors. The probability of the Mahalanobis distance for each case is $p > 0.001$. In addition, we checked the multicollinearity of independent variables by calculating the variance inflation factor (VIF) for each variable, and all VIFs were less than the stringent threshold of 3, as proposed by Hair et al. [100].

Although the constructs were validated in previous studies [35,87], we validated all constructs again to ensure that the test or instrument would reliably and accurately measure the theoretical construct it was intended to measure. Since the sample size was rather small, we used a mixed-methods approach to validate constructs.

Firstly, we conducted EFA with maximum likelihood extraction and oblique rotation, as suggested by Fabrigar et al. [101]. Bartlett's test of sphericity was significant and indicated that the correlation matrix was not random: $\chi^2(105) = 543.86$, $p < 0.001$. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was 0.85, which is well above the minimum standard for conducting factor analysis (0.5) [102] and for analyzing the EFA output. The communality of all items extracted with maximum likelihood estimation (MLE) was above 0.55 (all values were between 0.55 and 0.75). The results of EFA suggested that the three-factor solution explained 64.6% of the variance, which is above the threshold of 0.5–0.6 suggested by Hair et al. [103]. Loadings smaller than 0.5 were excluded from the pattern matrix and from further analysis. The same procedure was followed for strategic thinking constructs, for which Bartlett's test of sphericity was also significant ($p < 0.001$)

and KMO correlation was 0.73. All extracted communality values were above 0.6. EFA revealed a three-factor solution, and it explained 61.65% of the variance.

Secondly, for convergent and discriminant validation of the constructs, we used the partial least squares (PLS) approach, which has several advantages when using small sample sizes (e.g., less stringent assumptions, ability to handle complex models, practical application, and validation) [104]. For the purpose of the present study, ADANCO v.2.4 software was used [104].

Convergent validity refers to the degree to which multiple indicators of a construct are correlated. It emphasizes the internal consistency of indicators measuring the same construct [105]. Evidence for convergent validity is established when the hypothesized measurement model fits the data adequately, and additional criteria such as standardized factor loadings and average variance extracted (AVE) values are met [105]. As shown in Tables 2 and 3, all AVE values are above the threshold of 0.5, whereas the square root of AVE (bold diagonal), McDonald's ω, and composite reliability (CR) is larger than 0.7, which is the threshold suggested by Hair et al. [106].

Table 2. Reliability of McDonald's ω, composite reliability (CR), square root of average variance extracted (AVE) (in bold), and correlations among systems thinking constructs (diagonal).

Latent Construct	ω	CR	AVE	ST 1	ST 2	ST 3
ST 1	0.89	0.88	0.54	**0.73**		
ST 2	0.83	0.82	0.56	0.71	**0.75**	
ST 3	0.82	0.81	0.55	0.72	0.64	**0.74**

Table 3. Reliability of McDonald's ω, composite reliability (CR), square root of average variance extracted (AVE) (in bold), and correlations among strategic approach orientation constructs (diagonal).

Latent Construct	ω	CR	AVE	Personal Effort	Reliance on Authority	Strategic Thinking
Personal effort	0.72	0.71	0.51	**0.71**		
Reliance on authority	0.80	0.79	0.62	0.35	**0.75**	
Strategic thinking	0.76	0.77	0.51	0.25	0.47	**0.79**

The values of correlation coefficients (off-diagonal) indicate medium to large convergence [107] for both scales, as shown in Tables 2 and 3. Thus, the results in Tables 2 and 3 indicate convergent validity for the adapted constructs, and high convergent validity supports the retention of all dimensions of systems thinking and strategic approach orientation.

Since convergent validity is confirmed for both scales, we can continue with establishing discriminant validity. In other words, if a construct is not accurately represented by its indicators, examining whether it can be distinguished from other constructs is meaningless [105].

Discriminant validity refers to the extent to which a construct is truly distinct from other constructs [108]. It has been shown that constructs that are supposed to be unrelated show low correlations [105]. In this study, discriminant validity was examined using the heterotrait–monotrait (HTMT) approach proposed by Hensler et al. [109] and controlled using the Fornell–Larcker criterion, which checks whether the AVE associated with constructs is greater than the shared variance between constructs [110]. As shown in Tables 4 and 5, the HTMT ratio of correlations is smaller than the threshold 0.85 [108], while the AVE values (on the diagonal) are larger than average shared variance (ASV) (in parenthesis).

Table 4. Heterotrait–monotrait ratio of correlations (HTMT) and Fornell–Larcker criterion results (in parenthesis) for systems thinking scale. AVE on the diagonal.

Latent Construct	ST 1	ST 2	ST 3
ST 1	0.54		
ST 2	0.71 (0.51)	0.56	
ST 3	0.72 (0.52)	0.64 (0.40)	0.55

Table 5. Heterotrait–monotrait ratio of correlations (HTMT) and Fornell–Larcker criterion results (in parenthesis) for strategic approach orientation scale. AVE on the diagonal.

Latent Construct	Personal Effort	Reliance on Authority	Strategic Thinking
Personal effort	0.51		
Reliance on authority	0.31 (0.13)	0.62	
Strategic thinking	0.24 (0.11)	0.46 (0.24)	0.51

A low ASV indicates that the constructs are distinct and measure different phenomena, while high shared variance suggests that the constructs overlap significantly, which could undermine discriminant validity [111].

Based on the results in Tables 4 and 5, we conclude that all variables demonstrate discriminant validity. Moreover, validation indicates that each item loads uniquely on only one construct [105].

3.1.2. Levels of Systems Thinking and Strategic Behavior

The first aim of this study was to examine the level of systems thinking of pre-service teachers and their orientation toward their strategic approach for study and work as a complement to systems thinking. The descriptive statistics summarizing the self-reported characteristics of pre-service teachers are shown in Table 6.

Table 6. Average scores for pre-service teachers' self-reported data expressed as mean (*M*) and standard deviation (*SD*) across subscales of systems thinking and strategic approach along with a measure of skewness (*S*) and kurtosis (*K*); 95% confidence interval (CI) in brackets.

	Variables	*M*	*SD*	*S*	*K*	95% CI
Systems thinking	ST 1	4.64	0.74	−0.44	−0.43	[4.46, 4.83]
	ST 2	4.85	0.68	−0.26	−0.06	[4.68, 5.03]
	ST 3	5.11	0.67	−0.62	−0.02	[4.94, 5.27]
	Total ST	72.40	9.23	−0.35	−0.43	[70.11, 73.00]
Strategic approach orientation	Personal effort	4.21	0.76	−0.59	0.42	[4.02, 4.40]
	Reliance on authority	2.94	0.77	0.06	0.34	[2.75, 3.00]
	Strategic thinking	3.86	0.65	0.17	−0.15	[3.69, 4.02]

The values for skewness and kurtosis shown in Table 6 are within the acceptable range (−2 and +2, −7 and +7, respectively) as proposed by Hair et al. [106], suggesting that the dataset possessed a normal distribution, as also confirmed by the Shapiro–Wilk test ($p > 0.05$). An average total score for systems thinking of 72.4 points (76%) is comparable with scores for nursing students, public health students [35], and architecture students [112], while medical students and mechanical engineering students scored lower, as reported in studies by Moore at al. [35] and Kurent and Avsec [112], which used the same instrument for data collection.

We also investigated whether systems thinking constructs were evenly developed in pre-service teachers or if there were significant differences among them. For that purpose, we used a repeated measures ANOVA, which met the assumption that the variances in differences between all combinations of related conditions (or construct levels) would be equal. Mauchly's test indicated that the assumption of sphericity was not violated ($\chi^2(2) = 1.08$, $p = 0.58 > 0.05$). Repeated measures ANOVA determined that systems thinking varied significantly across different dimensions ($F(2, 128) = 17.58$, $p < 0.001$), with a partial η^2 effect size of 0.22. A post hoc analysis using the Bonferroni correction for multiple comparisons to keep the type I error at 5% overall showed a significant difference between ST 1 and ST 2 ($p = 0.020$) and ST 3 ($p < 0.001$). A significant difference was also found between ST 3 and ST 2 ($p = 0.010$). The results indicate that dimension of systems thinking ST3, understanding sequences of events and causal sequences, was most developed, while ST1, understanding the possibility of multiple causations and variations of different types in systems, was less developed.

To find out whether the means of the three strategic approach orientation constructs were different, one-way repeated measures ANOVA was used. Mauchly's test, which evaluates the sphericity condition, showed that the assumption of sphericity was satisfied ($\chi^2(2) = 0.98$, $p = 0.61 > p = 0.05$) and the test of within-subject effects was significant ($F(1,64) = 66.52$, $p < 0.001$), with a partial η^2 effect size of 0.51. A pairwise comparison of mean differences based on estimated marginal means using a Bonferroni adjustment for multiple comparisons to reduce the risk of committing a type I error revealed significant differences between reliance on authority and both personal effort and strategic thinking ($p < 0.01$), while perceived personal effort in the technology-enhanced DTE course significantly differed from strategic thinking ($p = 0.009$).

Pre-service teachers who develop a strong systems thinking ability can better understand the complexity and interconnectedness of environmental, social, and economic systems, which are key to addressing global sustainability challenges. Higher mean scores for systems thinking compared to a strategy-oriented approach indicate a greater focus on pedagogical training and more intuitive skills for pre-service teachers. Teacher education often prioritizes understanding the complex systems in education, such as student diversity, societal influences, and learning environments [65,82]. By fostering a strategic approach orientation, such as personal effort and strategic thinking, pre-service teachers are better prepared to tackle sustainability issues holistically. This prepares them to create learning environments where students are taught to think critically about their roles within larger systems, contributing to the development of future generations who are equipped to drive sustainable change. The lower scores for the strategic approach results reflect the ongoing development of strategic problem solving skills that are often acquired through experience. Scores for the strategy-oriented approach were anticipated, as pre-service preschool teachers, due to their lack of experience, do not have well developed strategic thinking and reliance on authority.

3.2. Pre-Service Teachers' Attitudes Toward Stimulating Higher-Order Thinking

3.2.1. Normality Tests and Validity Evidence

The original SHOT questionnaire developed by Wijnen et al. [89] has four attitudinal factors. For the purpose of this study, we added three new constructs, also suggested by the authors of the original tool. The Shapiro–Wilk test of normality was conducted to determine whether the data for all seven constructs were normally distributed. The results indicate that we failed to reject the null hypothesis for all constructs ($p > 0.05$), and we concluded that the data were normally distributed.

Next, we checked for possible multivariate outliers that might violate multivariate normality. For both systems thinking and strategic thinking constructs, the Mahalanobis distance of the cases did not exceed the critical value of 24.31 for seven degrees of freedom. The probability of the Mahalanobis distance for each case is greater than $p > 0.001$. In addition, we checked the multicollinearity of independent variables by calculating the VIF for each variable, and all VIFs were less than the threshold value of 3 proposed by Hair et al. [100].

We conducted EFA to identify the underlying structure of the data and refine the scale if needed. MLE was employed as the extraction method, and oblique rotation was used to allow for correlated factors. After extraction, the communality ranged from 0.56 to 0.92 [113], demonstrating the proportion of variance in each item that was actually explained by the extracted factors. Most items had high extraction communality, suggesting that the extracted factors provided a good representation of the data [113]. The resulting EFA revealed a seven-factor structure, as was anticipated.

In addition to the EFA, we calculated the AVE, average shared variance (ASV), composite reliability (CR), and McDonald's ω to further explore the convergent and discriminant validity of SHOT subscales.

As shown in Table 7, all constructs of SHOT exhibit convergent validity, since all of the following three conditions are fulfilled: (a) CR and McDonald's ω are greater than 0.7, (b) all standardized factor loadings λ are greater than 0.5, and (c) AVE is greater than 0.5, as suggested by Hair et al. [106].

Table 7. Reliability of McDonald's ω, composite reliability (CR), square root of average variance extracted (AVE) (in bold), and correlations among SHOT's subscales (diagonal).

Latent Construct	ω	CR	AVE	PR	PSA	SE	CD	ENJ	ANX	PD
PR	0.85	0.85	0.59	**0.77**						
PSA	0.90	0.89	0.60	0.22	**0.78**					
SE	0.93	0.83	0.77	0.35	0.14	**0.88**				
CD	0.81	0.80	0.52	0.24	0.70	0.33	**0.72**			
ENJ	0.94	0.95	0.82	0.36	0.02	0.54	0.13	**0.90**		
ANX	0.93	0.93	0.74	0.07	0.51	0.05	0.69	0.11	**0.86**	
PD	0.81	0.80	0.58	0.11	0.29	0.34	0.68	0.31	0.70	**0.76**

In this study, we assessed discriminant validity using HTMT correlations. Following the guidelines proposed by Henseler et al. [109], we considered HTMT values below 0.85 as indicative of adequate discriminant validity. We computed HTMT values for each pair of constructs using ADANCO software [104].

An examination of discriminant validity showed that we fulfilled all four criteria: first, there is evidence of convergent validity; second, there are no indicator cross-loads on other constructs; third, AVE is equal or greater than 0.50 and greater than ASV [105,111]; and finally, all correlations between SHOT constructs are less than the threshold of 0.85 (Table 8) [108].

Table 8. Heterotrait–monotrait ratio of correlations (HTMT) and Fornell–Larcker criterion results of ASV (in parenthesis) for SHOT's subscales. AVE on the diagonal.

Latent Construct	PR	PSA	SE	CD	ENJ	ANX	PD
PR	0.59						
PSA	0.22 (0.05)	0.60					
SE	0.37 (0.13)	0.14 (0.02)	0.77				
CD	0.24 (0.07)	0.70 (0.49)	0.33 (0.11)	0.52			
ENJ	0.36 (0.14)	0.02 (0.01)	0.54 (0.30)	0.13 (0.02)	0.82		
ANX	0.07 (0.01)	0.52 (0.26)	0.05 (0.01)	0.69 (0.48)	0.11 (0.02)	0.74	
PD	0.11 (0.01)	0.29 (0.09)	0.34 (0.11)	0.68 (0.47)	0.31 (0.10)	0.70 (0.49)	0.58

3.2.2. Pre-Service Teachers' Attitudes Toward Stimulating Higher-Order Thinking and the Relationship to Systems Thinking Ability

To address our second research question, first we used descriptive statistics to describe the mean values for pre-service teachers' perceptions of SHOT subscales, as reported in Table 9.

Table 9. Average values of pre-service teachers' self-reported scores expressed as mean (*M*) and standard deviation (*SD*) across SHOT subscales along with measures of skewness (*S*) and kurtosis (*K*); 95% confidence interval (CI) in brackets.

	Subscales	***M***	***SD***	***S***	***K***	**95% CI**
SHOT	PR	5.60	0.81	−0.54	1.13	[5.40, 5.80]
	PSA	3.78	1.12	−0.01	0.06	[3.51, 4.06]
	SE	4.59	1.07	0.11	0.08	[4.33, 4.86]
	CD	4.31	0.92	0.26	1.51	[4.08, 4,54]
	ENJ	5.58	1.01	−0.04	−1.11	[5.32, 5.83]
	ANX	3.12	1.28	0.91	0.95	[2.80, 3.44]
	PD	4.31	1.06	0.16	0.21	[4.05, 4.58]

Most mean values are above the midpoint of the scale (4), except PSA and ANX, which was expected based on the original research of Wijnen et al. [89]. For PSA, the results indicate that pre-service teachers believe that higher-order thinking is suitable for low-achieving children. Moreover, pre-service teachers do not feel anxious when organizing and conducting activities for children to enhance their higher-order thinking.

Although the assessment scale we used had 7 points compared to the original 5 points, the rank of subscales based on the mean is the same.

Next, we performed regression analysis to investigate whether scores on the SHOT subscales had predictive value for pre-service teachers' systems thinking, as measured by the total score, which was represented as the sum of responses for each item on the scale.

Regression analysis revealed that SHOT subscale scores predicted pre-service teachers' system thinking ability: adjusted $R^2 = 0.35$, $F (7, 57) = 5.91$, $p < 0.001$. As shown in Table 10, the attitude factors SE, PSA, and ANX are significant predictors for systems thinking ($p < 0.05$).

Table 10. Unstandardized and standardized coefficients with *p*-values in MLR analysis; 95% confidence interval (CI) in brackets.

Model	**Unstandardized Coefficients**		**Standardized Coefficients**	***t*-Statistic**	***p*-Value**	**95%CI**
	β	**Std. Error**	**β**			
PR	0.88	1.28	0.08	0.68	0.497	[−1.69, 3.46]
PSA	2.42	1.06	0.30	2.29	0.026	[0.30, 4.56]
SE	3.81	1.11	0.44	3.44	0.001	[1.58, 6.02]
CD	−0.56	1.55	−0.06	−0.36	0.724	[−3.65, 2.56]
ENJ	−0.71	1.14	−0.08	−0.62	0.538	[−2.99, 1.57]
ANX	−2.97	1.12	−0.41	−2.63	0.011	[−5.22, −0.71]
PD	−0.21	1.33	−0.03	−0.15	0.876	[−2.88, 2.47]

Pre-service teachers' attitudes toward stimulating HOTS are essential for sustainable education as HOTS are directly linked to problem solving, creativity and critical thinking—skills required for sustainability. The study suggests that those who have a positive attitude towards HOTS are more likely to integrate sustainability topics into their future teaching practice. This attitude not only improves students' cognitive skills, but also supports their commitment to lifelong learning in sustainability and prepares them to tackle the complex problems of the future [84].

Pre-service teachers who considered themselves competent to pose challenging questions and prepare tasks for children to enhance HOTS also reported higher achievement in systems thinking. Moreover, pre-service teachers who were able to provide guidance and support for students during problem solving activities using various types of supports reported higher systems thinking ability. This capability may also enhance their effectiveness in self-regulation and problem solving [114]. Systems thinking as a holistic approach is particularly useful for understanding and managing classroom dynamics and student behavior; it can help to alleviate feelings of helplessness and stress that often contribute to teacher anxiety and can help them improve their methods and adapt to changing classroom dynamics, which can further reduce anxiety [30]. A greater perception of student's abilities and a high level of self-efficacy among pre-service preschool teachers serve as a positive indicator of systems thinking, as they are more inclined to pursue holistic, interconnected approaches to teaching. Belief in children's potential encourages teachers to consider the entire system that influences learning, while self-efficacy enables them to confront complex challenges with confidence [58]. On the other hand, anxiety depletes cognitive resources and impairs functions such as working memory and cognitive flexibility, all of which are essential for systems thinking. It also diminishes self-confidence and motivation leading to the avoidance of complex tasks [30].

3.3. Pre-Service Teachers' Engagement with Technology-Enhanced DTE Course

3.3.1. Normality and Validity Tests

To measure engagement in the technology-enhanced DTE course, we adapted a questionnaire already validated in another study [87]. Since the context, type, and quality of the sample and the setting of the current study differed, this could have affected the participants' understanding and ability to respond to questions, and potentially impact the reliability and validity of the data. Thus, by reassessing and confirming the questionnaire's factor structure, internal consistency, reliability, and construct validity, we could ensure that the instrument would function as intended.

The Shapiro–Wilk test of normality was conducted to determine whether the data of all five constructs were normally distributed. The results indicate that we failed to reject the null hypothesis for constructs of social and aesthetic engagement ($p > 0.05$), while for constructs of behavioral, cognitive, and emotional engagement, the test of the null hypothesis revealed that a set of the data came from a non-normal distribution ($p < 0.05$). We concluded that all variables did not follow normal distribution. For a comprehensive understanding of the distribution characteristics of the data, we also calculated measures of skewness and kurtosis. Skewness and kurtosis offer more nuanced information about the nature of the distribution's deviation from normality and can inform appropriate data transformations or statistical tests.

Next, we checked for possible multivariate outliers that might violate multivariate normality. The Mahalanobis distance of the cases did not exceed the critical value of 20.51 for the five predictors (max. = 14.43). The probability of the Mahalanobis distance for each case was greater than $p > 0.001$. In addition, we checked the multicollinearity of independent variables by calculating the VIF for each variable, and all VIFs were less than the threshold value of 3 proposed by Hair et al. [100].

We conducted EFA to identify the underlying structure of our data and refine the scale if needed. MLE was employed as the extraction method, and oblique rotation was used to allow for correlated factors. The KMO value was 0.72, which is above the desirable value proposed by Watkins [102]. The results of Bartlett's test indicated that the correlation matrix was not random ($\chi^2(190) = 655.59$, $p < 0.001$). After extraction, the communality ranged from 0.50 to 0.85 [113], demonstrating the proportion of variance in each item that was actually explained by the extracted factors. Most items had high extraction communality, suggesting that the extracted factors provided a good representation of the data [113]. Factor loadings λ smaller than 0.5 were excluded from the study. The resulting EFA revealed a five-factor structure explaining 67.76% of the variance.

In addition to EFA, we calculated AVE, ASV, CR, and McDonald's ω to further explore the convergent and discriminant validity of the engagement subscales.

As shown in Table 11, all constructs of engagement with the technology-enhanced DTE course exhibited convergent validity, since all of the following three conditions were fulfilled: (a) CR and McDonald's ω greater than 0.7, (b) all standardized factor loadings λ greater than 0.5, and (c) AVE greater than 0.5, as suggested by Hair et al. [106].

Table 11. Reliability of McDonald's ω, composite reliability (CR), square root of average variance extracted (AVE) (in bold), and correlations among engagement subscales (diagonal).

Latent Construct	ω	CR	AVE	BE	CE	EE	SE	AE
BE	0.83	0.84	0.58	**0.76**				
CE	0.77	0.78	0.51	0.58	**0.71**			
EE	0.86	0.85	0.55	0.64	0.43	**0.74**		
SE	0.73	0.75	0.50	0.21	0.02	0.07	**0.70**	
AE	0.80	0.81	0.58	0.16	0.55	0.22	0.32	**0.76**

In this study, we assessed discriminant validity using HTMT correlations. Following the guidelines proposed by Henseler et al. [109], we considered HTMT values below 0.85 as indicative of adequate discriminant validity. We computed HTMT values for each pair of constructs using ADANCO software [104].

An examination of discriminant validity showed that we fulfilled all four criteria: first, there was evidence of convergent validity; second, there were no indicator cross-loads on other constructs; third, AVE was equal or greater than 0.50 and greater than ASV [105,111]; and finally, all correlations between constructs of pre-service teachers' engagement in the technology-enhanced DTE course were less than the threshold of 0.85 (Table 12) [108].

Table 12. Heterotrait–monotrait ratio of correlations (HTMT) and Fornell–Larcker criterion results of ASV (in parenthesis) for SHOT subscales. AVE on the diagonal.

Latent Construct	BE	CE	EE	SE	AE
BE	0.58				
CE	0.61 (0.33)	0.51			
EE	0.65 (0.41)	0.44 (0.19)	0.55		
SE	0.21 (0.04)	0.04 (0.01)	0.08 (0.01)	0.50	
AE	0.16 (0.02)	0.56 (0.31)	0.22 (0.05)	0.34 (0.11)	0.58

3.3.2. Pre-Service Teachers' Engagement in Technology-Enhanced DTE Course and the Relationship to Systems Thinking Ability

To address our third research question, first we used descriptive statistics to describe the mean values for pre-service teachers' perceptions of engagement subscales, as reported in Table 13. As shown in the table, all mean values are above the scale midpoint of 3.5, supporting that student engagement in DTE was estimated as above average. Participants reported emotional engagement as highest and aesthetic as lowest. This indicates a higher level of satisfaction with the DTE course enriched with technology-related activities.

Table 13. Average values of pre-service teachers' self-reported scores expressed as mean (*M*) and standard deviation (*SD*) across subscales of engagement along with measures of skewness (*S*) and kurtosis (*K*); 95% confidence interval (CI) in brackets.

	Subscales	*M*	*SD*	*S*	*K*	95% CI
Engagement with technology-enhanced DTE course	BE	4.97	0.65	−0.61	−0.17	[4.81, 5.13]
	CE	5.10	0.65	−0.67	−0.13	[4.94, 5.26]
	EE	5.38	0.62	−1.21	1.05	[5.23, 5.53]
	SE	4.47	0.75	−0.38	−0.54	[4.28, 4.65]
	AE	4.15	0.95	−0.28	−0.49	[3.92, 4.39]

The values for skewness and kurtosis shown in Table 13 are in the acceptable range (−2 and +2, −7 and +7, respectively) as proposed by Hair et al. [106]. Since the Shapiro–Wilk test gave a p-value indicating the probability that the data were not normally distributed, when interpreting this, we should consider the full context of our analysis. The sample size was rather small, thus was more prone to variability and may not have accurately reflected the population distribution, such that descriptive statistics like skewness and kurtosis can be misleading. In order to find a relationship between the engagement construct and systems thinking ability, we conducted linear regression analysis, which does not assume normality for either predictors or outcomes. Since the assumption of normality in linear regression applies to the residuals, we tested their normality using the Shapiro–Wilk test, and $p > 0.05$ for unstandardized and standardized residuals indicated normal distribution.

Regression analysis revealed that engagement subscale scores predicted pre-service teachers' system thinking ability (adjusted $R^2 = 0.36$, $F(5, 59) = 8.11$, $p < 0.001$). As shown in Table 14, the factors CE, SE, and AE are significant predictors for systems thinking ($p < 0.05$).

Table 14. Unstandardized and standardized coefficients with *p*-values in MLR analysis; 95% confidence interval (CI) in brackets.

Model	**Unstandardized Coefficients**		**Standardized Coefficients**	***t*-Statistic**	***p*-Value**	**95% CI**
	β	**Std. Error**	**β**			
BE	0.83	1.84	0.05	0.45	0.654	[−1.69, 3.46]
CE	7.24	1.76	0.51	4.12	0.000	[0.30, 4.56]
EE	1.71	1.85	0.11	0.92	0.359	[1.58, 6.02]
SE	3.65	1.35	0.29	2.69	0.009	[−5.22, −0.71]
AE	−3.03	1.10	−0.31	−2.74	0.008	[−2.88, 2.47]

Engagement with technology-enhanced DTE courses plays a central role in promoting sustainable education. The study shows that pre-service teachers who actively engage in such courses develop better systems thinking skills, such as understanding interconnections, identifying feedback loops, recognizing patterns and trends, thinking in terms of causality, and resilience thinking, which are essential for understanding the complexities of sustainability. This engagement fosters an active learning environment where teachers can gain experience, experiment, and reflect on sustainability practices that they can later pass on to their students. By embedding sustainability concepts into technology-enhanced learning, this approach empowers pre-service teachers to integrate sustainability into their learning and teaching strategies.

Pre-service teachers who actively involved themselves in the DTE course by answering posted questions, carrying out conceptual mapping, and overcoming misconceptions scored higher on the systems thinking scale. Similarly, those who understood and built on peers' ideas, shared their own ideas, and were keen on teamwork reported higher achievement in systems thinking, suggesting that peer support might enhance systems thinking. Cognitive and social engagement are critical to the development of systems thinking as they foster analytical, collaborative, and reflective skills. Cognitive engagement ensures active mental investment, which is essential for understanding complex systems [90]. Social engagement provides the collaborative environment and communication skills necessary to consider multiple perspectives [115]. On the contrary, pre-service teachers who focused on artistic values in the DTE course and integrated an aesthetic vision in technology-enhanced design-based work reported lower achievement in systems thinking. In addition, an intense emphasis on aesthetics consumes cognitive resources and limits systems thinking skills. Preschool education often prioritizes aesthetic skills and creativity [116] over systems thinking. Additionally, aesthetic engagement encourages divergent thinking, which can conflict with the convergent thinking required for systems analysis [3,36].

3.4. Pre-Service Teachers' Perception of Flow State in DTE Course and the Relationship to Systems Thinking

3.4.1. Normality and Validity Tests

To measure the flow state of students in the technology-enhanced DTE course, which occurs when students are totally connected to the performance and their personal skills are equal to the required challenges, we used an adapted FSS, developed by Jackson and Marsh [92]. Because the context, type, and quality of the sample and the setting of the study, which can affect students' understanding and responses to questions, were different compared to previous studies, we reassessed the questionnaire's factor structure, internal consistency, reliability, and construct validity. In this way, we could ensure that the instrument functioned as intended. The Shapiro–Wilk test of normality was conducted to determine whether the data of all nine constructs were normally distributed. The results indicate that we failed to reject the null hypothesis for constructs CSB, UF, CTH, LSC, TT, and AE ($p > 0.05$), while for AAM, CG, and PC, the test of the null hypothesis revealed that a set of the data did not come from a normal distribution ($p < 0.05$). We concluded that all variables did not follow a normal distribution.

Next, we checked for possible multivariate outliers that might violate multivariate normality. The Mahalanobis distance of the cases did not exceed the critical value of 27.87 for the nine predictors (max. = 27.23). The probability of the Mahalanobis distance for each case was greater than $p > 0.001$. In addition, we checked the multicollinearity of independent variables by calculating the VIF for each variable, and all VIFs were less than the liberal threshold value of 5 proposed by Hair et al. [100].

We calculated AVE, CR, and McDonald's ω to further explore the convergent and discriminant validity of the flow state subscales. As shown in Table 15, all constructs of students' engagement with the technology-enhanced DTE course from the perspective of flow exhibit convergent validity, since all of the following three conditions are fulfilled: (a) CR and McDonald's ω are greater than 0.7, (b) all standardized factor loadings λ are greater than 0.5, and (c) AVE values are greater than 0.5 as suggested by Hair et al. [106].

Table 15. Reliability of McDonald's ω, composite reliability (CR), square root of average variance extracted (AVE) (in bold), and correlations among FSS subscales (diagonal).

Latent Construct	ω	CR	AVE	AAM	AE	CG	CSB	CTH	LSC	PC	TT	UF
AAM	0.83	0.84	0.67	**0.81**								
AE	0.88	0.89	0.74	0.76	**0.86**							
CG	0.90	0.90	0.77	0.82	0.88	**0.88**						
CSB	0.79	0.80	0.61	0.89	0.89	0.84	**0.78**					
CTH	0.84	0.86	0.67	0.73	0.91	0.91	0.86	**0.82**				
LSC	0.77	0.77	0.60	0.61	0.44	0.54	0.54	0.58	**0.77**			
PC	0.88	0.88	0.73	0.84	0.79	0.88	0.86	0.88	0.50	**0.85**		
TT	0.71	0.73	0.54	0.67	0.74	0.55	0.54	0.58	0.62	0.49	**0.74**	
UF	0.85	0.86	0.69	0.89	0.81	0.92	0.93	0.82	0.52	0.93	0.42	**0.83**

The interconstruct correlation values (diagonal) range from 0.28 to 0.85, indicating that the measures have medium to large convergence [107].

Next, we examined discriminant validity using the HTMT approach, as proposed by Hensler et al. [109] and Shaffer et al. [117]. Table 16 shows that a few of the HTMT ratios of the correlations exceed even the liberal threshold of 0.90 [117]. With a small sample and a larger number of constructs, as in our case, establishing discriminant validity using a fixed threshold like 0.90 without considering statistical inference can lead to incorrect conclusions [109]. In this case, the standard approach of Fornell–Larcker has unacceptably low sensitivity, which means that it is largely unable to detect a lack of discriminant validity [118]. Thus, we used as a complement the $HTMT_{inference}$ criterion, as proposed by Henseler et al. [109]. To implement $HTMT_{inference}$, we used a bootstrapping procedure (specifying a bootstrap sample of 2000) to generate confidence intervals around the HTMT values. The upper bound of the confidence interval for the HTMT value was below 1, suggesting that the constructs are distinct, which supports discriminant validity, as proposed by Henseler et al. [109].

Table 16. HTMT results.

Latent Construct	AAM	AE	CG	CSB	CTH	LSC	PC	TT
AE	0.76							
CG	0.82	0.88						
CSB	0.89	0.89	0.84					
CTH	0.73	0.91	0.91	0.86				
LSC	0.61	0.44	0.54	0.54	0.58			
PC	0.84	0.79	0.88	0.86	0.88	0.50		
TT	0.67	0.74	0.55	0.54	0.58	0.62	0.49	
UF	0.89	0.81	0.92	0.93	0.82	0.52	0.93	0.42

In Table 16, the values greater than 0.90 indicate a discriminant validity problem according to the $HTMT_{0.90}$ criterion, while $HTMT_{inference}$ does not indicate a discriminant validity problem in these cases (confidence intervals: CTH<->AE [0.78,0.99], CTH<->CG [0.77,0.98], UF<->CG [0.87,0.97], UF<->CSB [0.86,0.99], and UF<->PC [0.87,0.99]).

3.4.2. Flow State and Predictive Analysis

To address our fourth research question, first we used descriptive statistics to describe the mean values for pre-service teachers' perceptions of flow state subscales, as reported in Table 17. As shown in the table, all mean values are above the scale midpoint of 4, supporting that the student flow state in DTE was estimated as above average. Students scored the autotelic experience highest and time transformation lowest. In general, this indicates a higher level of flow state perceived in the DTE course enriched with well-designed technology-enhanced activities.

Table 17. Average values of pre-service teachers' self-reported scores expressed as mean (*M*) and standard deviation (*SD*) across subscales of flow state along with measures of skewness (*S*) and kurtosis (*K*); 95% confidence interval (CI) in brackets.

	Subscales	*M*	*SD*	*S*	*K*	95% CI
Pre-service teachers flow state at technology-enhanced DTE	CSB	5.61	0.89	−0.69	0.75	[5.39, 5.83]
	AAM	4.97	1.01	−0.51	−0.43	[4.72, 5.22]
	CG	5.54	1.07	−1.11	1.16	[5.27, 5.80]
	UF	5.33	0.81	−0.76	0.29	[5.13, 5.53]
	CTH	5.58	1.01	−0.64	0.07	[5.33, 5.83]
	PC	5.46	0.91	−0.89	0.57	[5.24, 5.69]
	LSC	5.26	1.03	−0.37	−0.35	[5.01, 5.52]
	TT	4.68	0.97	−0.47	0.01	[4.44, 4.92]
	AE	5.86	0.90	−0.57	−0.38	[5.63, 6.07]

The values for skewness and kurtosis, shown in Table 17, were within the acceptable range (−2 and +2, −7 and +7, respectively), as proposed by Hair et al. [106]. In order to find a relationship between FSS constructs and systems thinking ability, we conducted linear regression analysis, which does not assume normality for either predictors or outcomes. Since the assumption of normality in linear regression applies to the residuals, we tested their normality using the Shapiro–Wilk test, and $p > 0.05$ for unstandardized and standardized residuals indicated normal distribution.

Regression analysis revealed that self-reported flow predicted pre-service teachers' system thinking ability (adjusted $R^2 = 0.56$, $F(9, 55) = 7.99$, $p < 0.001$). As shown in Table 18, the factors AAM, CG, CTH, TT, and AE are significant predictors of systems thinking

($p < 0.05$). Collinearity statistics revealed that all VIFs are smaller than the liberal threshold of 5, proposed by Hair et al. [100], while the tolerance value is less than 1 for all cases.

Table 18. Unstandardized and standardized coefficients with *p*-values in MLR analysis; 95% confidence interval (CI) in brackets.

Model	Unstandardized Coefficients		Standardized Coefficient	*t*-Statistic	*p*-Value	95% CI
	β	Std. Error	β			
CSB	0.98	1.54	0.09	0.63	0.527	[−2.11, 4.08]
AAM	3.36	1.35	0.36	2.48	0.016	[0.65, 6.06]
CG	3.59	1.64	0.41	2.18	0.033	[0.29, 6.89]
UF	−2.39	2.22	−0.20	−1.07	0.286	[−6.85, 2.06]
CTH	−2.70	1.28	−0.29	−2.10	0.040	[−5.28, −0.13]
PC	−1.45	1.89	−0.14	−0.76	0.446	[−5.24, 2.13]
LSC	1.51	1.04	0.16	1.44	0.153	[−0.58, 3.60]
TT	−2.09	1.02	−0.21	−2.03	0.047	[−4.14, −0.03]
AE	3.91	1.30	0.38	2.99	0.004	[1.29, 6.52]

As shown in Table 18, we found both positive and negative predictors of FSS in systems thinking. When experiencing flow, at least one dimension is present, but typically all are present [14]. The flow dimensions can be classified into three phases, as proposed by Šimleša et al. [93]: First is the pre-experience phase, which involves a balance between challenge and ability, clear goals, and immediate feedback. Second is the experience phase, which is perceived during flow and involves a combination of activity and awareness, concentration, and a sense of control. Third is the effects phase, which describes the individual's internal experiences, such as loss of self-awareness, altered experience of time, and autotelicity. Autotelicity of experience refers to self-upgrading, where an intrinsic motivation can be seen as a product of satisfying the fundamental needs of perceived competence, perceived autonomy, and relatedness [15].

The study shows that pre-service teachers' experience of flow during the DTE course significantly enhances their systems thinking skills, which are essential for sustainable education. By fostering a flow state, the learning environment becomes more conducive to exploring sustainable solutions and concepts, enhancing the overall effectiveness of sustainability education in preparing future educators. As shown in Table 18, all phases of flow have predictive value in systems thinking. Students who were so deeply involved in the flow during activities that it became spontaneous or automatic reported higher scores in systems thinking ability, a key driver of sustainable education. The same was true for students who perceived that the learning goals were clearly defined and engaging in the course was an intrinsically rewarding experience. It seems that autotelic experience as a dimension of flow and as the effect phase might affect systems thinking, while a loss of the sense of time will predict lower scores in systems thinking. The same was found in the experience phase regarding the perception of concentrating on the task at hand. Students who explicitly focused strongly on the task reported lower scores in systems thinking.

3.5. Relationship Between Pre-Service Teachers' Self-Reported Flow and Their Achievement in DTE Course Mediated by Systems Thinking

The exploration of the relationship between flow state, systems thinking, and achievement began with a review of the relevant bivariate correlations (see Table 19). As expected, flow as measured by the self-reported FSS was positively correlated with systems thinking and final exam achievement. This correlation was statistically significant at the 0.01 level.

Table 19. Means, standard deviations, correlations, and McDonald's ω (diagonal values in parentheses) for all variables.

Variable	*M*	*SD*	Flow	Systems Thinking	Final Exam Score
Flow	193.45	26.17	(0.92)		
Systems thinking	72.40	9.23	0.51 **	(0.94)	
Final exam score	69.84	16.11	0.38 **	0.54 **	(0.82)

** Correlation is significant at 0.01 level (2-tailed).

This preliminary exploration served several important purposes: establishing correlation and causation, assessing the presence of mediation, avoiding misinterpretation due to confounding variables, making an informed decision about sample size, and ensuring that constructs were valid and reliable, as argued in [119].

To examine the relationship between flow and students' achievements in the DTE course as represented by the final exam score, and the possible mediational role of systems thinking, path analysis was used to test the proposed model and study hypotheses. The analysis was conducted to estimate the direct and indirect paths, as depicted in Figure 3. All analyses were conducted with ADANCO software using variance-based SEM, as proposed with strict guidelines by Nitzl et al. [120].

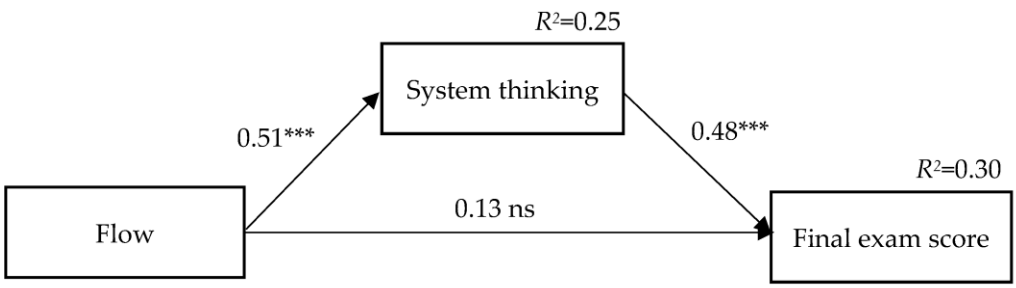

Figure 3. Mediation model of systems thinking in relation between flow and final exam score. *** $p < 0.001$; ns, nonsignificant.

The path analysis results show a significant direct effect of flow on systems thinking (β = 0.51, $p < 0.001$, Cohen's $f^2 = 0.36$ (strong effect size)) and a nonsignificant effect on final exam scores ($p > 0.05$). The effect of systems thinking on final exam scores was significant (β = 0.48, $p < 0.001$, Cohen's $f^2 = 0.25$ (moderate effect size)).

The bootstrap estimation procedure (specifying a bootstrap sample of 1999) was used to test the significance of the mediation effect of systems thinking on the relationship between flow and final exam score. The results indicate that systems thinking mediates the relationship between flow and final exam score (indirect effect = 0.25, CI [0.11, 0.38], $\upsilon^2 = 0.053$), and the effect size can be classified as medium [98].

Pre-service teachers who experience a higher degree of flow during DTE activities exhibit stronger systems thinking capabilities, leading to higher scores at final exam. This suggests that engagement through flow not only boosts academic performance but also enhances the teacher's ability to apply systems thinking in sustainability contexts. By facilitating environments that support flow, educators can deepen pre-service teachers' understanding of sustainability, thus preparing them to teach sustainability-related subjects effectively and contribute to SDG 4, by fostering a more sustainable future in their educational practice. Moreover, through enhanced engagement and systems thinking, these educators are better prepared to teach subjects related to sustainability, indirectly supporting other SDGs such as SDG 12, SDG 13, and SDG 17 [4,24].

The impact of flow on final exam scores in a DTE course mediates systems thinking by redirecting the increased engagement through flow into deeper understanding and improved performance. This may be because flow increases engagement and focus [14], while systems thinking fosters holistic understanding [3,34]. In DTE, this entails recognizing how various components, processes and technologies interact within a project or system. By harnessing the positive effects of flow, particularly autotelic experience, action-awareness merging, and clear goals, systems thinking can enhance learning outcomes, resulting in a better understanding of complex systems and ultimately improved exam results.

4. Discussion

The following subsections present the findings of our study that address the interplay between pre-service preschool teachers' systems thinking and their attitudes toward stimulating HOTS and engaging in a technology-enhanced educational environment from the perspective of flow theory. Findings on the potential impact of an optimal ICT experience on pre-service preschool teachers' performance in a DTE course mediated by systems thinking are also presented.

4.1. Self-Reported Systems Thinking and Strategic Approach Orientation of Pre-Service Preschool Teachers

In this subsection, we answer RQ 1, which refers to the self-assessed level of systems thinking of pre-service preschool teachers and the even development of its dimensions. The level of systems thinking of pre-service preschool teachers in terms of both the dimensions and the total score was above average and comparable to that of nursing students [35]. The results indicate differences in self-reported levels of development of all dimensions of systems thinking and some differences in the strategically oriented approach. Pre-service teachers gave the highest assessment for items in the dimensions of event sequence and causal sequence (examples include "I think that systems are constantly changing", "I recognize system problems are influenced by past events", "I consider the past history and culture of the work unit", "I consider that the same action can have different effects over time, depending on the state of the system"). This could be because students follow a specific sequence (structure of activities) when preparing for kindergarten activities and learn the importance of children developing a concept of sequence (numerical or otherwise). Sequences form the basis of children's mathematical thinking, counting, and computational thinking [121], and are increasingly being incorporated into curricula, as lessons on coding and early robotics (concepts of sequences, algorithms, loops, debugging, etc.) are encouraged in the preschool years [23,121,122]. Number sequencing is probably the first abstract concept children learn. Sequencing is also constantly practiced later, e.g., when developing morning and daily routines in kindergarten. Sequence-based activities such as storytelling, cooking/following a recipe, dancing/learning choreography, making ornaments and products, and doing other project-based activities are also very present in the preschool years [55].

Pre-service teachers rated the dimensions of relationships and feedback statistically significantly lower than sequencing, and the dimension of variety of causes and variations lowest. The results align with [65], in which the authors propose paying more attention to feedback, given its lower assessment. In fact, feedback has already been found to be challenging in the education process [123]. De Klejin [124] proposed a model to support the feedback literacy of students and teachers, which comprises four phases: searching for feedback information, making sense of the feedback information, using the feedback information, and responding to feedback information. These phases are nonlinear and interrelated [124]. The concept of sequence may also be easier to understand than the dimensions of relationships and feedback or cause–effect relationships, which were rated lower in this respect, as expected.

As far as the extended dimensions related to strategic approach orientation, there were statistically significant differences between all dimensions. Students rated the dimension of personal effort highest, including items such as "I concentrate on the effort people put into their work", "I think that lasting change relies on personal effort and motivation", and "I think people who do not get their desired results/outcomes did not work hard enough." According to Gray and Mannahan [125], students connect personal effort with academic achievement, as well as other factors such as liking the teacher, liking the subject, and natural ability. Due to the emphasis on personal effort, it is to be expected that reliance on authority (example: "I think the leaders of the organization have the best ideas") was rated lower in this study. Depending on authority can also be an obstacle to developing one's own strategies and working methods. In addition, modern approaches to education are changing and becoming more child-centered, moving away from traditional authority-based models. Educators are embracing diversity and adapting to different kinds of children in this respect, so that "blind" following of authority is no longer prevalent and innovative approaches are given more weight [126].

4.2. Pre-Service Preschool Teachers' Attitudes Toward Stimulating Higher-Order Thinking Skills in Relation to Systems Thinking

This subsection answers RQ2, which deals with pre-service teachers' attitudes toward teaching methods that aim to promote HOTS and how these attitudes might affect their systems thinking. The rating of items was mostly above average, which indicates that the teachers generally consider stimulating HOTS in children to be important and have a rather positive attitude toward it. This supports the findings of Aisyah et al. [48], who also found that in order to promote HOTS, most preschool educators provide different contexts in which children can develop HOTS and optimize situations for the purpose of promoting HOTS. The importance of HOTS was shown by Frausel et al. [127], who established a link between higher-order thinking talk and subsequent higher achievement in HOTS in elementary school. On the other hand, the dimensions of perceived student ability and anxiety were rated lower than the average. Given the items "I think that 'weak' students cannot handle assignments that require higher-order thinking" and "I think that most assignments that require higher-order thinking are too difficult for 'weak' students", pre-service teachers did not see much point in developing HOTS for less gifted children. This could be because preparing such activities is more demanding and requires a lot of energy, which is also related to the dimension of anxiety [128]. For the items in the anxiety dimension, which mainly relate to feelings of discomfort when preparing tasks, activities, and discussions that require HOTS, pre-service teachers indicated lower agreement that they do not experience feelings of anxiety when preparing HOTS activities.

The results show that there is a relationship between certain dimensions of HOTS stimulation and systems thinking; namely, that pre-service teachers who scored higher in the areas of self-efficacy and perceived ability and lower in anxiety rated their systems thinking higher. Pre-service teachers who rated their self-efficacy higher, i.e., they noted that they were able to pose questions to stimulate HOTS, prepare and instruct tasks to stimulate HOTS, etc., also rated their systems thinking skills higher. This is a logical consequence considering the close relationship between HOTS and systems thinking [46] and the connection between the positive influence of mastering beliefs and actual performance, as claimed by Brauner [129], who studied the latter in STEM subjects.

Pre-service teachers who believed that activities that require HOTS are also suitable for weaker children and that they can also develop HOTS also rated their systems thinking higher. The perception and understanding of children's needs and how to stimulate HOTS require a broader understanding in order to identify patterns and relationships and recognize how various factors influence children's learning and development, which is consistent with the theory of systems thinking [3,34]. Anxiety is seen as a mental and physical state of negative expectation, and systems thinking helps to reduce it by being able to understand and manage complex situations [3]. The items in the anxiety dimension refer to the teachers' feelings of being stressed, anxious, and tense when guiding children through assignments, questions, and open-ended discussions to stimulate HOTS. In other words, pre-service teachers who reported higher levels of systems thinking did not report feeling tense, uncomfortable, or stressed when stimulating HOTS by preparing activities, asking questions, etc. This is to be expected, as both HOTS and systems thinking are interdisciplinary and require effort and an understanding of multiple perspectives and aspects [2,3,34]. In this regard, it is important to be aware of the interdependence of content when stimulating HOTS and systems thinking.

4.3. Pre-Service Preschool Teachers' Engagement in ICT and DTE Course Enhanced by Digital Tools

The following describes the engagement of pre-service preschool teachers in the DTE course supported by ICT and digital tools, and specific dimensions of engagement that influence ICT-enhanced systems thinking (RQ3). At all levels of engagement that were reviewed, pre-service teachers generally rated engagement above the mid-point of the scale in the technology-enhanced DTE course, but differences emerged in their reporting of emotional and aesthetic engagement. Emotional engagement items addressed the excitement, enjoyment, or boredom regarding activities related to using ICT, while aesthetic items referred to the awareness of creative and interpretive processes and integration of an aesthetic vision in working with ICT and digital tools. Engagement is seen as an important factor, providing a unique insight into student satisfaction. In his research, Deng [130] showed that emotional engagement is the most important factor influencing learner satisfaction in massive open online courses.

High emotional engagement when working with digital tools and ICT could be related to self-concept with regard to ICT, which was generally reported to be above the mid-point of the scale in [65]. The exciting, satisfying component of emotional engagement can also be affected by the difficulty of the task and further optimal experiences with ICT [15,62], while lower aesthetic engagement would not be expected when working with digital tools and ICT, given the preschool teachers' general perceived importance of aesthetics. In contrast, it is likely that they suppressed or did not pay as much attention to the aesthetic component given the nature of the DTE course, which emphasizes material knowledge, processing technology, and the functionality of products and systems rather than visual appearance [83]. In addition, preschool teachers tend to be creative, since creativity is known to be crucial in early education [116], and this was probably limited given the tasks they worked on with ICT and digital tools, as the applications they used included pre-made elements, avatars, and scenes. On the other hand, it might be less complicated to produce more aesthetically elaborate products (graphic designs, presentations, etc.) with digital support than with hands-on activities, but this strongly depends on the task, purpose, applications, tools, etc.

It was statistically significant that pre-service teachers who were more cognitively and socially engaged and less aesthetically engaged reported higher levels of systems thinking. In this regard, cognitive and social engagement are expected predictors of systems thinking, as applying systems thinking is extremely challenging for individuals in a complex environment and is easier in a group [115]. Groups with effective collaboration are better able to make decisions because they have more knowledge and experience, along with more opinions and interpretations. This finding is supported by research showing that heterogeneous teams perform better than homogeneous teams. The effective functioning of a group requires the development of group skills, which is considered challenging and can only take place in a group [115]. The aesthetic component is not emphasized in the literature on systems thinking [3,34], so the results align with expectations based on the theory. In contrast, White [131] emphasized aesthetics in the context of systems research and reflection. Paying attention to aesthetics as a method of cognition is important in understanding systems practice. The author presents aesthetics as a means of challenging systemic thinking through what he calls critical imagination, a way of looking at the emotional and symbolic aspects of decision making and organization in complex environments [131].

4.4. Pre-Service Preschool Teachers' State of Flow in the Technology-Enhanced DTE Course

This subsection addresses RQ4, which deals with the perception of flow among pre-service preschool teachers engaging in a technology-enhanced DTE course. In addition, the components of flow that may impact their development of systems thinking skills are described. Pre-service preschool teachers rated the state of flow in relation to the use of ICT in the DTE course above average, indicating they did enter the flow state. The autotelic dimension (item example: "The experience left me feeling great") was rated highest, followed by the balance between challenge and skills and concentration on the task (item example: "I had total concentration"). Transformation of time was rated lowest, although still above average. The autotelic experience is closely related to digital entertainment such as games [67], which could be linked to certain tasks that the teachers carried out using ICT as part of the DTE course, and a sense of fun/play in game-based learning (e.g., using Scratch and Scratch Junior for programming, a stop-motion video application to create animations, or Tinker Cad for 3D modeling) [70].

The low score for the time transformation dimension (examples include "The way time passed seemed to be different from normal" and "Time seemed to alter") can be explained by the fact that the exercises and lectures always lasted a maximum of 90 min [83], and pre-service preservice teachers did not interact with ICT the whole time because the introductory part, the explanation of the theory, the instruction, or other preparations were taking place. The time transformation was therefore probably not as pronounced as it could have been due to the already time-limited activities. Furthermore, the awareness of time limitation can significantly impact the ability to enter the flow state. The less one thinks about time, the greater the chances of getting into flow [66].

In general, it was found that pre-service teachers who achieved a higher state of flow also rated systems thinking higher. Clear goals preserve the objective of complex systems, and receiving feedback is already clearly defined in the theory and, therefore, a common attribute of both concepts [30,62], as well as concentration, which was expected to lead to deeper analysis and synthesis. The results show that the dimensions of merged action and awareness, clear goals, concentration on the task at hand, time transformation, and autotelic experience when using ICT and digital tools had statistically significant predictive value for systems thinking; in contrast to the other dimensions, concentration on the current task and time transformation had negative predictive value. This may be the case because systems thinking refers to a broader view and a bigger picture and does not rely too much on details or so-called tunnel vision, which is certainly the case when there is a high focus on the task. A higher focus during complex tasks was found to lead to higher performance [132], but attention to details could lead to difficulty distinguishing between important and unimportant details, failure to understand how the problem of the task fits into the big picture, blurring of the importance of other factors or perspectives, being able to adapt to changing circumstances, and spending a lot of time on unimportant aspects of a problem, which are detrimental to the overall effectiveness of systems thinking [3,30,35].

Given that the flow state and systems thinking both require engagement and involve complexity and challenge, and place importance on feedback and adaptation [62,64], we would expect this dimension of systems thinking to have significant predictive validity. This relation should be investigated further, as the feedback dimension was poorly developed in the sample of pre-service preschool teachers [65].

4.5. Impact of the State of Flow on Pre-Service Preschool Teachers' Performance Mediated by Systems Thinking

In the following we answer RQ5, which refers to the influence of flow on the performance of pre-service teachers when mediated by systems thinking. Regarding the flow state as it related to the ICT-enhanced DTE course, it had no significant effect on the final exam score (indicating technological and engineering literacy), but it had a significant effect on systems thinking, which in turn had an effect on the final exam score. Thus, the state of flow related to ICT had an indirect effect on the assessment of DTE, and its mediator was systems thinking.

The effect of flow on systems thinking when using ICT aligns with the literature, which suggests the need to support systems thinking with ICT and other digital tools [32,43].

In the educational setting, achieving a flow state can enhance the learning experience by fostering deep engagement and sustained attention. This relationship between flow state and task performance has been documented, indicating that individuals who experience flow are more likely to perform tasks effectively and efficiently [15,62].

Furthermore, systems thinking, defined as the ability to understand and analyze complex systems by recognizing interconnections and patterns, is crucial for developing comprehensive problem solving skills [30]. The literature suggests that ICT and digital tools can significantly enhance systems thinking by providing interactive and dynamic learning environments [32,43]. In addition, the relation between systems thinking and ICT has already been investigated. Systems thinking improves students' self-concept regarding ICT [65], which is related to their confidence in using digital tools.

The study's findings suggest that the flow state experienced during the ICT-enhanced DTE course indirectly affected the final exam scores through its impact on systems thinking. This implies that while flow itself may not directly enhance technological and engineering literacy, it fosters a mindset conducive to systems thinking, which in turn positively influences academic performance [62]. This mediation effect underscores the importance of integrating systems thinking into educational curricula to effectively harness the benefits of the flow state. This is particularly relevant in the context of technology and engineering education, where systems thinking is considered a fundamental practice [1]. Additionally, the combination of systems thinking with project-based learning has proven effective for developing an understanding of engineering problems among pre-service teachers, even those with limited prior knowledge of engineering and technology content [45]. Systems thinking has also been shown to improve skills related to engineering and technology and is considered an important complement to traditional teaching methods [39,41,42]. This highlights the need for educational strategies that not only engage students but also develop their systems thinking, thereby improving their overall academic performance.

The results of this study underline the important role of systems thinking in improving educational outcomes in sustainability. The study shows that higher levels of cognitive and social engagement of pre-service preschool teachers in a technology-enhanced DTE course led to improved systems thinking skills. This is a critical competency for addressing sustainability challenges as it equips future educators with the ability to think holistically about complex, interrelated issues such as environmental degradation and social equity [84].

Furthermore, using flow theory as a framework for analyzing engagement in the study provides important insights into how to optimize the educational environment for sustainability education. When pre-service teachers experience a flow state characterized by deep immersion and focused engagement, they are more likely to develop the systems thinking skills they need to promote sustainable practices in their future classrooms. This research therefore not only highlights the potential of technology-enhanced learning to improve systems thinking, but also provides a model for creating immersive educational experiences that promote sustainability.

4.6. Limitations, Implications, and Future Work

As with all research, especially in the field of education, this study has some limitations. The sample studied consisted of students from the Faculty of Education at the University of Ljubljana. The results could be different with a larger sample. It would therefore make sense to include students of this degree program from other universities in Slovenia in the sample. The sample was not analyzed by gender because, due to the nature of the work, most preschool teachers are women. Another limitation of the study can be seen in the experimental design, as it was a pre-experiment. To provide solid evidence on experimental results in future study, we will use control group, pre-posttest research design and randomization to reduce biases. An important aspect of the research is also the use of self-assessment questionnaires, which do not necessarily reflect the actual situation, thus more objective methods of measuring characteristics would have to be used. The latter is especially true for assessing the level of systems thinking, in contrast to flow/optimal experience, engagement, and attitude toward stimulating HOTS, where self-assessment questionnaires are useful.

Additionally, in research attention must be paid to the quantity of measurement tools, because when many questionnaires are used, participants may become saturated and not assess the actual situation, but just complete the questionnaires as quickly as possible. Given the flood of surveys, this is an important factor to consider in further research.

There are also some implications of the study. The findings regarding the mediating role of systems thinking in student performance indicate that while the state of flow does not directly enhance technological and engineering literacy, it fosters a mindset conducive to systems thinking, which subsequently positively influences academic performance. This mediating effect highlights the critical importance of incorporating systems thinking into curricula to effectively leverage the benefits of the flow state. The flow state associated with ICT and DTE courses indirectly enhances assessment outcomes by promoting systems thinking. In conjunction with other models for integrating ICT and digital technology, flow has been demonstrated as a suitable complement to systems thinking, enabling the achievement of positive outcomes through appropriate application. This underscores the need for educational strategies that not only engage students but also cultivate their systems thinking skills, thereby enhancing their overall academic performance. Through synergies between systems thinking and flow theory, educators and instructional designers can create technology-enhanced learning environments that promote the flow state and enable learners to engage and achieve in their studies to develop 21st-century sustainable skills.

There are a variety of factors (cognitive, behavioral, motivational, emotional, contextual, cultural, etc.) in educational environments that influence the educational process, and all actors involved. It would be advisable to use the findings of this study to improve the learning process to achieve a flow state in multiple dimensions, improve systems thinking, and increase student performance. It would also be advisable to investigate students' preferences for subjects, their attitudes toward subjects and topics, and their views on the importance of subjects in pre-school education. As Kartal and Taşdemir [133] stated, female pre-service teachers should be encouraged to develop a positive attitude toward engineering and technology. In addition, it would be advisable to investigate students' self-efficacy, self-direction, self-regulation, etc., when new approaches are introduced. As mentioned in previous research [65], more attention needs to be paid to feedback. In addition, the lack of development of relational understanding should be considered and an optimal environment to improve the learning flow should be found to achieve better learning outcomes. As the study was a pre-experiment prior to the main study, we plan to improve the learning–teaching model to promote technological and engineering literacy using the technology-enhanced systems thinking approach. Our enhancement of the learning mode will be extended using robotic sets suitable for early coding in kindergarten, with the goal of improving preschool teachers' understanding of functional dependencies, relations, and feedback as critical dimensions of systems thinking. We also aim to include VR content to achieve a better time transformation, and thus a flow state [66], in order to develop emotional engagement and empathy as important parts of the design of the DTE course.

5. Conclusions

Finally, we present the most important results of the pre-experiment. It was found that there is still room for improvement in the systems thinking of pre-service preschool teachers, particularly in terms of feedback and understanding interrelationships. With regard to the attitude toward stimulating HOTS, it was found that preschool teachers had a rather positive attitude. A predictive value for systems thinking was shown for the component of self-efficacy and perception of children's abilities. Pre-service preschool teachers who know children better, recognize their needs, adjust their level, and feel that tasks that stimulate HOTS are not frustrating or too challenging for weaker children have more developed systems thinking according to their self-assessment. The level of systems thinking was also rated higher by teachers who did not feel uncomfortable, stressed, or frustrated when preparing activities and discussions to stimulate HOTS.

Pre-service teachers engaged in the targeted ICT-enhanced DTE course at all levels showed greater engagement with ICT and digital tools at the emotional level and slightly lower engagement at the aesthetic level. The predictive value of such engagement for systems thinking was evident in cognitive, social, and aesthetic engagement, with the latter being in a negative direction. Pre-service teachers who were more cognitively engaged (e.g., linking knowledge, understanding errors) and socially engaged (understanding others' ideas, collaborating with others, etc.), and less aesthetically engaged (e.g., contributing an aesthetic vision) with ICT activities reported higher systems thinking. In addition, entering the flow state during activities with ICT was assessed, and it was found that autotelic experience led to flow most frequently, as opposed to the time dimension, suggesting that teachers did not perceive time too differently while using ICT in the DTE course. The predictive validity of the flow dimensions in relation to systems thinking was shown here to be in a positive direction for clear goals, merged action and awareness, and autotelic experience, while teachers who were more concentrated on the tasks and perceived time differently during the ICT tasks rated systems thinking lower.

Lastly, the path analysis pointed to the mediating value of systems thinking between the flow state in the use of ICT and learning performance in DTE. This indicates the useful value of ICT-enhanced systems thinking for the development of learning performance in design, engineering, and technology education. In an increasingly digital world, the convergence of systems thinking, and technology-enhanced learning offers the opportunity to revolutionize educational experiences. This research underscores the applicability of flow theory to exploring the synergy between systems thinking and technology-enhanced teaching. It offers a holistic approach to fostering engaging, immersive, and impactful learning environments and suggests the need for further exploration of systems thinking among students who are not as engaged in technology-enhanced DTE courses to identify factors for suitable approaches that promote effective education for all. Additionally, the conclusions of this study confirm its contribution to sustainable education by demonstrating that the integration of systems thinking and flow theory into technology-enhanced learning can significantly improve the engagement and learning outcomes of pre-service preschool teachers. This is particularly important in the context of sustainability, as systems thinking is a critical skill for understanding and addressing global challenges. By demonstrating that flow experiences in educational contexts enhance systems thinking, this research provides a foundation for developing sustainable and resilient technology-supported teaching strategies that are both engaging and effective in promoting sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16219319/s1, Students' perceptions of and experiences with the DTE course.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the author. The data are not publicly available due to privacy issues.

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