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Review

Empowering Vocational Students: A Research-Based Framework for Computational Thinking Integration

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Abstract: Vocational Education and Training (VET) faces significant challenges in equipping individuals for modern workplaces, which increasingly require digital literacy and Computational Thinking (CT) skills. This paper addresses the imperative of integrating CT into VET programs and outlines key research questions. Our methodology primarily involves a systematic literature review, resulting in the identification of 29 relevant papers. Through qualitative content analysis, we develop a CT integration framework that connects CT practices and integration elements to the engineering design process, while highlighting the VET context. Arguably, the innovative aspect of this framework lies in its core dimensions of harnessing computational power for enhanced efficiency. Raising the question of whether computers can optimize the efficiency and effectiveness of specific tasks is paramount for addressing challenges in technology-rich environments. Therefore, this inquiry merits unwavering attention at every stage of the process. The proposed framework provides educators with a structured approach to identify integration opportunities and help prepare students for multifaceted vocational careers. Furthermore, other key findings underscore the inherently interdisciplinary nature of VET, the growing demand for STEM competencies, and the transformative potential of CT integration. Implications emphasize the need for further research, supportive policies, and practical CT integration. Despite limitations, this study strongly advocates for CT integration, empowering VET students for success in the contemporary workforce.

Keywords: computational thinking; computing literacy; STEM; vocational education

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1. Introduction

In an ever-evolving and highly competitive society, job requirements are undergoing significant shifts to keep pace with rapid technological advancements. Developments in genetics, artificial intelligence, robotics, nanotechnology, and biotechnology, among others, are reshaping the global economy, marking the advent of what the World Economic Forum [1] has termed the Fourth Industrial Revolution.

Within this fast-changing landscape, industry expectations have soared. Being technically and technologically educated today is no longer sufficient to secure future job success [2]. Workers must possess the ability to learn swiftly, adapt, and grasp intricate new technologies [3]. Vocational Education and Training (VET), which equips individuals to enter the workforce, must therefore also be agile and forward thinking in response to these evolving demands. Those entering the labor market require immediate job skills in addition to competencies commonly referred to as 21st-century skills [4,5], but implementing 21st-century skills competences in VET programs is not without challenges [6].

Regarding technological advances and changing job demands, the ability to solve problems in technology-rich environments has been identified as a crucial skill [5–7]. Moreover, as the technologies that drive this revolution are predominately digital in nature (e.g., The Internet of Things, big data, cloud computing, artificial intelligence) [8,9], education has shifted its attention to the skills required to understand these technologies and solve problems in technology-rich environments. This set of digital skills can be grouped under the term computational thinking (CT) and are gaining importance in many national curricula [10,11]. Yadav et al. [12] argued that CT is an inseparable part of digital literacy and should be an important competence domain within VET, but much of the educational research concerning this 21st-century skillset fails to address the specific challenges associated with VET. In our preliminary literature search, we explored several databases, including ERIC, Web of Science, and ACM Digital Library, using the following query: ("Vocational education" OR "VET" OR "Career education") AND (Publication Type: "Journal Articles"). While each of these search terms generated a substantial amount of material when used individually, we observed that combining these specific terms resulted in a notably limited number of publications. Although in the last decade there has been an enormous growth in interest and research on CT in education [10], attention on CT in VET is lacking [10,12]. Moreover, previous research has shown that VET-trained adults score lower on the ability to use digital technology, communication tools, and networks to acquire and evaluate information, communicate with others, and perform practical tasks [2]. Given the role of computing in VET occupations, the competence to solve problems in technology-rich environments is essential.

The literature indicates, however, a growing trend in fostering students' CT in Science, Technology, Engineering, and Mathematics (STEM) [10,13,14]. An integrated STEM approach can serve as a valuable guide for incorporating CT into VET. Internationally, STEM education has garnered significant attention from education ministries due to the recognition of STEM-related competencies as being crucial for economic growth and global workforce competitiveness [15]. Furthermore, STEM education exhibits a natural synergy with VET [16], particularly in technical VET branches such as industrial automation and mechatronics. Even non-technical VET branches intersect with STEM disciplines. For instance, healthcare incorporates medical technology, logistics management utilizes data analysis, and environmental sciences apply scientific principles. Moreover, STEM education is defined as inclusive of society as a whole, aiming not only to provide technical skills for occupations in demand (such as electricians and data scientists) but also to enhance the foundational capacity for life and work in general. As indicated by Siekmann [17], "STEM education aims to improve scientific and technical literacy for all" (p. 6).

In response to these challenges faced by VET in preparing individuals for modern workplaces, where digital literacy and CT skills are increasingly crucial, this paper aims to address a gap in the attention given to CT within the realm of VET. The overarching problem lies in the need for effective integration of CT into VET programs to equip students for multifaceted vocational careers in technology-rich environments. To tackle this, this study aims to explore the intersections and potential benefits of CT, particularly as cultivated within STEM education, and its practical application and integration into the VET context. This serves two purposes: firstly, to provide educators with a structured approach for identifying integration opportunities and preparing students for the demands of contemporary vocational careers; secondly, to shed light on the inherently interdisciplinary nature of VET, the increasing demand for STEM competencies, and the transformative potential of CT integration. To achieve these aims, this study employs a methodology primarily grounded in a systematic literature review.

In the upcoming sections, we will begin by providing a clear description of the concepts of VET, STEM, and CT. Following this foundation, we will proceed to formulate the research questions that will guide this study.

1.1. Vocational Education and Training

VET is fundamentally concerned with equipping individuals with the knowledge and skills necessary for success in the workforce [18]. While terms such as VET, technical-vocational education and training (TVET), and career and technical education (CTE) have been used interchangeably [19], this study specifically adopts the term "VET". It is a comprehensive concept encompassing a diverse range of educational and training programs meticulously designed to prepare individuals for specific careers or trades, while TVET is a more specialized subset that focuses on technical and vocational skills development. The choice of terminology may vary by region and educational system, but both VET and TVET are important for preparing individuals for careers in specific fields and industries. Despite the global recognition of VET, classifying VET programs can often be challenging [20,21]. Each country is shaped by its unique socio-cultural, political, technological, and economic context, all of which profoundly influence how VET is perceived and structured [18]. Acknowledging the potential for a broad interpretation of the description, we opt to narrow our focus to secondary education vocational programs, specifically those falling within the scope of ISCED [22] levels 2 (lower secondary education) and 3 (upper secondary education), aligning with the domain of pre-higher education VET. While the specific programs may exhibit variations based on regional and national educational frameworks, examples of secondary education vocational programs that frequently align with ISCED levels 2 and 3 include CTE. These programs offer a blend of academic and technical coursework, providing students with practical, hands-on training in specific vocational fields. Another example is Vocational High Schools, where the focus lies in delivering vocational education alongside traditional academic subjects, thereby preparing students for diverse careers across various industries [18].

1.2. STEM Education

STEM, an acronym for the fields of science, technology, engineering, and mathematics, is often used to underline the importance of these four disciplines and to emphasize their inherent interconnectedness. Although the importance of STEM is internationally recognized [10], the term itself does not have a long history. The STEM education movement came about at the beginning of the 1990s in response to a mounting concern over the growing skill gaps and their impact on economic competitiveness. These concerns proved valid as modern economies still have a rising demand for qualified researchers, technicians, and other STEM-related professionals, and not enough students choosing a STEM-related profession or career [23,24]. Thus, one major reason for advocating STEM education is to prepare the workforce for the future and to ensure economic growth [15,23].

Given the significance of STEM, it has found its way into educational policies and practices, contributing to a dynamically evolving landscape of research [10]. This however is complicated by the lack of consensus on what constitutes as STEM education. From a broad perspective it includes education in the individual disciplines of STEM (i.e., science, technology, engineering, and mathematics), as well as interdisciplinary or cross-disciplinary combinations of these disciplines [25]. Seeking coherency in STEM education, Kelley and Knowles [26] defined integrated STEM education as “the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning”. Several other studies [27,28] also describe integrated STEM pedagogy to be based on: real-world, authentic contexts; student-centred pedagogies (e.g., inquiry-based and problem-based learning); the development of 21st-century competencies (e.g., creativity, collaboration, communication, and critical thinking); and explicit connections between the STEM disciplines.

Where STEM education in the past focused predominantly on improving science and mathematics as isolated disciplines [29] with little integration and attention given to technology or engineering [30], it has evolved into a meta-discipline, an integrated effort that removes the traditional barriers, and instead focuses on innovation and the applied process of designing solutions to complex contextual problems using current tools and technologies [15,28].

STEM education and VET share the common goals of enhancing employability and practical skills development but differ in focus and content. STEM emphasizes a broad understanding of scientific and technical disciplines, spans various educational levels, and is offered in both theoretical and practical contexts [15]. VET, on the other hand, concentrates on specific trades or industries [20]. Both fields recognize the importance of hands-on learning, problem-solving, and labor market alignment, with an emerging trend of integrating STEM principles into VET programs to bridge the gap between general and vocational education [2,31].

1.3. Computational Thinking

The world is presently witnessing a transformative wave of industrial revolution, primarily catalysed by the rapid development and diffusion of digital technologies [8]. Scholars such as Wing [32] have long emphasized that a comprehensive grasp of these emerging technologies necessitates the cultivation of CT. Wing [33] defines CT as a universally applicable mindset and skill set essential for problem-solving, system design, and understanding human behaviour, rooted in fundamental computer science concepts. This perspective has gained widespread acceptance, positioning CT as a vital skill for the twenty-first century [34].

While the significance of CT is widely acknowledged, numerous definitions and conceptualizations exist, leading to ongoing debates and variations in its boundaries [10,35,36]. To address this complexity, Shute et al. [35] synthesized the CT literature and identified six core facets of CT. They defined CT as “the conceptual foundation required to solve problems effectively and efficiently, algorithmically, with or without the assistance of computers, and with solutions that are reusable in different contexts”. This emphasis on problem-solving aligns with Wing’s perspective [33] and the viewpoint of other scholars, e.g., [10,12,14,36–38] who consider CT as a comprehensive competence extending beyond coding and programming. While computer programming plays a role in fostering CT through activities involving abstraction, algorithmic thinking, and problem decomposition, scholars argue that CT transcends coding and programming and should be applied across diverse fields [12]. In the context of CT and problem-solving, there exists some ambiguity, as these two concepts are often perceived as interchangeable or overlapping, e.g., [39–41]. However, research has consistently shown that these are distinct and separate concepts that should be assessed independently [42–44]. Conversely, some research argues that CT can be viewed as a subset of problem-solving, particularly within a technological context [45].

Emerging from the recognition of CT versatile problem-solving and analytical skills [33], a notable shift towards integrating CT into disciplinary education, particularly within the STEM fields, has become evident [10,13]. This evolution suggests that CT’s cognitive framework holds value across diverse subjects, transcending its initial confines within computer science. The integration of CT into STEM education is a dynamic and continually evolving domain, as underscored by recent research findings, e.g., [10,13,14,36]. For instance, Paltz et al. [36] synthesized the relationship between CT conceptualizations found in the literature, highlighting five seminal articles, i.e., [33,46–50], connecting CT to the problem-solving process. Similarly, Wang et al.’s recent literature review [13] on CT integration in STEM education emphasized problem-solving skills as the driving force for CT development in STEM, while noting that programming served as a primary means of learning about CT in STEM. Additionally, they identified Weintrops et al.’s [37] taxonomy, which frames CT as component practices particularly popular in science education. However, they emphasized the need for further research to operationalize CT in other STEM disciplines, such as exploring its relationship with design thinking in engineering education, strengthening the proposal made by Li et al. in 2020 [10] that CT should be approached as a discipline-specific thinking practice.

1.4. Purpose and Research Questions of This Study

In an era characterized by continuous technological progress, the contemporary workforce is experiencing significant transformations. VET plays a crucial role in empowering individuals with the necessary skills and competencies to navigate this ever-evolving landscape. However, there exists a noticeable gap in the attention given to CT within the domain of VET. Aligned with Wang et al.’s call for further research to operationalize CT in broader STEM contexts [13] and enhance its integration into VET, our study aims to explore the intersections and potential advantages of CT as nurtured within STEM education. Our goal is to develop a framework that allows for the flexible integration of CT into VET programs. The following research questions guide our inquiry, helping us to navigate and comprehend the multifaceted aspects of our study:

1. How is CT and STEM education related to VET, and which connections can be identified?
2. What significant points of intersection and potential advantages can be identified between CT as nurtured within STEM education and its practical application and integration within VET?
3. Can these insights inform the development of a comprehensive framework for CT integration within an integrated STEM curriculum in VET programs?

2. Materials and Methods

2.1. Search Strategy and Literature Search

To find relevant articles, databases ERIC and Web of Science and the ACM Digital Library were consulted. The exploration of the databases took place by means of Boolean search strings (see Table 1). To answer our research questions, we focused on peer-reviewed journal publications that bridged the following concepts: "computational thinking", "STEM", and "VET". These keywords were not limited to the title or abstract, to include all potentially relevant studies. The application of these search phrases resulted in a total of 837 hits (search conducted in August 2023). To maintain the quality of the review, we iteratively reduced the initial sample of studies by removing duplicate records found from the three databases.

Table 1. Overview of the literature search hits.

Search Phrase	Sources			Total Unique Papers
	ERIC	**Web of Science**	**ACM Digital Library**	
Computational thinking AND STEM AND (VET OR vocational education, OR career education)	0	1	3	3
Computational thinking AND STEM	128	235	112	502
Computational thinking AND (VET OR vocational education, OR career education)	5	2	6	9
STEM AND (VET OR vocational education, OR career education)	209	73	27	269

Our approach to identifying and selecting relevant articles follows the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [51]. After eliminating duplicate articles (n = 118), we carefully screened the remaining pool of articles (n = 783) through two distinct screening phases. These phases were conducted in adherence to defined inclusion and exclusion criteria, which can be found in Table 2. These steps were essential to ensure the chosen articles were well-suited to address our research questions and uphold the highest standards of quality and relevance within the academic literature that constitutes our review.

For this systematic literature review, we include peer-reviewed articles published in English from the year 2006 onwards. This decision is underpinned by the pivotal work of Wing in 2006, wherein she articulated a compelling call for the exploration of CT. By commencing our review from this significant juncture, we seek to encapsulate the trajectory of research that burgeoned in response to Wing's influential call. To be eligible for inclusion, papers should address CT with a comprehensive perspective beyond just coding or programming. Additionally, we consider papers that concentrate on integrated STEM education. Furthermore, we assess papers on vocational education, but only if they directly relate to secondary education, specifically pre-vocational and vocational education, corresponding to ISCED levels 2 and 3. Exclusion criteria apply to papers published before 2006, those not in the English language, non-peer-reviewed sources, higher education contexts, research that narrowly focuses on coding without a broader view of CT, and studies that do not relate to integrated STEM education within the pre-higher education context or lack a clear connection to secondary education.

Table 2. Inclusion and exclusion criteria used in the literature review.

Criteria Category	Inclusion Criteria	Exclusion Criteria
Publication Year	Papers published from 2006 onwards.	Papers published before 2006.
Language	English-language publications.	Papers not in the English language.
Peer-Reviewed	Peer-reviewed articles.	Non-peer-reviewed sources, such as conference abstracts, theses, and reports.
Educational Level	Pre-higher education.	Higher education contexts (above ISCED level 3).
Computational Thinking (CT)	Papers addressing a comprehensive perspective of CT, not limited to coding or programming.	Papers exclusively focused on coding without a broader view of CT.
Integrated STEM Education	Papers focused on integrated STEM (science, technology, engineering, and mathematics) education within pre-higher education settings.	Research not related to integrated STEM education within a pre-higher education setting.
Vocational Education	Papers relating to vocational education and its connection to secondary education, specifically pre-vocational and vocational (ISCED 2 and 3).	Vocational education research that lacks a direct link to secondary education at ISCED levels 2 and 3.

In the initial phase of our screening process, which involved an examination of the titles and abstracts of the initially identified papers, a total of 716 papers were excluded from further consideration. This curation was guided by specific criteria to ascertain the alignment of the selected papers with our research objectives. Twenty-five papers were excluded due to their focus on higher education, while 614 fell short of the intersection criteria, as many were limited in focus to just STEM, VET, or CT without fully addressing the integrated perspective we sought. However, among these exclusions, notable clusters of focus were observed within the intersection of the terms STEM and CT, with 11 primarily centered on assessment aspects, 37 addressing issues of equity, and 23 exploring the perceptions and perspectives of educators. Similarly, in the intersection of STEM and VET, 30 papers predominantly emphasized students' decision-making processes in educational choices, and 27 tackled equity-related matters. While these areas are noteworthy for further exploration, they do not constitute the specific focus of the current research. As a result of this screening process, a total of 67 papers were identified for further screening of the full paper.

In the second phase of our study, we conducted a screening process to determine eligibility, resulting in the exclusion of an additional 38 papers from our analysis. Among these, two papers were disqualified due to the unavailability of full text in the English language. Furthermore, six of the eliminated papers primarily centered on teacher perceptions and training, which did not align with the primary focus of our research. The remaining 30 papers were excluded because they either lacked a direct connection to the themes of Vocational Education, Integrated STEM Education, or did not provide a comprehensive perspective on CT within the context of these domains.

The full process is summarized using the PRISMA framework in Figure 1, illustrating the systematic and methodical approach employed in our paper selection and screening procedure. We identified 29 papers that met our inclusion criteria and were selected for further analysis. The surface characteristics are described in the Section 3.

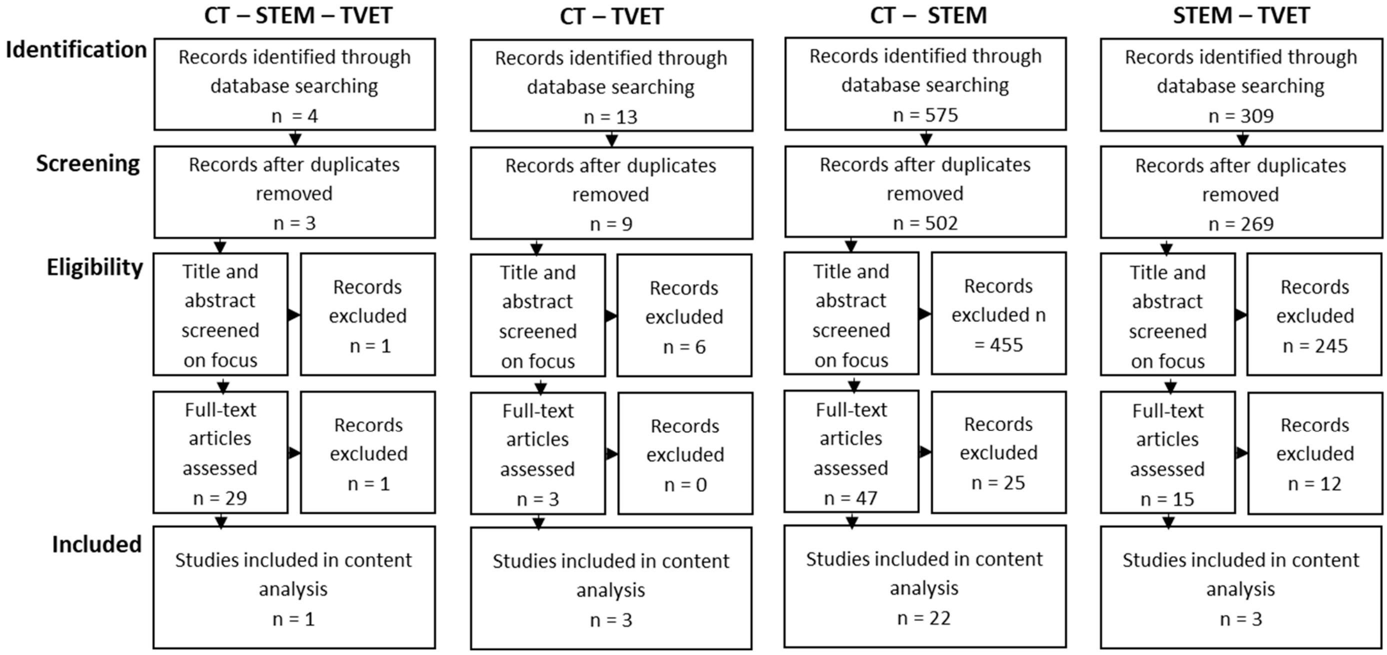


Figure 1. Overview of the search procedure.

2.2. Analysis

To thoroughly address our research inquiries, we conducted a systematic literature review guided by Cohen et al.'s framework [52]. Subsequently, we employed qualitative content analysis as outlined by Neuuendorf [53]. Using specialized coding software, Nvivo (release 1.5), and adopting an inductive coding method by Saldana [54], we extracted the relevant information that aligned with our research questions, enhancing both transparency and the robustness of our study. A detailed breakdown of our coding tree is available in Appendix A. Addressing our first research question, we initially reviewed seven papers to uncover thematic connections between CT and VET, as well as between STEM and VET.

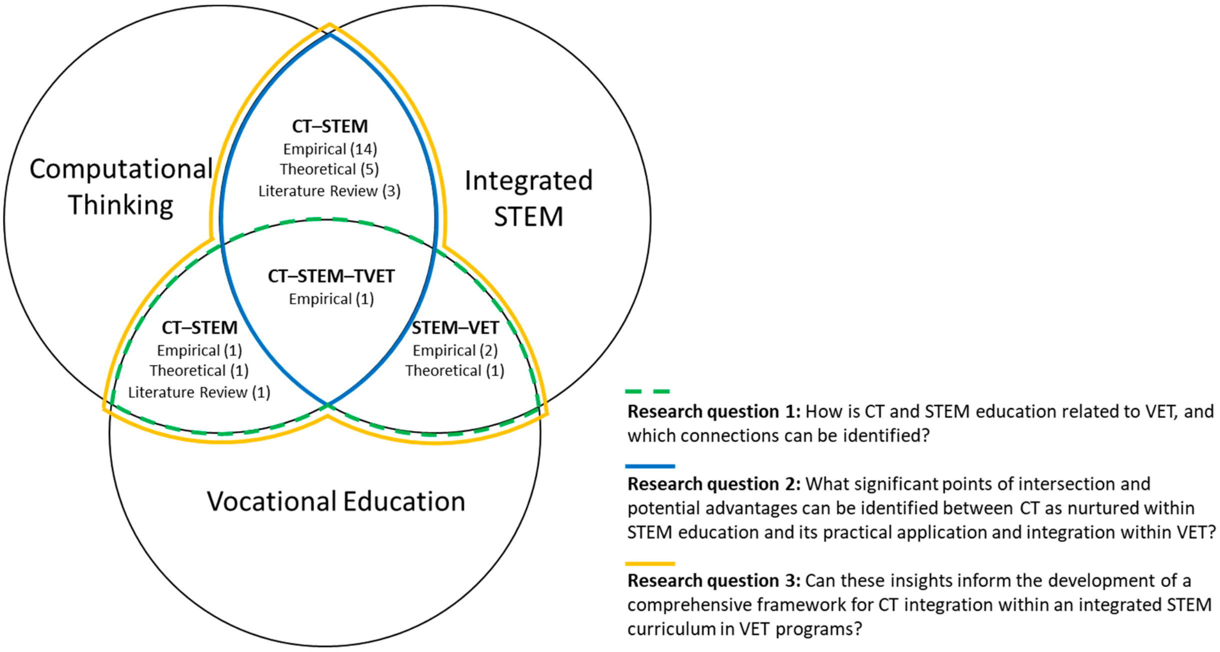
For our second research question, we analyzed the 23 identified papers, focusing on the intersection of CT and STEM education. Our emphasis was on CT–STEM integration practices and frameworks and their potential relevance in VET programs. This approach allowed us to delve deeply into the conceptualizations of CT within the context of STEM and assess its pertinence when integrated into the specific domain of VET. Our reporting of outcomes encompassed both qualitative and quantitative aspects.

To address our third research question, we systematically synthesized the insights obtained from the first two research questions to inform the development of a comprehensive framework for integrating CT into integrated STEM curricula within VET programs. Our objective was to leverage these cumulative insights and knowledge to establish a foundation for a comprehensive framework that facilitates the seamless integration of CT into integrated STEM curricula within the specialized domain of VET programs. Our methodology encompassed a holistic perspective that considered both theoretical and practical dimensions. We aimed not only to identify conceptual linkages but also to unearth practical strategies that bridge the theoretical and pedagogical aspects identified in the first two research questions.

In terms of the robustness of our content analysis, it is important to highlight that the primary coding responsibility was undertaken by a single researcher. To ensure intracoder reliability, we maintained consistency by having the same researcher apply the coding scheme throughout the analysis, emphasizing internal coherence. To assess intracoder reliability, the primary coder reevaluated 8 out of the 29 papers after a two-week interval, maintaining consistency in the coding scheme across both sessions. The percentage agreement between the two coding sessions reached 78%, indicating a substantial level of intracoder reliability [53].

3. Results

In the initial part of the Section 3, we will provide an overview of the papers we withheld. The papers were categorized based on their primary focus within the intersecting areas (see Figure 2).



Research question 1: How is CT and STEM education related to VET, and which connections can be identified?

Research question 2: What significant points of intersection and potential advantages can be identified between CT as nurtured within STEM education and its practical application and integration within VET?

Research question 3: Can these insights inform the development of a comprehensive framework for CT integration within an integrated STEM curriculum in VET programs?

Figure 2. Number of publications by intersection, research questions and type. Results.

Chondrogiannis et al. [55] conducted pioneering research at the crossroads of CT, STEM, and VET with a specific emphasis on agricultural education. Their insightful case study underscored the pivotal role of STEM and CT in nurturing critical thinking, problem-solving skills, and the practical application of knowledge within VET. However, their work also brought to light a significant gap in the integration of STEM and CT into VET curricula, thereby prompting calls for policy reforms and an enhanced focus on teacher training to address this discrepancy.

In the realm of the intersection between CT and STEM, our literature review unearthed 22 papers. Within this corpus, three papers were dedicated comprehensive literature reviews, i.e., [13,14,36], offering valuable syntheses of existing knowledge, while an additional five papers provided valuable theoretical or conceptual insights into this interdisciplinary domain, i.e., [10,38,56–58]. Most of the papers, totaling 14, contributed empirical research findings, further enriching our understanding of the practical implications of CT within STEM contexts, i.e., [59–72].

Within the intersection of STEM and VET, our examination yielded three pertinent papers. Two of these papers were grounded in empirical research, i.e., [31,73]. Additionally, one paper contributed to our theoretical understanding of this intersection, i.e., [74], adding depth to the scholarly discourse on the subject.

Exploring the intersection of CT and VET revealed three noteworthy papers, each approaching the topic from a distinct angle. These encompassed one empirical research paper, i.e., [75], providing valuable real-world insights, one literature review, i.e., [76], which synthesized existing knowledge, and another that adopted a theoretical approach, i.e., [12], further contributing to the theoretical foundations of this interdisciplinary field.

3.1. Research Question 1: How Is CT and STEM Education Related to VET, and Which Connections can Be Identified?

To answer our first research question, we systematically classified and coded the selected papers (n = 7), leading to the identification of several recurring themes. These themes have been documented in Table 3, located below for reference. For a comprehensive overview of our coding process, including the complete code tree, we have included an appendix (Appendix A). Following the categorization of themes, we present a detailed qualitative analysis in this report, shedding light on the insights and intersections discovered within the withheld papers.

Table 3. Identified themes in CT–VET, and STEM–VET intersections.

	STEM	CT
VET	**VET is inherently interdisciplinary**, with STEM integration varying according to specific vocations [55,73].	**CT is a crucial 21st-century skill** applicable to all individuals, including VET students [12,76].
	Society and industry are evolving, resulting in changing VET profiles and an increased demand for STEM-related skills in VET (e.g., Problem solving, Critical thinking, Technological literacy) [31,55,73,74].	**Society and industry are evolving**, resulting in changing VET profiles and an increased demand for CT-related skills in VET (e.g., Problem solving, Digital literacy) [12,55,76].
	STEM-related vocations are in high demand, warranting a qualitative education approach to attract and retain more students [31,73].	Integrating CT can **enhance the VET learning** experience [75,76].

3.1.1. STEM–VET

This section offers a comprehensive exploration of the STEM–VET intersection, focusing on three key themes as outlined in Table 3. Firstly, both Chondrogiannis et al. [55] and Asunda [73] contribute significantly to the STEM–VET intersection by emphasizing the interdisciplinary nature of VET. Chondrogiannis et al. [55] highlight the inherent involvement of all four STEM subjects in agricultural education, underscoring the importance of STEM integration in VET. Asunda [73] recognizes the relevance of VET programs to STEM-related careers, acknowledging that VET encompasses science, mathematics, and technology components to cater to diverse career paths.

Secondly, including Chondrogiannis et al. [55], Asunda [73], Reiss and Mujtaba [74], and Wannapiroon et al. [31] collectively emphasize the overarching theme that societal and industrial evolution is reshaping the landscape of VET. This transformation is accompanied by a growing demand for STEM-related competencies within the VET domain, encompassing essential skills such as problem-solving, critical thinking, and technological literacy. Chondrogiannis et al. [55] highlight the transformative impact of Education 4.0 in addressing educational gaps and adapting to the evolving demands of agricultural careers. Asunda [73] underscores the increasing need for technical and critical thinking skills in the 21st-century workplace, advocating for STEM integration in VET programs. Reiss and Mujtaba [74] delve into the significance of incorporating careers education into STEM, addressing the limitations of non-specific career guidance in VET. Wannapiroon et al. [31] emphasize the necessity for a mindset shift among vocational educators, promoting innovation and interdisciplinary skills, including STEM, to meet the evolving demands of the industry.

Lastly, a pivotal theme on which both Asunda [73] and Wannapiroon et al. [31] converge is the increasing demand for STEM-related vocations, necessitating a qualitative educational approach to attract and retain students in these fields. Asunda [73] cites the Association of Career and Technical Education, highlighting that infusing STEM concepts into VET curricula enhances students' STEM literacy and encourages them to consider STEM-related careers. In alignment with this perspective, Wannapiroon et al. [31] argue that the hands-on, skill-oriented nature of STEM education makes it a fitting choice for vocational education. They propose that this approach benefits not only foundational subjects but also job-specific ones, reinforcing the notion that a high-quality, pragmatic STEM-focused education better prepares vocational students for successful careers in STEM fields.

3.1.2. CT–VET

This section delves into the intersection of CT and VET through three key themes (see Table 3). Firstly, CT emerges as a vital 21st-century skill with relevance even in VET contexts. Yadav et al. [12] stress the significance of introducing CT concepts early in education, advocating for its integration, including Information Technology and Computer Science, from primary school onwards. Additionally, Pöllänen and Pöllänen [76] shed light on Finland's National Core Curriculum, where technology integration transcends disciplinary boundaries, highlighting the cross-disciplinary importance of CT in education. These findings underscore CT's role as a universal 21st-century skill, accessible across all educational levels, from primary education to VET, to prepare individuals for an increasingly digital world.

Secondly, the evolving societal and industrial landscape reshapes the demands placed on VET, accentuating the need for CT-related skills. This theme resonates across multiple papers. Chondrogiannis et al. [55] emphasize CT's critical role in addressing the requirements of Agriculture 4.0, characterized by digitalization, IoT, robotics, and AI. They also highlight the synergy between CT, STEM, and Agricultural Education and Training (AET), enhancing the problem-solving skills crucial for future agricultural careers. Yadav et al. [12] point out that individuals with only VET qualifications may find themselves ill-prepared for the rapidly changing 21st-century job market. This drives the imperative for VET programs to incorporate CT and related skills, equipping students with essential technical expertise. Pöllänen and Pöllänen [76] argue that CT is indispensable in the 21st century due to the ubiquity of information, technology, and automation in the workforce. They stress the importance of educational systems in training students with adaptable technical competencies. Additionally, they highlight emerging technologies, digital design tools, and 3D printing, underscoring the necessity of integrating CT into education to bridge the divide between traditional skills and contemporary industry demands.

Lastly, the integration of CT into VET enriches the learning experience, as evidenced in two research papers. Pöllänen and Pöllänen [76] emphasize the role of technology, programming, and hands-on applications in fostering CT-based learning experiences. Their study illustrates how specific tools can cultivate CT skills within crafts and design education. In a different context, Souza et al. [75] conducted a study on educational robotics in a Brazilian technical high school, showcasing improvements in student performance as a result of CT integration.

3.2. Research Question 2: What Significant Points of Intersection and Potential Advantages Can Be Identified between CT as Nurtured within STEM Education and Its Practical Application and Integration within VET?

To address our second research question, we analyzed the 23 selected papers. We did this by systematically categorizing and coding the information they contained. This process helped us identify recurring themes. After categorizing these themes, we provide a detailed qualitative analysis in this report. Additionally, we outline the integration frameworks and practices we identified to give you a complete picture of our findings.

Table 4 presents an overview of the main eight themes (i.e., Problem-Solving Skills, Data Analysis, Modeling and Simulation, Technology Integration, Future Workforce Preparedness, Computer Science, and Pedagogical benefits) identified during the coding process (see Appendix A) and highlights the relationship between CT and STEM education.

Table 4. Identified themes in CT–STEM intersections.

	STEM
CT	**Problem-Solving Skills:** CT emphasizes problem-solving, which is highly relevant to STEM fields. Both CT and STEM educations promote the critical thinking and analytical skills required for addressing complex real-world challenges [13,14,38,57,64,65,69,71,72].
	Data Analysis: STEM subjects often involve data collection, analysis, and interpretation. CT skills, such as data practices and pattern recognition, are valuable for processing and drawing insights from scientific data [13,14,38].
	Modeling and Simulation: STEM education frequently employs modeling and simulations to understand complex systems. CT can support these activities by providing students with the ability to create computational models, simulate real-world scenarios, and analyze outcomes [13,38,56,57,60,64,68].
	Technology Integration: STEM fields rely on technology, and CT encourages students to leverage technology tools for problem-solving [10,14,56,61,69,70].
	Future Workforce Preparedness: Both CT and STEM skills are described as essential in future careers [36,38,58,60,61,65].
	Computer Science: CT has its roots in computer science, making it an inherent and vital component of STEM and its associated domains [10,14,61,69,70].
	Pedagogical benefits: CT integration in STEM learning has a positive effect on STEM learning [14,38,59,71].

Regarding *problem-solving skills*, numerous papers directly link CT to problem-solving. Biddy et al. [63] even note that some teachers struggle to differentiate between CT and traditional problem-solving methods. Paltz and Pedaste [36] conducted a systematic literature review and categorized six original articles on CT [33,46–50]. They concluded that most of the underlying elements attributed to CT can be grouped into three categories related to problem-solving: defining the problem, solving the problem, and analyzing the problem. A similar approach is evident in the work of Yang et al. [64] and Juskevicience [72], who connect the elements of CT to the problem-solving process and design thinking. Several authors [13,14,38,57,64,65,69,71,72] have made a distinct connection between this conceptualization of problem-solving within the framework of CT and problem-solving within the context of STEM.

Furthermore, Weintrop's taxonomy [33] categorizes CT practices into four primary domains: Data practices, Modeling and simulation, Computational problem solving, and Systems thinking. This taxonomy serves as a foundational reference in 16 out of the 23 papers and provides the basis for several frameworks aimed at integrating CT into STEM education, as demonstrated in the works of Juskeviciene [65] and Yang [64]. Several authors [13,14,38] emphasize the significance of incorporating data analysis into STEM work and the direct relevance of CT. Additionally, Hutchins et al. [60] highlights the widespread use of modeling and simulation in STEM, aligning with the conclusions drawn by several other authors [13,38,56,57,60,64,68].

Another recurring theme throughout the literature is the integration of technology. Sivaraj et al. [56] advocate for the pivotal role of technology in STEM, viewing it through the lens of CT and portraying CT to harness technology for innovative solutions to address complex real-world STEM problems. This perspective is shared by several other papers [10,14,56,61,69,70]. The utilization of technology is closely linked to the concept of *Future Workforce Preparedness*, as highlighted by researchers [36,38,58,60,61,65]. They emphasize that industries are undergoing significant transformations due to technological advancements that are mainly digital in nature [1]. This seamlessly brings us to the next identified theme: *Computer Science*. Numerous scholars [10,14,61,69,70] emphasize that CT can be thought of as the foundational cognitive process that underpins computer science, and that computer science is an integral part of STEM because it provides the computational and technological foundation that supports and enhances various STEM fields.

Moreover, four distinct studies [14,38,59,71] collectively underscore the profound *pedagogical benefits* of integrating CT into STEM education. Peel et al. [67] demonstrated that combining CT with science content led to significantly higher learning gains in understanding natural selection, suggesting its potential for broader integration in scientific processes. Cheng et al.'s meta-analysis [71] of 21 eligible studies between 2013 and May 2021 revealed a substantial positive effect of CT integration on STEM learning performance in K-12 education. Yin et al.'s experiment [68] confirmed that CT–STEM activities significantly improved both cognitive and affective learning outcomes. Hutchins et al.'s experiment [60] using the C2STEM environment showcased positive impacts on students' learning gains in kinematics and CT, promoting flexible problem-solving strategies and deeper conceptual understanding.

3.2.1. CT–STEM Integration Frameworks

In their literature review, Wang et al. [13] identified four significant frameworks for defining CT, much like how Paltz and Pedasta [36] categorized five influential works in their own review. It is worth noting that among these conceptualizations, only Weintrop's framework [38] offered a clear focus on STEM. As mentioned earlier, Weintrop's taxonomy of CT practices stands as a cornerstone reference, referenced in 16 out of the 23 papers, and serves as the foundational structure for various other frameworks, e.g., [64,65].

Out of the 23 articles focused on CT–STEM, nine of them present their unique frameworks or guidelines for incorporating CT into one or more STEM fields. We categorized these frameworks into three distinct groups: one focusing on levels of integration [62], five on computational practices and integration elements [38,58,60,61,69], and three on design thinking and the problem-solving process [36,64,72].

Regarding *integration levels*, Waterman et al. [73] addressed the challenge of integrating CT skills into already packed school curricula without standalone computer science courses. They therefore categorized their approach into three levels of CT integration:

- Exist: Recognizing existing CT concepts within lessons.
- Enhance: Adding tasks to enrich disciplinary concepts with CT connections.
- Extend: Creating new lessons that use disciplinary concepts as a basis for CT exploration.

With respect to the *design thinking and the problem-solving process*, Juskeviciene et al. [72] linked the CT practices of Weintrop et al. [38] to the design thinking process to create a framework for CT–STEM integration. Similarly, Palts et al. [36] and Yang et al. [64] provide models for developing CT skills in STEM based on the problem-solving process. By doing so, they moved away from relying on decontextualized ideas and practices and instead drew on real-world instantiations of CT by relying on the application of the practices identified in contexts distinct from computer science. Although they build on different CT components, similarities between the frameworks are apparent. They all describe how CT components that focus on forming and solving problems can be mapped on to one or more engineering design processes. Yang et al. [64] point out that the mapping of one CT component onto a specific engineering design process does not mean that this CT will not be used in other processes. The manifestation of CT practices is very much dependent on the specific tasks at hand. According to them the main benefit of mapping CT on the engineering design process is to be able to recognize CT applications and practices in learning STEM content and solving problems.

Moreover, Lee and Malyn-Smith [61] have played a significant role in the development of integration elements. They adopted a holistic approach and introduced five CT Integration Elements (CTIEs) to serve as a bridge connecting CT skills with CT integration fields. These elements encompass understanding complex systems, innovating with computational representations, designing solutions that leverage computational power and resources, engaging in collective sense-making around data, and understanding the potential consequences of actions. Similarly, Hutchins et al. [60] focused on scientific modeling practices [77] to establish integrated domain maps and the acquisition of CT skills.

3.2.2. Teaching Practices

Both Wang et al. [13] and Ogegbo and Ramnarain [14] conducted reviews of the literature to investigate teaching practices used for integrating CT. While their findings are not entirely congruent, both reviews identified Modeling-Based Learning as a widely utilized practice. However, Wang et al. [13] emphasized the significant application of Problem-Based Learning, which was not noted by Ogegbo and Ramnarain [14]. Our own literature exploration (see Appendix A) aligns with Wang et al.'s. [13] observation that problem-based methodologies are frequently employed in CT integration. The analysis of reviewed studies reveals that problem-based learning, project-based learning, and design- based learning were predominately used, mostly in combination with programming and collaborative learning. Most of these are also described by Ellis et al. [27] and Thibaut et al. [28] as good practices of integrated STEM pedagogy. Although in our review we excluded studies that focused only on CT as a computer programming intervention, computer programming still forms a common teaching practice for integrating CT in STEM.

3.3. Research Question 3: Can the Insights from RQ1 and RQ2 Inform the Development of a Comprehensive Framework for CT Integration within an Integrated STEM Curriculum in VET Programs?

By delving into the inquiry posed by Research Question 1 and Research Question 2, a collection of distinctive and valuable insights has arisen, presenting singular viewpoints regarding the incorporation of CT within Vocational VET, facilitated through the prism of STEM methodologies.

One of the salient themes that prominently surfaces in both Tables 3 and 4 is the paramount importance of problem-solving skills. Whether it be the computational problem-solving emphasized in CT or the real-world problem-solving challenges posed by STEM, the ability to navigate complex issues is a shared focal point. As VET endeavors to equip students with practical skills for real-world careers, this shared emphasis on problem-solving aligns seamlessly with VET's mission to prepare learners to address complex challenges in their chosen vocational fields. Therefore, the frameworks that link CT practices to design thinking and problem-solving processes, as demonstrated by Juskeviciene et al. [72], Palts et al. [36], and Yang et al. [64], can serve as a blueprint for integrating CT–STEM into VET. These frameworks emphasize the real-world application of CT skills in solving problems, aligning with the pragmatic goals of VET programs.

Moreover, Lee and Malyn-Smith's introduction of CT Integration Elements (CTIEs) [61], including understanding complex systems, innovating with computational representations, designing solutions, sense-making around data, and understanding consequences, offers a holistic perspective. These elements can be applied to VET contexts to ensure a comprehensive integration of CT into STEM, catering to the specific needs of vocational students.

As educators in VET, many are potentially already incorporating various CT practices into their existing curricula. Therefore, it is crucial for them to first identify these practices. This aligns well with the categorization of CT integration levels proposed by Waterman et al. [73], which includes categories such as "Exist", "Enhance", and "Extend". This framework can be adapted effectively for VET settings. It enables VET educators to evaluate the presence of CT concepts within their curriculum, enrich these concepts with CT connections, and even design new lessons rooted in CT exploration within vocational subjects. Hence, we propose a comprehensive framework that combines the insights from existing theoretical frameworks for integrating CT in STEM to identify CT learning opportunities and help identify and enhance CT in a VET-integrated STEM curriculum (see Figure 3).

Distinct parts: the Engineering Design Process (1), CT Practices (2), Leveraging Computational Power (3), Integration Levels (4), and the VET Context (5). In the subsequent sections, we will provide detailed explanations and elaborations on each of these components.

The framework depicted in Figure 3 is the result of our literature review, incorporating various insights and elements that emerged during our research. To enhance its clarity and practical application, we have divided the framework into five distinct parts: the Engineering Design Process (1), CT Practices (2), Leveraging Computational Power (3), Integration Levels (4), and the VET Context (5). In the subsequent sections, we will provide detailed explanations and elaborations on each of these components.

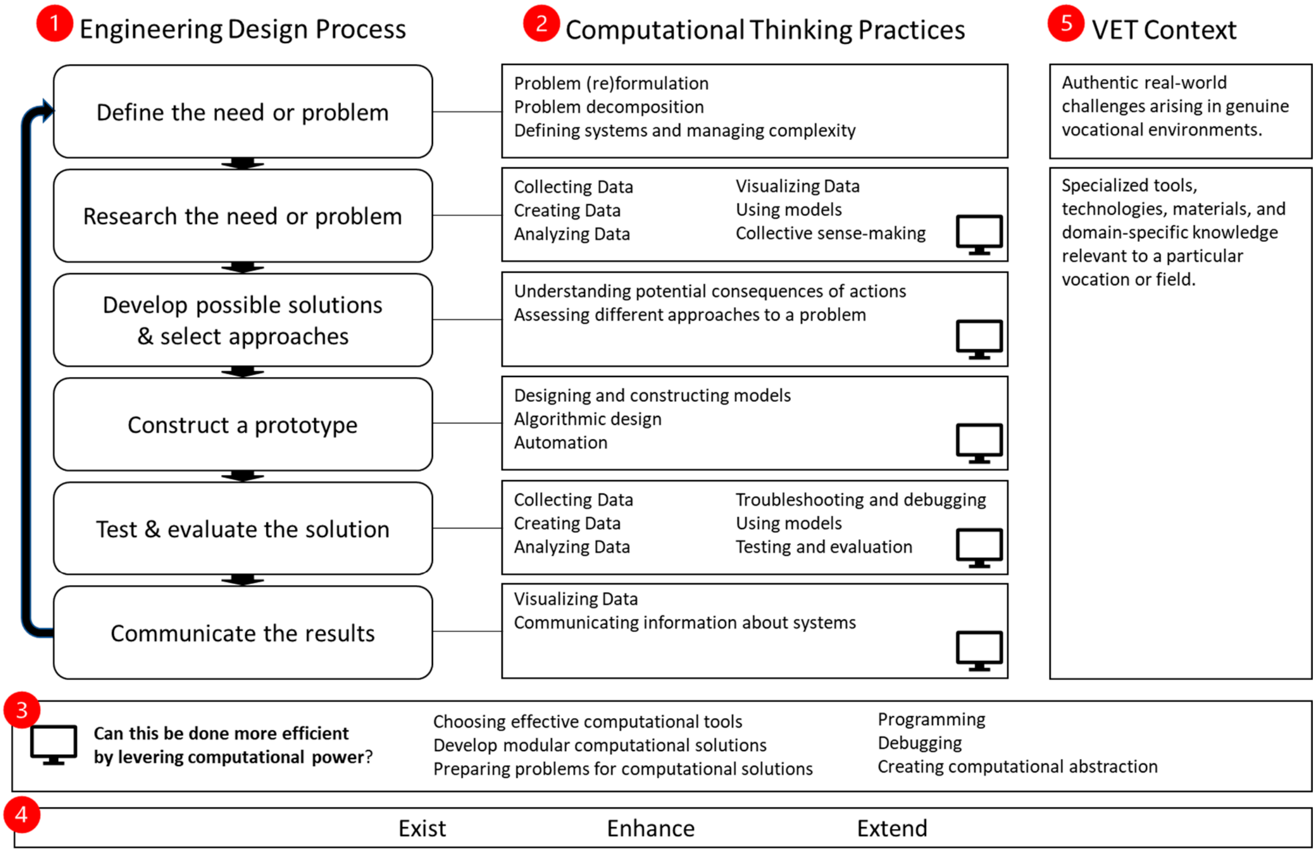


Figure 3. Combining CT and engineering design to identify and enhance CT in a VET-integrated STEM curriculum.

3.3.1. Engineering Design Process

Through our literature review, we identified problem-solving and the engineering design process as common practices across various contexts. Recognizing their significance, we have positioned them as cornerstones of our framework. This provides a structured framework for students to apply scientific principles and mathematical concepts to solve real-world problems. Moreover, it is particularly relevant in VET as it aligns with the practical, hands-on approach typically emphasized in VET.

Although several models can be found, we based our steps of the engineering design process on those suggested by Hynes [78]. They examined the understanding and teaching of the engineering design process by middle school teachers. These steps (see Table 5) include: Identify and define problems (1), Research the need or problem (2), Develop possible solutions (3), Select the best possible solutions (4), Construct a prototype (5), Test and evaluate the solutions (6), Communicate the solutions (7), and Redesign (8).

3.3.2. Computational Thinking Practices

We drew upon examples from Palts and Pedaste [36], Yang et al. [64], and Juskeviciene et al. [65] to align CT practices with specific phases of the problem-solving cycle, particularly within the context of the engineering design process. To structure our approach, we leveraged Weintrop's CT taxonomy [38], which encompasses data practices, system thinking practices, modeling and simulation practices, and computational problem-solving practices. Additionally, we enriched this framework with CT integration elements from the work of Lee and Malyn-Smith [61], including understanding complex systems, innovating with computational representations, designing solutions that leverage computational power and resources, and engaging in collective sense-making around data, while also considering the potential consequences of actions.

Table 5. Engineering design process [78].

Engineering Design Process Step	Description
1. Identify and define problem(s)	The goal should be for students to deal with ill-defined problems, identify the necessary constraints imposed on the problem, and acknowledge desired specifications. It is important that the problem is open-ended with many possible solutions.
2. Research the need or problem	Students must conduct some background research. Students should understand that there are many things to consider when solving an issue and recognize that they need to fully explore the challenge to be well-informed as to how to solve it.
3. Develop possible solution(s)	Recording multiple ideas for the task takes into consideration the need for planning, resources, and teamwork.
4. Select the best possible solution(s)	Students need to be able to justify and reason their own solution to pursue.
5. Construct a prototype	The prototype is a representation or model (physical, virtual, or mathematical) of the final solution. It is important to allow students to fail and learn from those failures as they iterate on their solution.
6. Test and evaluate the solution(s)	Students must create fair tests based on the constraints and requirements of the problem to judge whether their prototype is successful. Determining appropriate testing procedures may cause students to reengage in the research step (2) as they determine what methods and tools will help determine how well their prototypes meet the requirements.
7. Communicate the solution(s)	Part of engineering is sharing your ideas and findings with others for feedback and marketing purposes.
8. Redesign	Redesigning the key problems with the intent to optimize the design.

3.3.3. Leveraging Computational Power

While many CT practices remain applicable independently of computers, “Leveraging computational power” underscores the crucial connection between CT and computer science. The elements within this framework, including choosing effective computational tools, preparing problems for computational solutions, developing modular computational solutions, programming, debugging, and creating computational abstraction, draw from Weintrop’s [37] taxonomy and Lee and Malyn-Smith’s integrative elements [61]. They prompt the question of whether computers can enhance the efficiency and effectiveness of specific tasks, exemplifying the concept of leveraging computational power in problem-solving.

3.3.4. Integration Levels

As Waterman et al. [62] noted that CT skills and practices are already present in existing approaches and can simply be called out or elaborated upon, this aspect was included to emphasize that integrating CT is a matter of identifying CT practices or learning opportunities in existing lessons that can then be enhanced or extended.

3.3.5. VET Context

While this framework holds potential beyond the confines of VET, it is critical to underscore the unique benefits that VET provides. VET stands out by offering a direct pathway to engaging with real-world challenges encountered in actual vocational settings. It grants learners access to an array of specialized tools, technologies, materials, and domain-specific knowledge that are directly relevant to their chosen vocations. In VET, the relevance of specific vocational contexts cannot be overstated; thus, the integration of domain-specific knowledge into the learning process is essential for effective problem-solving.

Domain-specific knowledge plays a pivotal role in the problem-solving process by offering the foundational background, concepts, and terminologies necessary to navigate and comprehend problems unique to a particular field. This specialized knowledge equips learners with the ability to identify, frame, and address problems in a manner that is pertinent and directly applicable to their vocational domain. Furthermore, when domain-specific knowledge is woven together with CT practices, it significantly boosts learners' capabilities in utilizing computational tools and methodologies with greater efficacy. For instance, in a vocational course focusing on automotive technology, learners might employ simulation software to model and analyze engine performance. This process not only involves the application of computational simulations (CT practice) but also a deep engagement with automotive systems (domain-specific knowledge). Such an approach exemplifies how integrating domain-specific knowledge with CT practices not only enriches the learning experience but also ensures that learners are adept at applying theoretical knowledge to practical, real-world problems in their field. This integration is paramount in preparing students for the complex demands of their future careers, making them more adept and versatile professionals.

4. Discussion

The findings of this comprehensive study shed light on the dynamic intersections of CT, STEM education, and VET. The integration of CT into VET, as explored through the systematic literature review, presents several noteworthy implications and insights for educational research, policy development, and practical implementation.

One of the central themes that emerged from our analysis is the inherent interdisciplinary nature of VET. Chondrogiannis et al. [55] emphasized the involvement of all four STEM subjects in agricultural education, highlighting the importance of STEM integration within VET. This interdisciplinary aspect aligns with the essence of CT, which transcends disciplinary boundaries. CT is a 21st-century skill applicable to all individuals, including VET students [12,76]. Therefore, integrating CT within VET curricula can provide students with valuable problem-solving and critical thinking skills that are essential in addressing real-world vocational challenges.

Moreover, our review identified a growing demand for STEM-related skills within the VET domain. Societal and industrial evolutions, as noted by Asunda [73] and Wannapiroon et al. [31], are reshaping the landscape of VET and necessitating the inclusion of STEM competencies. This transformation, characterized by digitalization, IoT, robotics, and AI, underscores the relevance of CT skills in addressing the requirements of what is often referred to as "Education 4.0". The ability to incorporate CT-related skills, such as problem-solving and digital literacy, into VET programs is essential for adequately preparing students for the evolving job market.

Central to our findings is the development of a novel CT integration framework specifically tailored for VET. This framework, building upon the insights of researchers such as Juskeviciene [72], Palts [36], and Yang [64], establishes a clear blueprint for CT integration within VET contexts. It emphasizes the practical application of CT skills in solving real-world problems, closely aligning with the pragmatic goals of VET programs. Additionally, our framework incorporates CT Integration Elements (CTIEs) introduced by Lee and Malyn-Smith [61]. These CTIEs encompass critical aspects such as understanding complex systems, innovating with computational representations, and designing solutions that leverage computational power. This holistic perspective offers an effective approach that can be seamlessly applied within VET settings. By integrating these elements into vocational education, students can develop a deep understanding of the potential of CT in addressing complex, domain-specific challenges. Moreover, by formulating "Levering Computational Power" as a separate dimension, it becomes a core element of the framework. When frameworks predominantly focus on problem-solving, the association with computer science can become muddled. Raising the question of whether computers can optimize the efficiency and effectiveness of specific tasks is paramount for addressing challenges in technology-rich environments. This inquiry merits unwavering attention at every stage of the process. Connecting CT practices to familiar steps of the engineering design process can assist teachers with recognizing existing learning opportunities and developing new ones.

Perhaps a significant observation is the potential for enhancing VET learning experiences through CT integration. Several studies [14,38,59,71] highlighted the pedagogical benefits of integrating CT into STEM education. Improved learning gains, deeper conceptual understanding, and enhanced problem-solving skills were among the reported outcomes. The hands-on, skill-oriented nature of VET education makes it a fitting context for CT integration, as emphasized by Wannapiroon et al. [31].

4.1. Implications for Research, Policy, and Practice

The findings of this study have several important implications for research, policy, and practice. Firstly, the proposed framework for integrating CT within VET programs provides a structured approach to enhance CT skills in vocational contexts. Educators and curriculum designers can use this framework to identify and develop learning opportunities that bridge CT and vocational skills, better preparing students for the demands of modern industries. As our review indicates, integrating CT into VET programs holds promise in equipping students with the skills needed for the ever-evolving demands of modern industries while enhancing the learning process. However, it is crucial to note that additional research is needed before definitively establishing the framework's efficacy in arming students with these skills and determining the extent to which it enhances the learning process. Moreover, further exploration of equity considerations within this integration is imperative to ensure that the benefits are accessible and inclusive for all students. The identification of CT practices within the engineering design process underscores the potential to align VET programs with industry needs, promoting workforce readiness. In terms of policy, this study highlights the need for educational policies to recognize the importance of CT in VET and support its integration through curriculum guidelines and teacher training. Policymakers can consider incentivizing collaborations between educational institutions and industries to ensure that VET programs remain responsive to evolving workforce requirements. Lastly, for practice, educators in VET can benefit from this research by integrating CT practices in a context-relevant manner, enhancing students' problem-solving abilities and digital literacy. These implications collectively contribute to advancing CT integration in VET, enhancing the employability and adaptability of vocational graduates.

4.2. Limitations

While this study provides valuable insights into the integration of CT within VET programs, several limitations must be acknowledged. First, the sample size and diversity of the included research papers were relatively limited, potentially restricting the breadth of findings. Moreover, heterogeneity in CT definitions and contextual variations in VET programs could introduce variability into the framework's applicability. Furthermore, the study primarily relies on qualitative analysis. The external validity of the proposed framework requires further empirical validation. Teacher perspectives and direct impact evaluations on student outcomes were not explored in-depth.

5. Conclusions

In conclusion, this study has delved into the intersection of CT, STEM education, and VET. By systematically analyzing the relevant literature, we have identified recurring themes, integration frameworks, and a novel CT integration framework tailored for VET contexts. The results illuminate the inherent synergy between CT, STEM, and VET, emphasizing the significance of problem-solving skills, data analysis, modeling, technology integration, and workforce readiness. The proposed framework aligns CT practices with the engineering design process, offering educators a practical tool to enhance vocational education. Moreover, by formulating "Leveraging Computational Power" as a separate dimension, it becomes a core element of the framework. When other frameworks predominantly focus on problem-solving, the association with computer science can become muddled. Raising the question of whether computers can optimize the efficiency and effectiveness of specific tasks is paramount for addressing challenges in technology-rich environments. This inquiry merits unwavering attention at every stage of the process.

Crucially, this study underscores the imperative for policy backing in incorporating CT into VET curricula. Recognizing CT as an indispensable 21st-century skill with universal applicability, there is a pressing need for deliberate attention to CT integration within VET to address equity concerns. Furthermore, the integration of CT holds promise for positively influencing learning outcomes and enriching the overall VET educational experience. This acknowledgment reinforces the profound significance of our findings in narrowing the divide between classroom instruction and real-world application, thereby empowering students with a diverse skill set essential for success in vocational careers across various domains in the 21st century.

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Appendix A

Table A1. Breakdown of Coding Tree Analysis.

Code	Description	Papers	Count
STEM–VET connection		**4**	**28**
Evolving VET Profiles	The dynamic development of VET programs to keep pace with changing industry needs and technological advancements.	4	7
Interdisciplinary nature of STEM and VET	The recognition that STEM and VET overlap and require interdisciplinary approaches.	2	3
STEM-related VET	VET programs that provide practical skills and knowledge relevant to STEM-related careers.	2	2
CT–VET connection		**4**	**23**
CT as essential skill for everyone	Recognizing CT as a fundamental skill required in today's digital age.	2	3
CT to support VET learning	The use of CT concepts and techniques to enhance and support learning within VET.	2	3
Evolving VET Profiles	The dynamic development of VET programs to keep pace with changing industry needs and technological advancements.	3	6

Table A1. *Cont.*

Code	Description	Papers	Count
CT–STEM connection		**20**	**61**
Computer Science	Computer Science is a fundamental discipline that underpins CT and many STEM fields.	11	15
Data Analysis	The process of examining, cleaning, transforming, and interpreting data to extract meaningful insights.	3	3
Pedagogical Benefits	The use of innovative approaches and technologies, including CT and STEM integration, to improve the quality and effectiveness of education and skill development.	4	5
Future Workforce Preparedness	The readiness of individuals to meet the evolving demands of the job market. This includes having the necessary skills and knowledge to excel in future careers.	9	12
Modeling and Simulation	Creating simplified representations (models) of real-world systems and using them to simulate and understand their behavior.	7	8
Problem-Solving Skills	The ability to analyze complex issues, identify challenges, and develop effective solutions.	9	10
Technology Integration	The incorporation of various technologies into educational and professional settings to enhance learning or problem-solving processes.	7	8
CT–STEM integration Frameworks		**12**	**18**
Integration Elements	Specific components, methods, or content areas that facilitate the integration of CT in STEM education.	7	11
Integration Levels	Different stages or levels at which CT and STEM are combined and woven into educational programs.	1	1
Problem Solving and Engineering design	Problem-solving techniques and engineering design processes that involve identifying, defining, and creating solutions for real-world challenges.	4	6
CT–STEM integration practices		**22**	**103**
Coding and Programming	The process of writing and designing instructions for computers to execute tasks.	13	21
Design-Based Learning (DBL)	An educational approach where students learn by engaging in the design and creation of tangible products or solutions to real-world problems, promoting problem-solving and creativity.	12	25
Game-Based Learning (GBL)	A pedagogical method that uses games, often digital or board games, to facilitate learning and skill development. It leverages game elements to make learning engaging and interactive.	4	4
Inquiry-Based Learning (IBL)	A student-centered approach where learning is driven by posing questions, investigating problems, and seeking solutions. It encourages critical thinking and exploration.	6	8
Modeling and Simulating	The process of creating simplified representations (models) of real-world systems or phenomena and using them to simulate and understand their behavior.	8	15
Problem-Based Learning (PBL)	A teaching method in which students learn through the exploration of complex, real-world problems.	13	17
Project-Based Learning (PjBL)	An instructional approach where students work on long-term projects, often interdisciplinary, to address real-world challenges.	4	5
Storytelling	The use of narrative techniques to convey information, engage students emotionally, and facilitate learning.	1	3
Theoretical introduction and Demonstration	A teaching strategy that involves providing students with theoretical knowledge and then demonstrating how that knowledge is applied in practice.	3	3
Tinkering	A hands-on, trial-and-error approach to learning where individuals engage in creative and exploratory activities to build understanding and develop problem-solving skills.	2	2

Table A1. *Cont.*

Code	Description	Papers	Count
CT Elements		**22**	**159**
Abstraction	The process of simplifying complex systems or ideas by focusing on essential details while ignoring unnecessary ones.	17	23
Algorithmic Thinking	The ability to break down processes into a sequence of well-defined steps or instructions, often represented as algorithms.	20	33
Collaboration	Working together with others to achieve common goals.	4	6
Communication	The ability to convey ideas, information, and results effectively through written, spoken, or visual means.	5	6
Conditional logic	Using conditional statements (e.g., if-else) to control the flow of a program based on specific conditions or criteria.	5	5
Creativity	The ability to think imaginatively and generate innovative solutions.	1	1
Critical thinking	The skill of analyzing, evaluating, and synthesizing information to make informed decisions and solve complex problems.	1	1
CT Vocabulary	The terminology and language associated with computational thinking.	2	2
Data collection and Analysis	Gathering information and using analytical methods to extract insights and make informed decisions from data.	15	26
Data Representation	Techniques and formats used to represent data in a structured way.	11	13
Decomposition	Breaking down a complex problem into smaller, manageable parts or subproblems to simplify problem-solving.	16	26
Evaluation and Efficiency	Assessing the performance and effectiveness of algorithms, programs, or systems, with a focus on optimizing resource usage and speed.	8	14
Generalization	Drawing conclusions or identifying patterns based on specific examples or data, extending understanding to broader contexts.	8	14
Mathematical thinking	Applying mathematical concepts and reasoning.	1	1
Modeling and Simulation	Creating simplified representations (models) of real-world systems or phenomena and using them to simulate and understand their behavior.	11	15
Parallelization	The technique of executing multiple tasks or processes simultaneously.	5	8
Pattern Recognition	Identifying regularities or recurring structures.	10	12
Problem formulation	The process of defining and articulating a problem clearly.	6	12
Problem solving (Computational)	The process of finding solutions to complex problems.	14	22
Programming and Automation	Writing code to instruct computers to perform tasks or automate processes.	14	27
Systems thinking	Viewing problems and solutions as part of interconnected systems, considering how changes in one part affect the whole.	9	10
Testing and debugging	The processes of identifying and correcting errors (bugs) in software code and verifying that it functions as intended.	8	9

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