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Scaffolding for Challenge-Based Learning in Sustainability Education: A Multiple-Case Study

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Abstract

Challenge-based learning (CBL) is a student-centered approach engaging learners in complex, open-ended problems. While such openness can foster deeper learning and creativity, it also demands high self-direction. Teachers must therefore provide sufficient scaffolding without undermining CBL's authenticity. This study examines how secondary education teachers design and enact scaffolding in sustainability-oriented CBL projects, and how students experience this support. A multiple-case study of three projects distinguished soft scaffolding (adaptive, just-in-time support) from hard scaffolding (predefined tools and structures). Data included teacher interviews (n = 3), student focus groups (n = 18), and classroom observations. Findings showed the scaffolding type and function depended on project open-endedness, teacher readiness, and alignment with project focus. In the most open-ended project, the teacher mainly used soft scaffolding to guide thinking and decision-making, whereas more structured projects relied on hard scaffolds for procedural support. Students' experiences varied: some thrived under autonomy, developing ownership and engagement, while others needed more explicit guidance. These results suggest that scaffolds should align with project goals, be explicit in their contribution to progress, match students' readiness for self-directed learning, be enacted by teachers comfortable in a coaching role, and include affective support to help students manage frustration and uncertainty.

Keywords: challenge-based learning; scaffolding; secondary education; sustainability education; multiple-case study

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1. Introduction

Education has seen an increase in student-centered pedagogies aimed at preparing students for this ever-changing world. The challenges we face today, including sustainability issues such as climate change, are ill-defined, open-ended issues that require a multidisciplinary approach to address them [1]. Developing sustainability competencies beyond the standard curriculum has therefore become an important objective in education [2], as reflected in policy initiatives such as the European GreenComp framework [3]. These initiatives emphasize the need for learners to develop the knowledge, skills, and attitudes required to address complex sustainability challenges and to recognize their role in promoting a sustainable future, ultimately contributing to more informed and responsible citizenship [4].

One suggested pedagogy that engages students in these real-life issues is challenge-based learning (CBL). In CBL, students tackle open-ended challenges, take ownership of their learning, acquire the necessary knowledge to address the problem, and develop both subject-specific and cross-disciplinary skills [1,5,6]. As an evolved form of other student-centered approaches, such as problem-based learning (PBL) and project-based learning (PjBL), CBL emphasizes taking action. This action-oriented aspect, calling for action competence, has been suggested as a key factor supporting students' agency in CBL-based sustainability education by positively influencing their readiness to act, both individually and collaboratively [7,8].

In addressing complex sustainability issues, CBL introduces students to a "big idea," a broad theme that serves as the foundation for their learning. Based on this theme, students formulate their own challenge—sometimes co-created with external stakeholders or challenge owners [9]—explore multiple perspectives, engage in deep content learning, and develop transdisciplinary skills (e.g., decision-making and collaboration) while working toward potential solutions [6,10]. The lack of a predefined challenge, clearly defined boundaries, and fixed content makes CBL demanding [11]. In this context, teachers, acting as facilitators, play a crucial role in scaffolding students to refine broad themes into manageable challenges [10,12], while also supporting their transition toward responsibility and ownership when engaging with complexity [5].

Although engaging with complexity when participating in CBL for sustainability has been shown to spark interest in sustainability [7,13], students often struggle with open-ended problems that lack clear solutions [14,15] and with self-directing their learning in CBL, which may lead to frustration and disengagement [16]. In addition to providing instructional support in dialogue with the students to mitigate these risks [1] and to encourage engagement in self-directed learning [17], scaffolding also helps keep students within pedagogical boundaries, ensuring that even relatively fixed curricular learning objectives are being met [18]. Furthermore, beyond dialogue, scaffolding can also involve structuring learning activities to support students in managing complexity [19]. Structuring strategies include the use of milestones to break tasks into manageable components [20,21], the implementation of formative checkpoints to monitor progress [22], incorporating artifacts and tools to support students' thinking and writing processes, and narrowing the solution space by setting parameters upfront [23].

However, while these scaffolding strategies, both in dialogue and through structuring learning activities can provide the necessary help, they may also reduce the perceived complexity and open-endedness of the challenge, making it feel artificial. The very elements that define CBL, complexity, openness, and autonomy, are also essential for fostering creativity, innovation, and critical thinking [7]. Over-structuring may limit these processes and reduce motivation, especially for students who thrive on challenge, while under-structuring may overwhelm those who require more guidance [17]. Providing the right amount of guidance in CBL across the cognitive, metacognitive, and motivational aspects of learning can be highly complex, and the guidance provided may not always align with students' needs [24]. This creates a pedagogical tension in practice, as teachers must balance maintaining the openness and authenticity of CBL challenges with providing sufficient scaffolding to support students' learning processes.

In sum, while CBL promotes the creation of a self-directed learning environment by introducing real-life challenges that are complex and ill-defined, achieving this in practice requires a careful balance of providing the right type, amount, and timing of scaffolding while also considering logistical and curricular demands. Although previous studies highlight the importance of scaffolding in student-centered learning environments, empirical insights into how scaffolding is designed and experienced in challenge-based learning for

sustainability remain limited. Existing research often focuses on the conceptual benefits of CBL or on general instructional support strategies, but provides less insight into how teachers balance hard and soft scaffolds in practice, particularly in secondary education contexts. As a result, there is still limited understanding of how different scaffolding approaches shape students' experiences when engaging with complex sustainability challenges. Therefore, this multiple-case study explores how teachers approach and operationalize this balance through scaffolding strategies in secondary education CBL for sustainability, and how students experience these scaffolding strategies. The study aimed to answer the following research question: how do secondary education teachers design and implement scaffolding in challenge-based learning environments on sustainability issues, and how is this scaffolding experienced by students?

1.1. Theoretical Background

Scaffolding is a broad concept encompassing all forms of assistance that facilitate students' learning [25]. Introduced by Wood et al. [26], the metaphor describes instructional support that enables learners to accomplish tasks or solve problems beyond their unassisted capabilities by temporarily controlling task elements that exceed the learner's current competence. Often associated with Vygotsky's socio-cultural theory, scaffolding helps bring complex tasks within students' reach, situating them in their zone of proximal development [27]. The zone of proximal development is represented by the gap between a student's current developmental level and their potential level in problem-solving, with guidance from an adult serving as a bridge from the one up to the other. This support reduces frustration and demotivation while making learning more manageable and accessible [28].

While a clear operationalization of instructional scaffolding is lacking in the literature, van de Pol et al. [29] identified contingency, fading, and the transfer of responsibility as key characteristics of scaffolding. Teacher scaffolding is contingent when it is adjusted to the student's level of performance and determined by ongoing diagnosis, allowing calibrated support [30]. Fading refers to the gradual withdrawal of guidance as students gain understanding, thereby scaffolding contingently [29]. Closely related to fading is the transfer of responsibility, in which students take increasing control over the task. This shift in responsibility can occur on the cognitive, metacognitive, or affective levels, with regard to such aspects as problem-solving strategies, self-regulatory skills, or motivation and confidence.

To analyze scaffolding strategies, van de Pol et al. [29] proposed a framework based on the work by Wood et al. [26] and Tharp and Gallimore [31]. The framework distinguishes between the means of scaffolding, which describe how support is provided, and the intentions of scaffolding, which specify what is being scaffolded. Intentions are organized into three domains. Metacognitive intentions involve direct maintenance of students' task-related engagement, which helps keep students on track. Cognitive intentions address cognitive structuring, which guides students' task-related thinking, and the reduction in degrees of freedom, which simplifies tasks. Affective intentions attend to recruitment, which boosts engagement, and frustration control, which helps with management of emotions. Scaffolding can be enacted through six means: giving feedback, giving hints, instructing, explaining, modeling, and questioning [29].

More recently, the concept of scaffolding has evolved beyond the process of giving timely and dialogic support based on students' needs [26,32] to include support embedded in technologies, tools, and curricula [33], alongside teacher–student dialogue [34]. The concept of scaffolding has broadened so much that it is increasingly difficult to distinguish it from general support [30,35]. However, the use of tools and artifacts as a scaffolding strategy can be considered justified, given that, in practice, teachers work with up to

35 students, each with their own zone of proximal development. The complexity of classroom settings makes one-on-one teacher–student interactions impractical [19,36]. As a result, scaffolding is typically implemented through more practical and feasible means, such as instructional materials, tools, and classroom activities that facilitate student interactions, including small-group dialogues and whole-class discussions [19].

1.1.1. Soft and Hard Scaffolds

When analyzing scaffolding, it is useful to distinguish between soft and hard scaffolds. Soft scaffolds, rooted in socio-cultural theory, are part of the adaptive, context-dependent process of teacher–student interaction, where support is fine-tuned to students' needs [37]. In contrast, hard scaffolds are the static tools and artifacts prepared before the lesson, representing predefined interventions provided to assist students in completing a task [19,37]. The key difference between these two forms of scaffolding lies in the timing of their planning and development. Soft scaffolds are provided in real time, whereas hard scaffolds are pre-planned based on the teacher's prior experience with areas that might be challenging for the students. In response to this experience, teachers develop materials in advance that students can use when and if needed [37,38].

It is important to distinguish hard scaffolding from traditional instruction or assignments. Hard scaffolds are predefined, designed to reduce task complexity or support specific aspects of learning that might otherwise exceed students' capabilities [19,35]. Furthermore, in contrast to tools that must be used in an ongoing way to perform at a certain level (e.g., calculators), hard scaffolds are not inherently required but are strategically introduced to support particular tasks or phases of learning, if necessary.

While van de Pol et al.'s [29] framework primarily addresses soft scaffolding as provided through contingent teacher–student interactions, we argue that it can also be applied to hard scaffolding. Hard scaffolds can be designed to preemptively address cognitive or metacognitive difficulties through strategies such as instruction, explanation, or structured representations (e.g., graphic organizers). Furthermore, for hard scaffolds to be effective, they also need to be contingent and to promote processes of fading and the transfer of responsibility. Moreover, hard scaffolds can facilitate soft scaffolding by reducing task complexity, thereby creating opportunities for teachers to assess and deepen students' understanding through adaptive questioning [19].

1.1.2. Scaffolding in CBL

Challenge-based learning is considered a flexible pedagogy or approach that has seen implementation in varying educational settings. Since its origins in a secondary education project launched by Apple in 2008, CBL has been conceptualized in several ways [5,6,11,39,40]. Early work by Nichols et al. [39] framed CBL as a process in which students collaboratively investigate real-world challenges and develop actionable solutions through phases of engagement, investigation, and action. Later frameworks originate from higher education but are nonetheless relevant for the development of the CBL approach. For instance, Gallagher and Savage [11] highlighted key characteristics of CBL implementations, including authentic global challenges, collaboration with stakeholders, and the use of technology to support inquiry and solution development. In higher engineering education, Malmqvist et al. [40] conceptualized CBL as a process of identifying, analyzing, and designing solutions to socio-technical problems, emphasizing multidisciplinary collaboration and sustainability considerations. More recently, Van den Beemt et al. [6] proposed a broader framework, the CBL Compass, which distinguishes between vision, teaching and learning practices, and institutional support systems, while identifying indicators such as authentic challenges, integration of disciplinary knowledge, and activities that promote deep learn-

ing. In the study of Schutte et al. [18], this CBL Compass was implemented in secondary education. The study found that meaningful challenges situated in students' interests were sometimes more relevant and feasible than working with a designated challenge owner. In such cases, authenticity was achieved through other forms of involvement, such as expert interviews or guest lectures. Despite these variations, most conceptualizations converge on the use of real-world challenges and some form of interdisciplinary student-driven inquiry as core elements of CBL.

Situating CBL in the broader field of education, its active, self-directed nature and focus on real-world contexts reveal similarities with other pedagogies such as problem-based learning (PBL), project-based learning (PjBL), and design-based learning (DBL) [9]. As such, it shares roots in broader educational theories such as active and experiential learning, as well as motivational theories like self-determination theory, where student motivation and ownership are emphasized [5]. Furthermore, as active participation in the learning process is fundamental to CBL, knowledge is actively constructed, reflecting the social constructivist paradigm. However, on closer inspection, CBL differs from these related approaches in that challenges are typically co-defined and refined by students, often in interaction with external stakeholders, while teachers mainly take on a facilitative role [9,10,12]. By contrast, PBL and PjBL more commonly begin with problems predefined by teachers to support disciplinary knowledge acquisition [6]. DBL, in turn, tends to involve more narrowly specified design tasks aimed at developing concrete products or artifacts [5,41].

From a transformative learning perspective, CBL's self-directed and action-oriented nature provides students with opportunities to develop autonomy and agency, essential for engaging with complex sustainability challenges. Studies have shown that CBL can enhance students' ability to formulate and address complex problems while deepening their understanding of sustainability issues [13,42,43]. Furthermore, it fosters responsibility, initiative, and independent pursuit of learning opportunities [44], supporting transformative learning by encouraging reflection, critical thinking, and engagement with multiple perspectives [45]. This aligns closely with sustainability education principles, emphasizing pluralism, collective learning, and democratic engagement [46–48]. By navigating uncertainty and engaging with interdisciplinary, real-world sustainability challenges, students develop the agency and skills to contribute meaningfully to sustainability transitions [6,11].

Among the various CBL frameworks discussed in the literature, the three-phase model of engage, investigate, and act [39] provides a practical structure for analyzing and implementing scaffolding in our study. This framework aligns with the core elements of CBL identified above, including authentic challenges, student-driven inquiry, and iterative problem-solving, and highlights points in the project where teacher support can be strategically applied. In the engage phase, students explore a broad topic and refine their interests through essential questions, ultimately formulating a compelling, action-oriented challenge. Nichols et al. [39] categorized challenges into macro, mini, and nano levels. Macro-level challenges grant full student ownership across all phases, whereas mini and nano-level challenges are more teacher-directed, focusing on specific skills or content within a shorter timeframe. Nano-level challenges can also serve as gradual scaffolds or embedded learning activities to support larger projects [21,49].

During the investigate phase, students generate guiding questions, identify resources, and shape their learning trajectory. Teachers scaffold this process by providing cues, prompts, or checkpoints to direct students toward key questions, resources, or next steps [50]. The act phase—developing, prototyping, and implementing solutions—is closely interlinked with investigation, as students often cycle between research and action,

refining solutions iteratively. Teachers can scaffold transitions by signaling milestones, highlighting key questions, and offering strategic check-ins [14,21].

Across all phases, teachers primarily act as coaches and facilitators [5,6], providing soft scaffolding strategies and hard scaffolds that are available for use when needed. Common soft scaffolding strategies include posing open-ended questions, offering feedback, and encouraging multiple problem-solving approaches [51]. Since students have substantial autonomy, teachers must calibrate the intensity of the scaffolding. Five levels of teaching control were described by van de Pol et al. [52], from prompting elaboration to providing direct explanations; in CBL, lower degrees of control are generally preferable so as to support self-regulation while providing any necessary guidance.

In the further examination of scaffolding within a CBL context, it is important to acknowledge that working from an authentic real-life challenge often transcends disciplinary boundaries [6]. The problem itself becomes central, and CBL therefore frequently operates within an interdisciplinary framework. Interdisciplinary CBL thus adds an additional dimension to scaffolding [53].

In secondary education, interdisciplinary CBL can take different forms depending on its positioning within the school structure [18]. For example, if CBL is implemented in a multidisciplinary fashion, through collaboration between teachers from different subjects, the classification [54,55], that is, the strength of the boundaries between subjects, can be expected to be strong. In contrast, when CBL is implemented within inherently interdisciplinary subjects, such as science (biology, chemistry, and physics), or during project weeks outside the subject-based curriculum, classification may be considered weaker. This does not carry a negative connotation; rather, it indicates that disciplinary boundaries are less explicit and that awareness of disciplinary connections may be less apparent for students.

Moreover, within the related continuum of framing [56], where strong and weak framing relates to the degree of student and teacher control, environments with stronger student control often involve topics that are intrinsically motivated and based on students' interests. Consequently, themes frequently emerge from everyday life and are not necessarily situated within disciplinary structures. While it is important to situate learning in contexts familiar to students in order to connect to prior knowledge [57], teachers' scaffolding strategies must ensure that learning does not remain at the level of everyday reasoning but is eventually translated into school-based or disciplinary learning [58]. This is particularly relevant in CBL, where students often move from a broad theme to a concrete challenge based on their interests and interpretations [14,18]. Despite this student-centered approach, curricular standards may still need to be met. Teachers, in their role as coaches, therefore need to ensure, without fully taking control, though sometimes providing stronger direction, that curricular objectives are addressed within this learning process.

Closely related is the notion of knowledge differentiation [54,59], which distinguishes between disciplinary knowledge, typically academic and context-independent, and everyday knowledge, which is situated within social and cultural contexts [60]. Similar to the concept of framing, meaningful learning in CBL often begins with students' interests and experiences [14,18], meaning that everyday knowledge tends to dominate at the start of a project. In CBL, van den Beemt et al. [6] argue that both transdisciplinary skills and deep knowledge acquisition are vital to the CBL process; however, some nuance can be introduced depending on the aims of the project. If curricular goals must be met, teachers should scaffold students toward disciplinary forms of knowledge. In interdisciplinary projects, they should also help students recognize the underlying disciplinary structures, thereby reducing the risk that students become overwhelmed by large amounts of information and disengage [57,61]. At the same time, if broader competences, such as sustainability com-

petences or transdisciplinary skills like collaboration and communication, are prioritized, scaffolding strategies should be aligned accordingly [62].

In framing these broader competences, which should not be confused with competency (referring to a more specific skill set) [63], and in the context of interdisciplinary CBL addressing sustainability issues, we refer to the GreenComp competence framework [3], developed by the European Commission based on a review study by Bianchi et al. [64]. This framework is particularly relevant given its holistic nature [65] and results not only from research on sustainability competences but also from work on sustainability-oriented pedagogies [66]. Therefore, this framework is of particular interest for teachers designing CBL-oriented projects on sustainability issues and consequently falls within the scope of this study. The framework consists of four competence areas, each comprising three competences (see Table 1).

Table 1. The GreenComp competence framework [3].

1. Embodying Sustainability Values	2. Embracing Complexity in Sustainability	3. Envisioning Sustainable Futures	4. Acting for Sustainability
1.1. Valuing sustainability	2.1. Systems thinking	3.1. Futures literacy	4.1. Political agency
1.2. Supporting fairness	2.2. Critical thinking	3.2. Adaptability	4.2. Collective action
1.3. Promoting nature	2.3. Problem framing	3.3. Exploratory thinking	4.3. Individual initiative

2. Method

This study used a multiple-case design, investigating scaffolding in three different CBL projects [67]. By examining diverse cases through a constructivist lens, the study aimed to achieve theoretical replication, exploring how and why variations occur when applying the same theoretical lens regarding scaffolding across different contexts [67]. Furthermore, analyzing multiple cases allows for comparison across different contexts, which can enhance the robustness of the findings and provide a more nuanced understanding of how scaffolding is designed and experienced [67,68]. In line with this exploratory aim, the study focuses on teachers' and students' experiences and perceptions of scaffolding in practice.

According to Yin [67], a case study is an empirical method that investigates a contemporary phenomenon in depth and within its real-world context, particularly when the boundaries between the phenomenon and its context are not clearly defined. This emphasis on depth and contextual complexity necessitates the use of multiple sources of evidence to allow for a holistic understanding of the case. Accordingly, in this study data were collected through pre- and post-project teacher interviews, student focus groups, and classroom observations.

2.1. Selection and Context of Cases

This study was part of a large 4-year partnership involving seven secondary schools, 26 teachers, and a university teacher education program. The project aimed to integrate sustainability education into secondary school curricula, using CBL as the primary approach. The teachers involved met once per month in a cross-school professional learning community (PLC), wherein CBL projects were developed, shared, and evaluated. The CBL process was visualized (see Figure 1; figure translated from Dutch into English) together with the teachers, based on the frameworks of Nichols et al. [39] and Ambrosi and Hermsen [69]. Although many CBL implementations by the teachers involved in the PLC varied in design, all projects could be linked back to this figure.

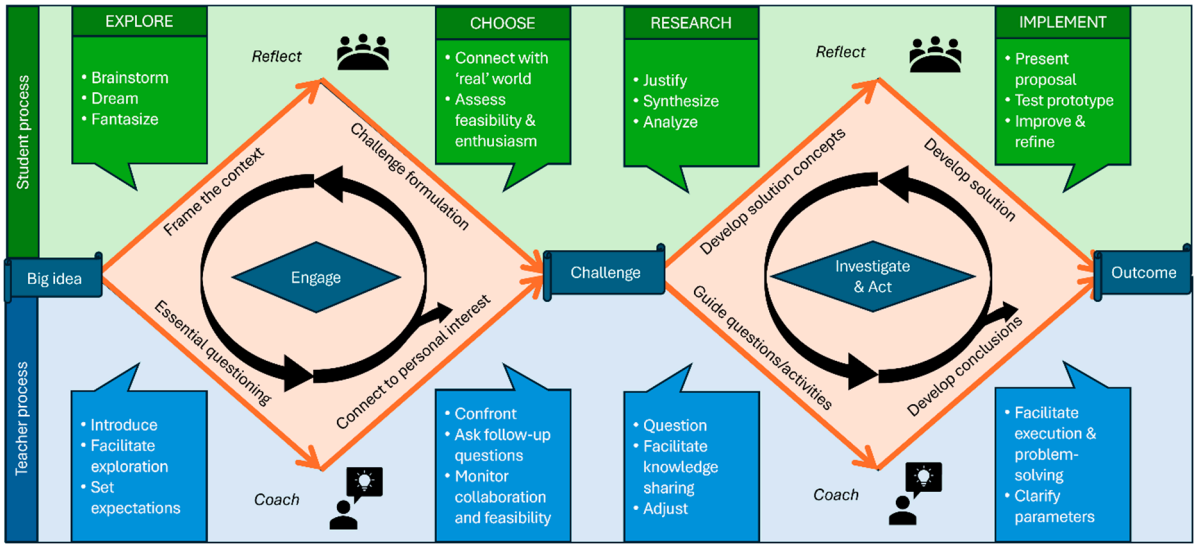


Figure 1. CBL process as agreed on by the teachers involved in the PLC.

Within this PLC, three cases from different schools were selected from a pool of CBL projects through purposeful sampling, specifically using the criterion sampling strategy [70]. Cases were selected based on three criteria. First, all selected projects shared a common focus on CBL for sustainability education, specifically incorporating the engage, investigate, and act framework, as well as situating learning in meaningful real-life contexts. Second, to capture the breadth of CBL implementations across different school contexts, cases were selected to reflect variety in their disciplinary scope. Third, the potential diversity in scaffolding approaches was considered by including cases from different grade levels. These criteria were chosen because they reflect meaningful differences in project design, disciplinary scope, and the sustainability focus of the projects, all of which are expected to influence how scaffolding is applied and experienced. Differences in classification between subjects, the way subjects are integrated, grade level, and the specific sustainability challenges addressed are likely to affect how teachers guide learning, the type of scaffolds they provide, and how students are supported in connecting knowledge across disciplines [54,62]. By examining projects with diverse characteristics, the study can provide insights into how contextual factors shape scaffolding strategies and student experiences, which is directly relevant to improving practice in sustainability-oriented CBL. The reason no additional cases were included is that some projects either integrated too few elements of CBL, had limited focus on sustainability, or were implemented outside the data collection period. See Table 2 for an overview of the teachers involved in the selected cases and their projects. Names are pseudonyms.

All three cases were implemented in secondary schools within the same region of the Netherlands. EcoKino took place in a traditional urban school offering tracks that prepare students for academic or applied university programs. The school provides multilingual instruction, allowing students to follow courses in English, including EcoKino. Save the Planet was implemented in an international school that does not follow the Dutch national curriculum but operates according to an international framework. Finally, the Insect Hotel project was conducted in a vocational-oriented school in a rural area. This school offers many practical profiles and has facilities for construction, 3D printing, and visual design. Education at this school is largely project-based, supporting hands-on and applied learning experiences.

Table 2. Overview of cases.

CBL Project	Sustainability Topic	Students Interviewed (Total)	Type of Implementation	Teacher Interviewed [e] (Total)	Timing in School Year
EcoKino	Social-ecological dilemma (e.g., plastic soup and fish population)	4 (25)	Subject-based project across two subjects: biology and arts	Ryan (2)	Third quarter
Save the Planet	Good health and well-being (SDG3 [a])	9 (28)	Integrated project involving two subjects in project week [b]: science and physical health education (PHE)	John (6)	Fourth quarter
Insect Hotel	Biodiversity	4 (41)	Integrated project involving vocational tracks in project week [b]: BWI [c] and PIE [d]	Ethan (8)	Fourth quarter

Note. More details on project specific characteristics (e.g., duration and structure project) will be outlined in the results. [a] stands for Sustainable Development Goal 3 (SDG3). [b], project week, refers to a week in the school year wherein students do not follow regular schedules. [c] is an engineering subject and stands for construction, living, interior (Dutch for Bouwen, wonen, interieur BWI). [d] is an engineering subject and stands for produce, install, energy (PIE). [e] denotes a teacher who was also observed during classroom visits.

2.2. Data Collection and Procedure

For triangulation of the findings, data were collected using multiple types of sources, including semi-structured teacher interviews (pre- and post-project), focus groups with students, and classroom observations (see Figure 2 for a flowchart of the study). Data triangulation strengthens the credibility, validity, and robustness of findings [67]. Two teacher interviews were conducted for each case: one before the project and one after. Focus groups consisted of student teams who collaborated on the project. For each case, two student teams were interviewed separately in a focus-group format at the end of the project, resulting in six focus-group interviews in total, each lasting approximately 30 min. In the EcoKino and Insect Hotel projects, the student groups consisted of two students each, while in the Save the Planet project, one group had four students and another five. Additionally, multiple project visits were carried out for each case, allowing for observations at different stages, reflecting the engage, investigate, and act phases of the CBL project. Data collection took place over 5 months. All interviews and focus groups were conducted in Dutch. Quotes presented in the results have been translated into English. The interviews were audio-recorded and transcribed verbatim; classroom observations were audio- and video-recorded. The field notes from the classroom observations served as the primary data source, while the recordings provided secondary data and served a confirmatory role, allowing for further investigation and examples of the observed interactions. Both the pre- and post-project interview protocols were pilot-tested to ensure question coherence, flow, and accurate interpretation, allowing for refinement prior to use in the study.

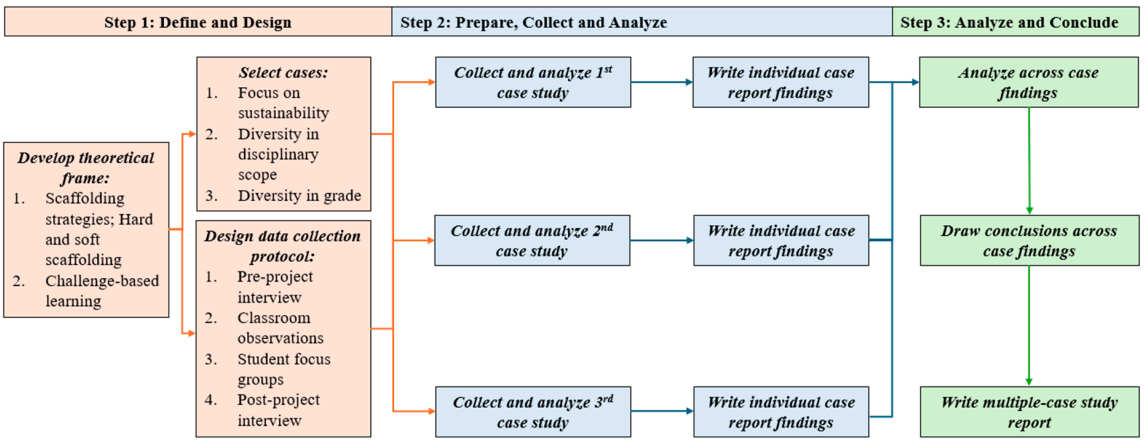


Figure 2. Flowchart of the multiple case study approach.

2.2.1. Teacher Interview—Pre-Project

The pre-project interviews lasted 30–45 min. The interviews focused on the hard scaffolds (e.g., worked examples, graphic organizers, guiding questions), the rationale for these decisions, and the degree of autonomy that teachers intended to allow students in regulating their work within the project theme.

2.2.2. Classroom Observations

For each case, several classroom visits were conducted throughout the project to capture all phases of the CBL process. Depending on the project format, observations consisted of either repeated lesson-based visits or continuous attendance during multi-day project weeks, resulting in approximately 7–11 h of observation per case. A camera placed at the back of the classroom recorded the sessions, positioned to avoid capturing students' faces. For ethical reasons, students who were uncomfortable with being recorded were seated out of camera range. The observer, positioned next to the camera, took detailed field notes documenting all teacher–student interactions. Field notes were structured using an observation protocol to ensure systematic data collection. Specific attention was given to instances of scaffolding, categorized as hard or soft, and whether it occurred at the whole-class, group, or individual level. Observations also focused on the effectiveness of these scaffolds, both hard and soft, examining whether they were interpreted as intended and used. Additionally, attention was given to how students processed scaffolding within their groups, such as discussing it with peers or applying it to their tasks.

2.2.3. Student Focus Group

After project completion, two student groups that had worked collaboratively on the CBL project were selected per case for a focus-group discussion. The selection was made in collaboration with the teachers: they asked the students who would be willing to participate, and from those volunteers, two groups were chosen per case, considering a variety in project performance. Each focus-group session lasted approximately 20 to 30 min and explored the students' experiences during the project. Questions addressed challenges they encountered, how they overcame them, and the role their teachers played in resolving these challenges. Students were also asked about the usefulness of tools and materials, their satisfaction with the process, and the balance between self-direction and teacher guidance. All focus-group sessions were conducted by the first author at the respective schools immediately after the completion of each project.

2.2.4. Teacher Interview—Post-Project

After the project, individual semi-structured interviews were conducted with the teachers. These interviews, which lasted 30 min, focused on reflections about the CBL project that had been implemented. Topics included evaluation of predetermined scaffolds, reflections on just-in-time scaffolds, and considerations for further project development. Teachers were asked about the balance between teacher and student control, whether new scaffolds emerged during the project that could become predetermined (hard) scaffolds in the future, and whether any scaffolds could be excluded.

2.3. Data Analysis

This multiple-case study used an embedded design and was analyzed through the lens of scaffolding theory. Sub-units of analysis included soft scaffolding (teacher strategies) and hard scaffolding (tools and artifacts). In addition, the study was guided by the challenge-based learning framework of Nichols et al. [39], including its phases of engage, investigate, and act, as well as processes such as challenge formulation and solution-focused

thinking. Key CBL characteristics, such as openness, interdisciplinarity, and self-directed learning, were also considered in the analysis [67]. This analytical approach allowed us to identify patterns in scaffolding design and student experiences directly related to our research questions. The data analysis was conducted using the ATLAS.ti (version 25) qualitative analysis software and was led by the first author (primary coder). The analysis followed a two-step process. First, each case was individually analyzed to capture its unique characteristics and contextual factors, grounding the findings in the specific data of each case. Second, a cross-case analysis identified patterns and built explanations across all cases [67,71]. Preliminary patterns and themes were developed after the first case analysis and used as a lens for analyzing subsequent cases. However, each case remained independently analyzed, allowing for validation or revision of patterns based on case-specific data. This iterative approach ensured a data-driven analysis while facilitating cumulative explanation building [67].

For the individual case analysis, thematic analysis was conducted using both deductive and inductive coding processes across all data sources [70]. The analysis of observation data involved three steps: (1) further familiarization with the scaffolding interactions highlighted by the field notes; (2) detailed transcription of selected interactions; and (3) application of analytical codes. The analysis was conducted through several iterative steps, guided by Boeije's [72] data analysis spiral. During this process, memos were written to capture initial interpretations of the data and to maintain a detailed step-by-step audit trail. All sources were seen as equally important during analyses, allowing converging evidence through a holistic approach rather than analyzing each data source separately [67]. In the first round of open coding, drawing on the literature on hard and soft scaffolding, the focus was on scaffolding intentions (cognitive, metacognitive, affective) and scaffolding means (e.g., feedback, hints, and questioning) as outlined by van de Pol et al. [29]. In addition to this deductive approach, in vivo inductive coding was used to capture the nuanced complexities of each case, minimizing oversimplification into narrow categories [73]. In the second phase of coding, related codes were clustered into categories through the process of axial coding. For instance, inductive codes derived from teacher and student interviews were systematically compared and clustered into overarching themes using a constant-comparison process, resulting in a first draft of a category structure. Examples of themes that emerged included *struggle with conceptual understanding* (EcoKino), *keeping students on track* (Save the Planet), and *tension in open-endedness* (Insect Hotel). In the final step, through selective coding, connections between categories were sought, as well as the interpretation of these categories in respect of the outlined theoretical framework. After the analysis of each individual case, to facilitate cross-case analysis using ATLAS.ti, codes from each case were color-coded and organized to examine the differences and similarities across cases [67,70].

To enhance both reliability and validity, pilot coding was conducted to test and refine the coding scheme, reflexive memo writing was used to track interpretive decisions and reduce researcher bias, and author meetings were held to discuss coding choices and emerging themes, ensuring that interpretations accurately reflected the data. During data collection, the first author adopted an observatory role to minimize influence on the educational process and followed semi-structured protocols to ensure consistency across cases [72]. In addition, data triangulation across observations, interviews, and artifacts helped reduce the influence of individual researcher interpretations [67].

3. Results

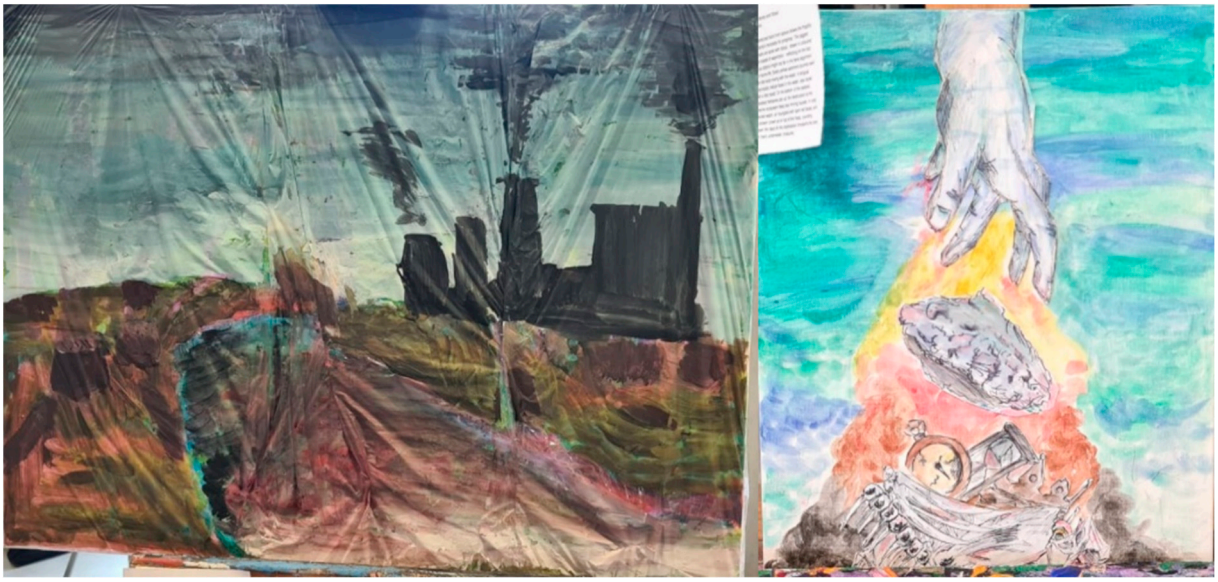
For readability and comparison purposes, the cases are presented in a similar structure, beginning with a brief overview of each case covering the disciplinary scope, project

context, process, sustainability themes, and student population, along with visualizations of the CBL process with soft and hard scaffolding (per case, and finally, the results of the cross-case analysis.

3.1. Case 1: EcoKino Project

The first case concerned a CBL project named *EcoKino*, primarily embedded in biology and supported by arts at a traditional secondary school. The project spanned eight biology lessons followed by two to three lessons in arts (approximately 11 h of student time) over a period of six weeks. Students attended two 45 min lessons per week on ecology in their biology class, which was a mandatory part of the curriculum. In one of these lessons, the teacher provided traditional instruction, explaining key concepts, while in the other lessons students worked on their projects.

Students were tasked with defining their own social-ecological dilemma and transforming this topic into an artwork. In the biology lessons, overseen by Ryan, they focused on identifying a dilemma and conducting research. In the subsequent art lessons, and supervised by artists from a museum, they translated their research into artistic products that emphasized both values and artistic expression. The project concluded with an exhibition at the school. Figure 3A shows a student artwork on "deforestation," where a forest painting created over 10 h was later covered with plastic and overpainted in 10 min with a factory scene (consent was given for the use of all pictures). This symbolizes how forests require long periods to grow, but can be destroyed within minutes. The artwork in Figure 3B depicts a hand polluting the sea, emphasizing human disruption of marine life.



(**A**) (**B**)

Figure 3. Student artworks on ecological dilemmas produced at the end of the EcoKino project. (**A**) Deforestation. (**B**) Marine pollution.

Learning objectives were mostly transdisciplinary in nature, despite the project being strongly positioned within the ecology-related biology curriculum. This was partly due to the structure of the project, in which instructional time was divided between traditional lessons, where conceptual knowledge was taught, and project work, where this knowledge was applied.

Accordingly, the project rubric included one criterion addressing how well content-related objectives were represented in the project, although specific objectives were not explicitly defined. Most criteria instead focused on intellectual quality. These included

the clarity of the project's purpose, the synthesis and construction of ideas, the integration of scientific knowledge and stakeholder perspectives, and the appropriate citation of sources. In addition, the rubric addressed aesthetic and technical quality, such as creativity and originality.

Although not explicitly assessed, the project aligned well with the competence area *embracing complexity in sustainability* from the GreenComp framework. In particular, it reflected aspects of *systems thinking*, as students were encouraged to approach the dilemma from both social and environmental sustainability perspectives, and occasionally from a political perspective as well.

3.1.1. Hard Scaffolds

Students worked in groups of two or three and chose between the subtopics of population ecology, ecosystem ecology, and community ecology (see Figure 4 for an overview of the project and the scaffolding that was provided). Within these broad themes, students had full freedom to define their own challenge. Examples chosen by the students included the extinction of wild bees, soybean farming in the rainforest, and the illegal shark fin trade.

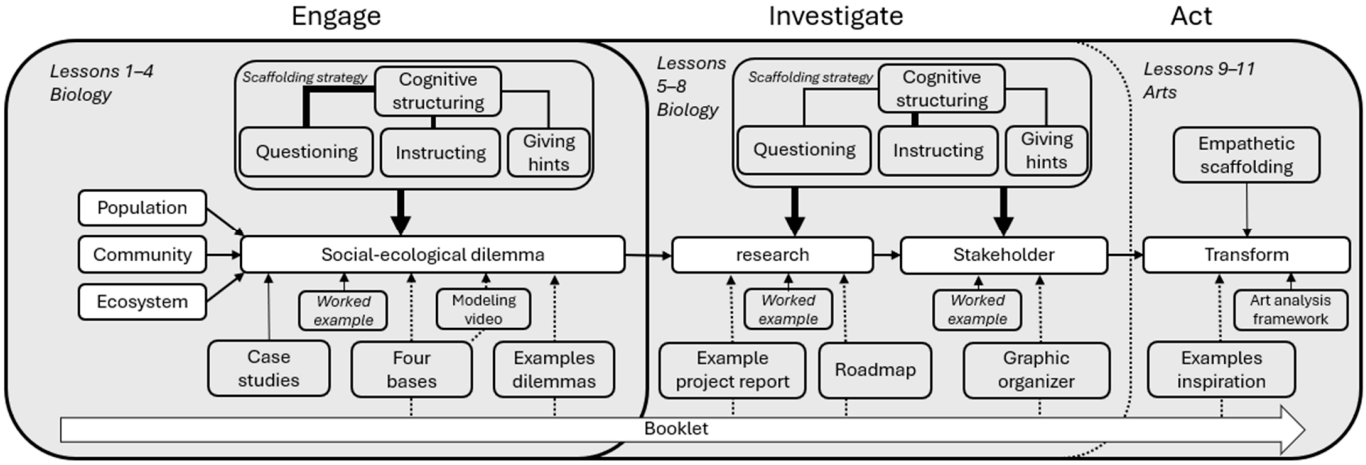


Figure 4. Overview of EcoKino project steps and scaffolding provided—Case 1. Note. The central pathway represents the project steps. Hard scaffolds are shown at the bottom and soft scaffolds at the top. The upper boxes display the most frequent soft-scaffolding strategies per CBL phase; the thickness of lines and arrows indicates the degree of their presence. The light gray shading of the boxes represents the level of openness in each phase, reflecting the extent to which students could shape their own learning path. Dashed arrows indicate the optional use of scaffolds. The dotted line between the investigate and act phases indicates their overlap in practice.

Because the assignment was open-ended, Ryan designed several hard scaffolds to support students in arriving at a concrete challenge and artwork. These were bundled in a booklet distributed at the start of the project. It included example dilemmas, a graphic organizer for mapping causes, consequences, and stakeholders, and a "four bases" task that helped students structure their thinking depending on their level of progress.

This latter hard scaffold formed the backbone of the engage phase of the project, namely in moving from a complex, broad sustainability topic to a concrete challenge, designed to structure cognitive processes, as Ryan described. The four bases allowed students the support needed to answer questions that would guide their thinking toward a challenge that interests them, while also adhering to the teacher's criteria, namely that it incorporates both an ecological as well as a social aspect.

The first base was meant for students who have no idea how to start and includes guiding questions about their interests, such as: Have you seen a movie or documentary that really triggered you emotionally? Which movie or documentary? What triggered the

emotion? And: Have a look at the booklet on pages 6–10. Which social-ecological dilemma interests you the most? And why? Base 2 further defines the dilemma and structures the thinking process by including questions on various sustainability and social aspects, such as: can you describe the complexity of the dilemma by analyzing the three Ps: Planet, People, and Prosperity? And: What stakeholders are involved in the dilemma? What are their interests? In Base 3, students are guided to think about their ecological theme, for example: describe how the external human factors in your social-ecological dilemma influence or disturb population growth, community interactions, or ecosystem interactions. Lastly, in Base 4, students are asked to arrive at a concrete challenge by selecting a few questions they would like to answer: Write down some possible questions that you would like to see answered. These questions are often open-ended and start with "how" or "why". Students concluding the last base marked the end of the engage phase of the project.

In contrast to the engage phase, the investigate phase showed little in the way of structured guiding questions from the teacher, but was primarily supported by guiding activities, for instance through the use of a graphic organizer. In researching their dilemma, and to avoid superficial engagement with the topic, this tool allowed for further analysis, as students were required to position the causes and consequences of their dilemma in a visualization. This structured their cognitive thought processes but also pushed them to think about the causes behind their initially identified causes, as well as the consequences of the consequences, thereby reaching a deeper level of content engagement.

Across the phases of the project, in addition to the booklet, Ryan used a whole-class worked example to illustrate the process. He introduced "forever chemicals" as a case, demonstrating how to move through the different phases of the project, including formulating a challenge, conducting research, and considering the perspectives of stakeholders.

All scaffolds in the booklet were optional, serving as support rather than mandatory tasks. Ryan observed considerable variation in how groups used them. While he considered the graphic organizer in the booklet to be particularly valuable, as it allowed for the visualization of some part of the complexity of the dilemma, some groups skipped it or treated the booklet mainly as inspiration, finding certain assignments redundant or too time-consuming. Others, however, regarded the diagram as essential for shaping their research, especially in the early stages. Time pressure and students' confidence seem to appear as factors influencing the effectiveness of these scaffolds. Ryan described this variability as a defining feature of the project, in which students were responsible for their own learning process. In the pre-project interview he explained:

> Some groups just dive right in and enjoy doing the research. Often that works fine, so they do not need much guidance. But some students struggle to come up with a dilemma or are less engaged. They need much more support. In those cases, a video, a booklet, or an overview of different topics and worked-out examples can spark ideas and keep them moving forward, so they don't get stuck.

Students responded differently to this autonomy. One group experienced it positively. They used the booklet only when necessary and, after a guided start, reported that they became increasingly independent and responsible for their own learning. This relatively low reliance on teacher guidance can be explained in part by the students' older age in this case. As one student in this group noted during the focus group:

> Naturally, you carry a lot of responsibility yourself, since it is your own project. In the beginning, our teacher gave us quite a lot of support, but after a while, we felt we could get started on our own. We thought we would rely on him less and only turn to him when we really needed to, instead of asking for help with every single step or challenge. We also wanted to be able to find answers ourselves. (S1)

Another group, however, struggled with the lack of structure. As one student in this group described during the focus group discussion: "More and more blocks were just thrown at us, and we had to build a tower ourselves, rather than being given the foundation on which we could continue building" (S2). They felt the materials were incoherent, lacked clear direction, and reported low motivation to engage. Although they recognized Ryan's intention to make them responsible, they often ignored suggestions to try certain tasks or explore new topics. Narrowing their broad theme into a manageable research question proved difficult, partly because they struggled to find suitable sources. While they valued the general explanations provided in content lessons, they felt disconnected from their own projects when the instruction shifted to ecological processes outside the scope of their dilemmas. Ryan acknowledged these struggles. He noted that some groups failed to engage deeply with ecological aspects, but explained this partly by the fact that students often became invested only at later stages of the project, which could hinder understanding at the outset.

The arts part of the project was supported by art lessons supervised by the arts teacher, and by guidance from museum artists, with whom students had several conversations to help develop their artworks. Students had complete freedom in design, but were introduced to three artistic aspects: content, form, and deeper meaning, using an art analysis framework. In an inspiration assignment, they explored an artwork related to their dilemma through this framework. The museum visits and artist talks mainly provided scaffolding for empathy. Students were confronted with complex artworks and were encouraged to express their feelings about them. A lecture by an artist and researcher showed how scientific knowledge can be translated into emotion. One student described a change in perspective after the visits:

> At first, I thought it was kind of boring. I looked at the art and didn't really get it. But then, when I learned more about the stories behind some pieces, it got more interesting. I started to see how there could be research behind it. The second time, when we saw how the artists worked, it made more sense. It was nice to see the art beforehand, so I could connect my own topic to what was shown in the museum. (S1)

3.1.2. Soft Scaffolding

Given the open-ended nature of the project, Ryan provided frequent just-in-time support during group work. Observations showed that most of his soft scaffolding focused on cognitive structuring, achieved primarily through questioning, but also through instruction and hints. Less frequently, he reduced the degrees of freedom or engaged in direct maintenance (helping students keep on track), which involved ensuring that students did not get sidetracked and stayed aligned with the project's goals. Feedback was provided only occasionally. A typical interaction during the engage phase was a check with the teacher whether the students were on the right path:

S: Sir, what do you think of animal testing as our topic?

T: How does animal testing affect the environment? What ecological effect?

S: I think less resources. . . and perhaps that stuff come in the nature that has a negative effect on it, or something like that. . .

T: Well, yes. . . Have a look at the chemicals and what they do. That leads to a question. This is a bit too broad still. The assignment is designed to narrow down your interest to a researchable actual topic. So do a bit more research, then you can think of different things.

S: Okay, I understand.

An example of another more frequent dialogue initiated by the students in the investigate phase when they felt they were stuck was:

S: Sir, we are stuck, we don't know how to answer the questions in the booklet.

T: You don't need to fill it in, if you are already passed that.

S: Is a dairy farm an ecosystem?

T: No, I think it is part of an ecosystem. So think broader, how do dairy farms affect the environment?

S: Nitrogen and methane?

T: Yes! So use these factors in your research.

As shown by these examples, through questioning as means to structure students' thinking and reduce some of degrees of freedom, Ryan aimed to gain insight into students' thinking without being overly directive. This approach reflected his belief that struggling with complexity is a vital part of deep learning: "Usually, I think it is actually very good when they get into such a struggle, because then they really start to delve deeper into the dilemma, and often it results in better work."

Furthermore, these examples illustrate the interplay between the predetermined hard scaffold and its use as a tool within the soft scaffolding dialogues. The teacher gauges whether students have gone through the steps involved in formulating their challenge and, if not, first advises them to work on these steps, coaching students on the next stages instead of providing them with a direct answer.

Students recognized this approach, though their appreciation differed. The student group that enjoyed the autonomy found the questioning helpful, as it encouraged independent inquiry and kept them moving forward. The other group, that struggled with the lack of structure, however, considered the guidance too vague and expressed a preference for more concrete direction. In their case, learning was impeded rather than scaffolded in the right direction, not because of conceptual difficulty, but because of difficulty navigating an open learning environment.

3.2. Case 2: Save the Planet—Good Health and Well-Being

The second case was part of a large-scale, 3-day project week organized by teachers involved in the professional learning community at an international school that followed the International Baccalaureate curriculum. The overarching theme of this project week was "Save the Planet." It is mandatory for an international school to provide one interdisciplinary unit per year, and given the fit with CBL, they chose to integrate the two. During the project week, each grade level's group undertook one project, developed through collaboration by teachers of two subjects. Each project addressed a challenge linked with the Sustainable Development Goals (SDGs), such as "Zero Hunger (SDG-2)" or "Quality Education (SDG-4)" The project explored in depth for this case was an integration between the subjects of science and physical health education (PHE), focusing on "Good health and well-being" (SDG-3) for the 13- to 14-year-old age group. Approximately 100 students participated at the start of the week but branched into smaller topic-based groups after the first day. The students who selected the topics heart, lungs, and sugar formed the focus of this study. The three days taken up by the project corresponded to the CBL framework of engage, investigate, and act (see Figure 5). Students worked on the project for approximately six hours per day during the first two days and three hours on the final morning.

On the first day, students participated in a frontloading phase, receiving several workshops run by several teachers from both science and PHE on topics related to the SDGs (see Figure 5). At the end of the day, they chose one of three topics to pursue in three subsequent deep-dive sessions, each introducing a different subtopic. After the deep dives, students selected a subtopic to continue investigating. For example, a student who selected the overarching topic personal health on Day 1 attended deep-dive sessions on heart, lungs,

and sugar on Day 2. After these sessions, students chose one subtopic, and groups were formed based on shared interests. These groups then began conducting their own research and designing a school-wide campaign to promote the SDG Good health and well-being during the second part of Day 2, continuing into Day 3. Figure 6 provides an example of such a campaign, "StepBeat," in which students proposed a school-wide competition which the class accumulating the most steps would win.

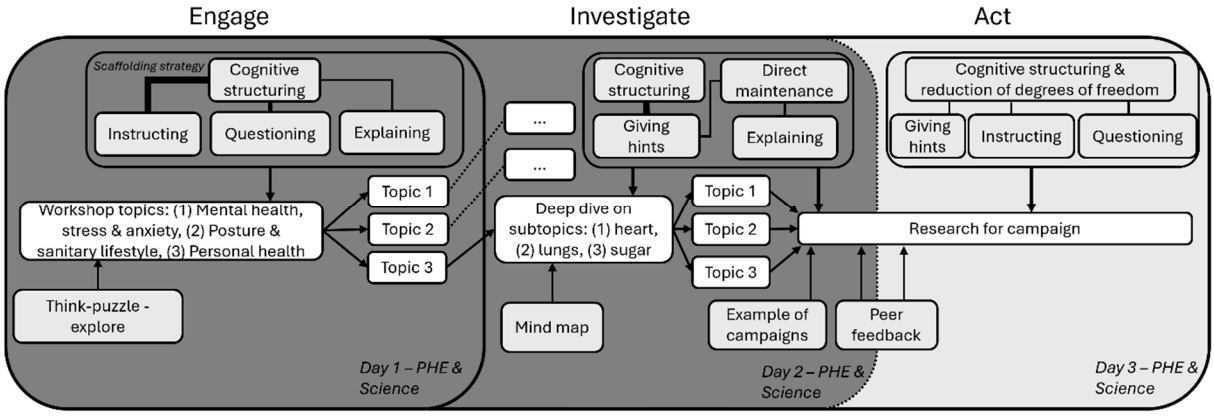


Figure 5. Overview of Save the Planet project steps and scaffolding provided—Case 2. Note. The central pathway represents the project steps. Hard scaffolds are shown at the bottom and soft scaffolds at the top. The upper boxes display the most frequent soft-scaffolding strategies per CBL phase; the thickness of lines and arrows indicates the degree of their presence. The shading of the boxes represents the level of openness in each phase, reflecting the extent to which students could shape their own learning path. The dotted line between the investigate and act phases indicates their overlap in practice.

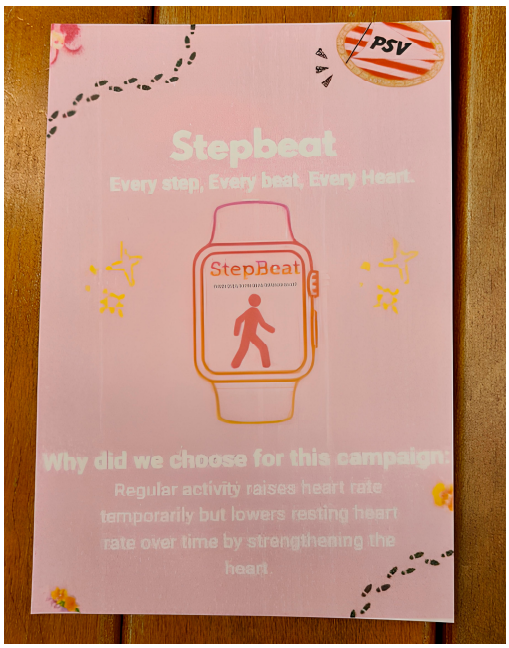


Figure 6. Flyer for students' campaign called StepBeat.

Learning objectives for the project primarily focused on synthesizing content from two subjects, science and PHE, into a product that communicates interdisciplinary understanding. Students were expected to justify how their product reflected this interdisciplinary integration. Although this form of knowledge integration was explicitly addressed in the rubric, the specific disciplinary content from each subject that students were expected to integrate was not clearly defined.

From the perspective of sustainability competences, the project, while not explicitly designed or assessed in these terms, aligned with the competence area *envisioning sustainable futures* within the GreenComp framework. In particular, the project encouraged students to experiment with novel ways of integrating the two subjects, which resonates with the competence of exploratory thinking. Furthermore, the project also relates to the competence area *acting for sustainability*, as students were tasked with developing a sustainability campaign. This activity particularly reflects the competence of collective action, since students were required to collaborate with peers and school staff to promote more sustainable practices within the school.

3.2.1. Hard Scaffolds

As described by John in the pre-project interview, the first phases of the project were structured, with several pathways provided for students, serving as a form of hard scaffolds, and two decision points: one after the workshops and one after the deep dives. At the project kick-off, John presented guiding questions to stimulate thinking, such as "What are the key elements of a healthy lifestyle?" and "How can science help us understand the human body and mind?" Next, the challenge was introduced: "You will participate in a health and wellness project that encourages positive lifestyle changes. This could take the form of a health campaign, an exercise program, or a scientific exploration of well-being." To support their thinking, students were provided with a "think, puzzle, explore" worksheet. In this format, they answered questions such as: "What do you think you know?", "What questions or puzzles do you have?" and "How might you explore these puzzles?". After the workshops and deep dives, just before students had the opportunity to explore ideas for their own campaigns, John provided examples of campaigns and a step-for-step process for reaching an end product, modeling the approach students could take in arriving at their own campaign.

From John's perspective, balancing between open-ended teaching through coaching and a more structured approach, or between student agency and task clarity, was experienced as unknown territory. On the one hand, John stated afterwards that there was too little time for students to work independently, which in his view partly affected the quality of the final products. He observed little creativity and limited motivation to truly engage in deeper learning, and mainly saw reproduction of knowledge that had already been provided during the frontloading phase. On the other hand, much time was devoted to the frontloading phase, in which the knowledge base was established, followed by a phase in which students could work on their own. This transition from structure to open-endedness leaving the student in charge of their learning trajectory, was challenging, as John stated:

Are we really helping the children with independent learning, or are we feeding them too much and holding their hand too tightly, and then complaining that they are not self-directed? I think we actually picked up on that quite well afterwards and said: 'OK, now we'll take another step back.' And when they came to us with questions, we would respond with a counter-question, holding up a mirror instead.

From the student perspective, they valued the shift from workshops and deep dives, which served mainly for information gathering, to the more open-ended phase in which they were in charge of doing research on translating this to an actionable campaign. Students described feeling more competent as they were granted greater autonomy. As one student explained in the focus group discussion:

> I think it actually worked out quite well, because mostly in our classes the teacher really fully explains everything to us. But in this process, I think we learned from ourselves that we must do. . . I feel like in this process we use our brain more. . .

> We had to research about the information, really learn it and I think that really helped us. I think this was a really good experience. (S3)

3.2.2. Soft Scaffolding

When looking across the observed soft scaffolding interactions, many were oriented toward cognitive structuring, often through giving hints, asking questions, and providing instruction, both at the student-team level and in whole-class settings. Alongside this, scaffolding also took the form of direct maintenance, as well as reducing degrees of freedom and, at times, frustration control. Cognitive structuring stood out as a recurring theme. At the student-team level of interaction, group work was often marked by the use of hints and questioning, while in whole-class settings instructing and questioning were especially visible. One example of cognitive structuring, as well as direct maintenance, in the engage phase of the project was initiated by the teacher while assessing student progress:

T: What is the most important question you thought of?

S: So what we came up with is, 'what is the standard of a good or bad habit?'

T: That it not specific enough, can I ask you whether this is about physical or mental health?

S: . . . Both.

T: If you want to, that is fine, you need to keep thinking, why do we do this? At the end you have to make a campaign, today you choose a topic.

A second example of the teacher in his role as coach during the investigate and act phases of the project is a dialogue initiated by a student group:

S: Can you give some feedback on our campaign?

T: You say healthy lifestyle, but what is healthy?

S: A balanced diet.

T: What is balanced? So think of the norms.

S: Okay. . . So give it in percentages or something?

T: For example, yes. Also make it specific, as that makes it easier for yourself. You do the whole of the school?

S: We need to think about that. . .

It becomes clear from these examples, as well as other observations, that student–teacher interactions were initiated by both parties. From the teacher's side, in his role as coach, interactions were aimed at assessing student progress and providing the right amount of steering to ensure that students stayed on track, as well as guiding them toward feasible project outcomes. Feedback from the teacher was often phrased as guiding questions, providing stepping stones for students to focus their attention and guide their research. Interactions were also initiated from the student side, as they sought validation or guidance on the next steps.

From John's perspective, this observation was supported, as he emphasized supporting students by validating and shaping their choices rather than instructing them directly. Instead of telling them what to do, John provided pathways for exploration, leaving options open and offering suggestions about possible directions. Students confirmed this perception, explaining that teachers mainly guided them by posing questions for further inquiry, providing examples for inspiration, or asking evaluative questions to check their understanding, as one student stated in the focus group discussion:

> But I think there was good balance, because like the teacher, they left you with questions to make you think instead of just leaving you with nothing because they could have either given us information or given us nothing. But instead, they guided us the way so that we could find our information ourselves, which made

> us more involved in what we want to make instead of just making something for the IDU [interdisciplinary unit] purpose. (S4)

3.3. Case 3: Insect Hotel

The third case, *Insect Hotel*, was part of a 1-week project at a vocational education school. Students aged 13–14 years from the vocational tracks BWI (Construction, Living, Interior) and PIE (Production, Installation, Energy) were tasked with designing and constructing an insect hotel, addressing the theme of biodiversity. Each morning, students worked in a workshop on the hotel itself, while afternoons were devoted to more traditional lessons, all linked back with the overarching theme of biodiversity and the insect hotel. For instance, during afternoon citizenship lessons, students prepared a presentation explaining the ecological effects of an insect hotel; in afternoon English lessons, they made a video on where and how to install the hotel; in mathematics, they applied geometry; and in science, they worked on assignments involving volume, density, and mass. All of these activities circled back to the design and purpose of the insect hotel.

Students from both tracks collaborated during the creation process, since expertise from both domains was required, so each group had one member from each track. Those from BWI contributed woodworking skills, while PIE students provided knowledge of welding and metalworking. At the end of the week, groups reflected on their process and presented their completed insect hotels to the rest of the class (see Figure 7).

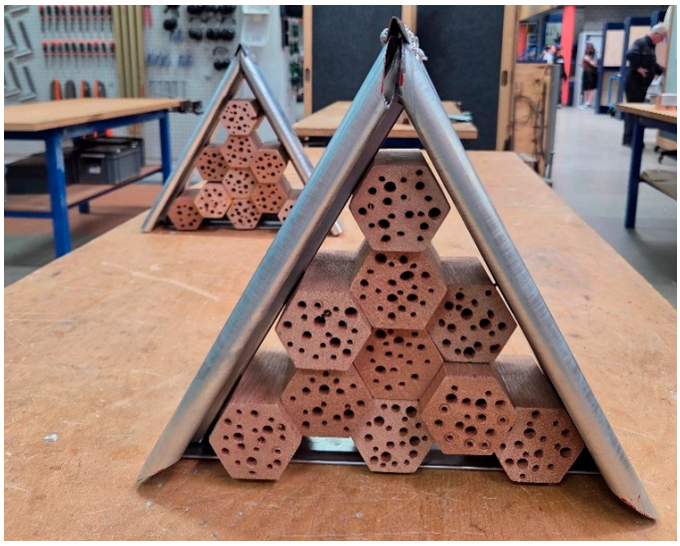


Figure 7. Insect hotel made by a group of students.

Objectives for this project were primarily situated in the realm of practical skills, such as welding or woodworking, rather than theoretical learning objectives. Students were also required to connect the project to the broader theme of biodiversity, although no specific content-related objectives were defined in this regard. The main objective of the project was the correct and timely construction and completion of an insect hotel.

From the perspective of the GreenComp framework, the project, although not explicitly designed or assessed in these terms, resonates with the competence area *embodying sustainability values*, particularly the competence of *promoting nature*. Throughout the project, students were made aware of biodiversity loss caused by human activities and how constructing an insect hotel in one's garden can contribute to supporting local ecosystems. The project also relates to the competence area *acting for sustainability*, particularly the competence of *individual initiative*, as students were encouraged to recognize their own potential role in taking action at a local scale.

3.3.1. Hard Scaffolds

This project was less open-ended compared to previous cases, since the product was clearly defined from the start (see Figure 8). Teachers provided a finished model of an insect hotel as a worked example. Students could closely examine this model, touch it, inspect it, and compare their own work against it, but they were not allowed to measure it directly. Instead, they had to make their own measurements based on a material list and technical drawings. The main challenge of the project lay in mastering the required techniques and in collaborating effectively with peers.

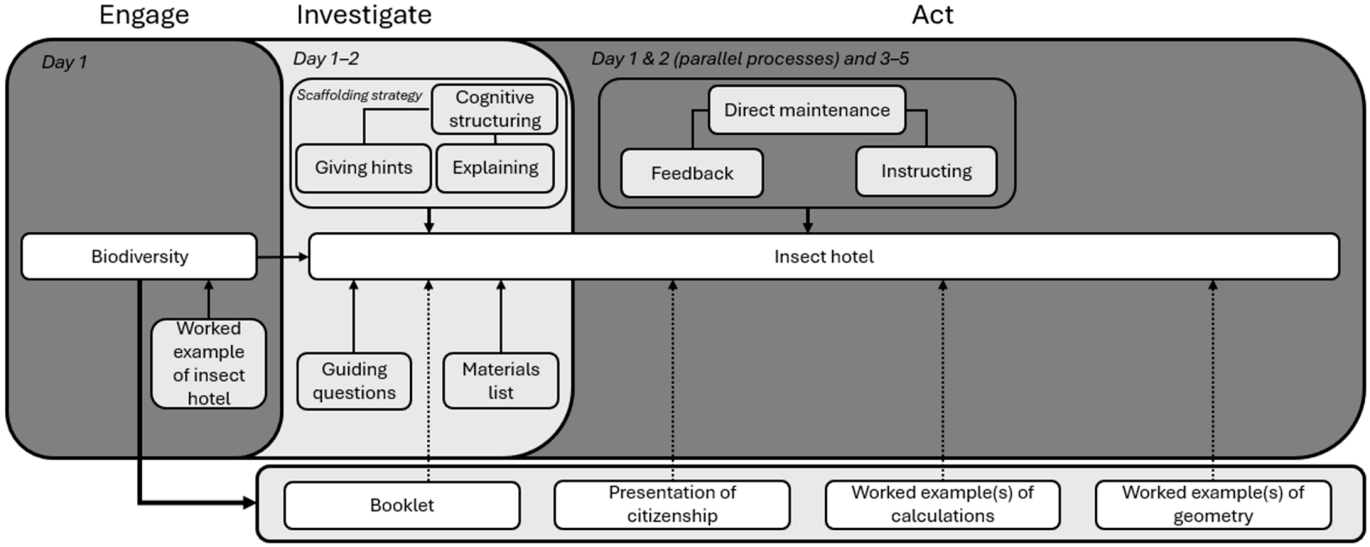


Figure 8. Overview of Insect Hotel project steps and scaffolding provided—Case 3. Note. The central pathway represents the project steps. Hard scaffolds are shown at the bottom and soft scaffolds at the top. The upper boxes display the most frequent soft-scaffolding strategies per CBL phase; the thickness of lines and arrows indicates the degree of their presence. The shading of the boxes represents the level of openness in each phase, reflecting the extent to which students could shape their own learning path. The box outside of the phases reflects the hard scaffolds provided by teachers from other subjects. The dotted arrows indicate indirect scaffolding.

The worked example functioned as a central hard scaffold. Along with it, Ethan provided a materials list to complete and a working document with guiding questions about the link between insect hotels and biodiversity, as well as links to short instructional videos. These videos explained important design considerations, such as the required depth and width of holes in the wood to allow different insect species to nest. While Ethan emphasized the value of these resources, students had autonomy in planning their process. They could decide, for example, whether to start with woodworking or metalworking, and how to distribute tasks within their group of two people. The only milestone was an early check-in, where teachers verified that the materials list had been filled in correctly. This prevented major construction errors later in the week. Ethan noted during the post-project interview that this open-ended process pushed both students and teachers outside their comfort zones, since in the workshop students are usually required to follow a process step-by-step. This is not only to ensure that they learn to carefully follow the protocols leading to a good product, but also for safety reasons, as it enables teachers to intervene more effectively. As Ethan noted:

> You guide them a little in a certain direction of thinking, but beyond that it is mainly about seeing what happens. That also takes some courage. Normally, as a teacher, you already have the final product clearly in mind. You know exactly where the pitfalls are and when to provide extra instruction, because that is

> where students often get stuck. That is a much more programmed approach, whereas this is far looser. But it also means that as a teacher you need to take on a different stance and sometimes improvise. You also pay much more attention to the individual, since everyone is working on different things.

Given the freedom and responsibility students had in planning, dividing tasks themselves, and organizing their workflow, outcomes varied widely. Some students completed their final product on time, while others did not finish at all. One interviewed student group mentioned that they did not have enough time to complete everything and, in retrospect, admitted they could have approached the project differently. Ethan confirmed this, concluding that success largely depended on a clear division of tasks and good communication, so that students were aware of what their peer was doing.

The subject-matter lessons in the afternoons could also be seen as indirect hard scaffolds. Worked examples of calculations involving volume, density, and mass, as well as geometry exercises (for instance, constructing hexagonal figures and fitting them within triangular shapes), reinforced students' understanding of design aspects directly applied in their insect hotels. However, for students, the transfer from these subject-matter lessons to their product was not always clear. As one PIE student stated in the focus group discussion: "I don't remember much about it. We all had to do assignments in different subjects, and they were somewhat connected, but not much more than that" (S5). Ethan confirmed this disconnect during the post-project interview, noting: "I also had the feeling that the essence, the real point, was not very clear for some students. They should understand why they are doing it. They know it to some extent, but it could have had more depth." As such, the misalignment between student and teacher aims, with students focused on completing the product and teachers emphasizing broader learning goals, appears to reduce the effectiveness of the scaffolding.

3.3.2. Soft Scaffolding

Given the open structure of the workflow, most observed soft scaffolding instances focused on direct maintenance through feedback and instruction. Ethan frequently commented on student progress and guided them toward more efficient ways of working to increase the likelihood of success by the end of the project week. One example of this occurred during the act phase, when the teacher intervened to ensure proper execution:

T: (while a student is drilling) What is the limitation here?

S: I think the length of the drill bit.

T: Yes, and also try to move it back and forth a bit, otherwise the drill will get too hot. I think the holes could be a bit deeper.

S: Okay, how deep then?

T: Don't forget the video [about insects and how they build their nests]; it explains the depth and width of the holes.

Cognitive structuring, through explanations and hints, was also very common, particularly at the beginning of the project when students had to collect and measure their materials using the materials list. For instance, during the engage phase, a dialogue between teacher and student unfolded as follows:

S: Should that [calculating how much material is needed] be done with or without extra material?

T: Look very carefully at the construction drawing, there are three different lengths...

S: Oh, that's so stupid of me.

T: That's not stupid at all, I make mistakes too.

S: Should I include the surplus value?

T: What do we normally do in other projects? Net or gross?

S: Net is the actual value, right?

T: Yes, and normally we work with gross, but for your project we already included the cutting loss.

S: Okay, that's fine. Then I'll write down all the actual values.

These interactions illustrate the teacher's role as a coach. Rather than providing direct answers, the teacher guided students through questioning, prompting them to draw on prior knowledge and consult relevant resources. At the same time, the teacher monitored students' progress during practical activities and provided small procedural hints when necessary. This approach encouraged students to take ownership of the task while still receiving targeted support when difficulties arose.

Regarding the support students received, all reported in the focus group discussion that they first asked their peer, and sometimes peers from other groups, when they did not know something, before approaching the teacher. Their questions were often about technical execution and the best way to approach a task. After a brief dialogue in which the teacher either provided hints or explained the procedure, students were usually able to continue with minimal further assistance. Trial and error was a common strategy, with students attempting tasks on their own before seeking help from their peers or teachers.

3.3.3. Cross-Case Analysis

In this section, the results across the three cases regarding instances of both hard and soft scaffolding in relation to project design and the creation of their product are presented, with Table 3 providing a comparative overview.

Table 3. Comparison of scaffolding instances across cases.

	EcoKino	Save the Planet	Insect Hotel
Main hard scaffolds	In biology, a booklet including example cases, graphic organizer, four bases. For arts, an art analysis framework	Mind map and peer feedback. Theme and topic selection through workshops and deep dives	Worked example of end product, guiding questions, materials list, assignments in subject-matter classes
Hard scaffold implementation	Optional scaffolds, with few milestones or structured paths students had to take	Structured the process through guided topic selection after workshops and deep dives, providing pathways within set themes	Embedded in the project process, guiding procedures and sequencing
Soft scaffolding strategy	Cognitive structuring through questioning, instructing and giving hints in biology and empathetic scaffolding in arts	Primarily cognitive structuring through hints, questioning, and instruction; complemented by direct maintenance via hints and explanations	Primarily direct maintenance through feedback and instruction; complemented by cognitive structuring via hints and explanations
Level of interaction by the teacher	Mostly group	Group and whole class	Group and individual

In comparing the three cases, the application of scaffolding was closely linked with the degree of open-endedness in each project. In the EcoKino project, students were responsible for shaping their own socio-ecological dilemmas, which led to an emphasis on just-in-time soft scaffolding and optional hard scaffolds for students to use as needed. Many hard scaffolds were available to support students, but their optional nature allowed learners to decide whether and how to engage with them. In the Save the Planet project, students selected topics within predefined themes and subtopics, with the project providing more upfront structure through frontloading workshops and deep dives. Scaffolding shifted

from strong initial guidance toward more open-ended inquiry, with choice of topic and choice of subtopic marking the transition to increased responsibility in designing their campaigns. Finally, in the Insect Hotel project, the challenge and final product were clearly defined, and fewer hard scaffolds were necessary; scaffolding was primarily focused on procedural guidance and maintenance. Across all three projects, teachers allowed students considerable freedom in planning, dividing tasks, and organizing the temporal sequence of activities. Placing the projects on a spectrum of open-endedness suggests that the function of hard scaffolds shifted from providing conceptual guidance in EcoKino (most open-ended), to supporting topic selection and inquiry in Save the Planet, to procedural sequencing in Insect Hotel (least open-ended).

Another pattern that can be identified across the cases is the balancing act between students' autonomy and their readiness for independent work. In the EcoKino project, where students enjoyed a great deal of autonomy and self-directedness in using certain scaffolds such as the booklet, this freedom also came with risks. Some students thrived, becoming independent, responsible, and self-directed, while others struggled. They felt lost, lacked clear direction, and sometimes ignored optional scaffolds. This implies that autonomy was productive only when students were ready to manage it; otherwise, it could lead to disengagement. In the Save the Planet project, students' readiness for independence appeared to grow gradually as scaffolding such as hints, questioning, and guidance supported those not yet fully capable of self-directed learning. As they assumed more control, students reported increased competence and motivation. On the other hand, the initial structured phase may have constrained creativity, reflecting the balance between support and readiness. Finally, in the Insect Hotel project, where the product and workflow were largely predetermined, students' readiness for independent work was less of a limiting factor, as autonomy mainly involved task sequencing and planning; scaffolding therefore focused on procedural guidance.

Furthermore, the way scaffolding was applied, whether through hard scaffolds such as setting boundaries or narrowing the project scope, or through soft scaffolding such as guiding students' thinking during the process, depended on the objectives of the projects and how these were situated within the interdisciplinary environment. Despite differences between the cases, such as project openness, duration, and educational level, none of the projects explicitly specified content knowledge objectives.

In the EcoKino project, conceptual knowledge was primarily addressed in parallel traditional lessons on ecology, while the project itself served as a context in which this knowledge could be applied. Although not formally assessed, the project emphasized exploring the complexity of sustainability issues. Students were confronted with all aspects of complex sustainability issues, encouraging them to recognize that these issues are not straightforward. Within this context, students were expected to formulate their own social–ecological dilemmas, considering stakeholders, causes, and consequences. This relative lack of structure required many instances of scaffolding to manage the breadth of the dilemmas chosen, both hard scaffolding in the form of a booklet including worked examples or guiding questions, and soft scaffolds. Soft scaffolds were primarily aimed at cognitive structuring: amid the complexity of the dilemmas, the teacher guided students' thought processes by responding to questions with further questions, rather than providing direct answers. In many cases, the teacher did not have a single "correct" answer due to the diversity of dilemmas chosen, making open-ended guidance essential to keep students on track.

Similarly, in the second case, Save the Planet, the primary aim was to integrate knowledge from two subjects into a combined product, but specific content knowledge objectives were not defined. Instead, the project focused on broader goals such as envisioning sustainable futures and acting for sustainability. Students were encouraged to link the disciplines

of science and physical health education, use creativity, and experiment with novel ideas. In response, teachers provided predefined pathways as hard scaffolds, offering clear boundaries and structured options that supplied students with the information needed to design a campaign. For soft scaffolding, teachers structured students' thinking by giving hints to guide and spark creativity, while also checking progress (direct maintenance). Since students had considerable autonomy but only limited time, this support ensured they stayed on track and ultimately converged on one concrete, actionable idea.

In the third case, the Insect Hotel project, objectives were primarily practical rather than theoretical. While subject knowledge played a supporting role in connecting the project to biodiversity, no specific conceptual learning objectives were defined. The project also aimed to connect students to broader sustainability values, such as promoting biodiversity and recognizing the importance of individual initiative at a local level. As such, hard scaffolds were primarily technical, supporting students in constructing the insect hotel and managing their time, and ensuring that they produced a concrete product that met the requirements. Soft scaffolds were directed at skill development and maintaining progress, including cognitive guidance and frustration control to ensure that students completed the project successfully.

Thus, across all three cases, both soft and hard scaffolding were primarily directed at guiding students within an open learning environment. Teachers provided occasional hints, feedback, or questions that helped structure students' thinking processes. However, scaffolding was less frequently aimed at supporting the acquisition of specific disciplinary knowledge.

With regard to interdisciplinarity, integration across subjects was mainly visible in the final products (see Figures 3, 6 and 7). Since specific disciplinary content was neither clearly specified nor formally assessed, scaffolding tended to focus on broader sustainability competences and on helping students move beyond everyday reasoning. In practice, this meant that scaffolding strategies were used to guide students' inquiry processes rather than to explicitly support the learning of particular conceptual knowledge within the disciplines.

4. Discussion

Challenge-based learning engages students in authentic, real-life challenges that are inherently complex and ill-defined, requiring them to take the lead in their own learning [5]. While this represents an ideal scenario, in practice a balance between students' self-directedness and appropriate instructional support, or scaffolding, is necessary to address such challenges [1,15]. Beyond the type, intent, and timing of scaffolding, logistical and curricular factors also influence the structures implemented to guide students toward a successful project outcome [18]. This study therefore investigated how scaffolding was designed and implemented in a CBL environment in secondary education, where teachers aimed to provide the right type and intensity of scaffolds to guide students just enough in the right direction within their self-directed learning process.

The main findings of this study indicate that the nature and frequency of scaffolding varied primarily according to the open-endedness of the project, which was partly a deliberate choice made by the teachers based on factors such as time constraints, the focus on general competences, student level, and comfort. The EcoKino project, a more open-ended project, tended to elicit the use of predominantly soft scaffolds that guided students in real time, whereas teachers relied more on predefined, hard scaffolds for the more structured Insect Hotel project. Similar patterns have been reported in other studies [12,74], showing that the level of project open-endedness affects scaffolding design. This makes sense, as increasing the open-endedness of a challenge and thereby embracing greater complexity introduces uncertainty and difficulties in self-directing one's own work, as well

as in directing how the group works together. Moreover, in CBL contexts, teachers often act more as coaches or facilitators rather than as subject-matter experts, given the autonomy expected and provided to students [5]. Consequently, more instances of soft scaffolding can be expected in open-ended contexts, where groups may pursue diverging directions within the same challenge, requiring adaptive and timely support [5,12,36,75].

Another factor influencing scaffolding in a CBL environment was the objectives of the projects and, by extension, their interdisciplinary nature. Across all subjects, the objectives, although not directly assessed, focused primarily on general competences that transcend specific disciplinary content. While disciplinary content provided the context, such as ecology in the EcoKino project and cardiac function and the role of exercise in science and PHE in the Save the Planet project, it was not the main focus of the projects. Consequently, scaffolding was not primarily directed at understanding conceptual knowledge. This is somewhat surprising, given that in all cases the classification between the involved subjects was strong, which would typically suggest a greater emphasis on disciplinary knowledge [54,57]. At the same time, Hattie and Donoghue [76] argue that higher order thinking processes such as critical and creative thinking need a strong foundation in disciplinary knowledge.

This observation may be explained by the nature of the CBL environment, where learning takes place within authentic and meaningful contexts and is driven by students' own interests [14,18]. Teachers, in their role as coaches, are expected to explore these interests in depth, challenge students to move beyond everyday thinking and knowledge, and scaffold them toward school learning [57,77]. In this respect, scaffolding in CBL differs from many other open learning environments, particularly in the engage phase, in which students themselves formulate their own challenge [9]. Given the broad themes and the diverse challenges that emerge from them, teachers provide scaffolding not only in terms of depth but also in terms of feasibility, guiding students in defining their challenge and translating broad themes into workable solutions.

In competence-oriented CBL environments, scaffolding therefore tends to focus on structuring diverging and converging thinking processes [6]. Rather than guiding students toward predetermined conceptual understandings, scaffolding supports students in exploring complex problems, considering multiple perspectives, and gradually narrowing down possible directions for action [14]. This aligns with the competence-oriented perspective underlying the GreenComp framework [3], as well as experiential and active learning theories [5], where learning involves not only acquiring knowledge but also developing ways of thinking and acting in response to sustainability challenges [44–46].

The three cases illustrate this dynamic. In the EcoKino project, scaffolding centered on challenge formulation and the competence area of embracing complexity in sustainability [3]. Teachers encouraged students to consider multiple perspectives on their chosen dilemma and used visual scaffolds to structure thinking beyond simple cause–effect relations. In the Save the Planet project, scaffolding supported exploratory thinking and the envisioning of sustainable futures [3]. By linking science and physical health education, teachers guided students toward creative sustainability campaigns that could mobilize collective action within the school. In the Insect Hotel project, scaffolding focused primarily on practical skills while simultaneously connecting the activity to broader sustainability values, particularly promoting nature and recognizing individual responsibility in addressing biodiversity loss [3].

Finally, it is important to note that all three cases were situated outside the formal curriculum, either in project weeks or parallel to traditional lessons. This positioning relieved the projects from the pressure of the content-heavy curricula typical of Dutch secondary education and allowed them to build on prior knowledge learned in more

traditional settings [18]. At the same time, this highlights a limitation of CBL in relation to scaffolding. Because CBL is based on student-driven challenges, it can be difficult for teachers to ensure that specific conceptual knowledge is acquired at the intended level. While scaffolding allows teachers to guide students' thinking without undermining their ownership of the learning process, ensuring systematic development of disciplinary knowledge within such open environments remains a complex challenge [78].

Building on the notion of project open-endedness, from the student perspective, another factor influencing scaffolding is students' readiness to engage in self-directed work. A challenge that is perceived as beyond students' skill level can, for instance, result in low engagement [14,15]. While some students thrived under the high level of autonomy provided in the EcoKino project, others experienced frustration and even disregarded the help offered by the teacher or through support materials. Previous studies have shown that students are not always ready to tackle self-directed CBL projects head-on, and therefore tend to prefer more structured learning environments [16,18,21]. In a similar vein, Baghban Karimi [79] found that when given a choice in an open-ended project context, most students opted for the more scaffolded option, and by the end of the project, most expressed a preference for even more scaffolding, thereby avoiding risk-taking. Beyond potential gaps in self-directed learning skills, or students' self-perceived readiness, this tendency may also be explained by students' unfamiliarity with CBL, as many are primarily accustomed to more traditional forms of education [5].

However, some students seemed to thrive under such open-ended conditions. While high autonomy can be challenging for some, for others it may have served as a stimulus for creativity and ownership. This possibly suggests that in the Save the Planet project, the more structured design with workshops and predefined topics may have inadvertently reduced opportunities for risk-taking. As the teacher observed, most student campaigns closely reproduced information from the frontloading phase, showing limited exploration beyond the given parameters. Research has shown that if scaffolds are too directive, students can possibly become dependent and thereby not take ownership of their learning [80]. Furthermore, such findings highlight the inherent tension within authentic, real-life CBL challenges, where teachers continually navigate the fine line between fostering autonomy and offering just enough support to keep students on track without constraining their ownership [24].

Furthermore, it is important to note that student dissatisfaction or a perceived lack of support does not necessarily mean that scaffolding was absent, but rather that the scaffolds in place, whether soft or hard, were possibly not as effective in meeting some students' needs. In the EcoKino project, for example, some students felt overwhelmed by what they perceived as unstructured support, while others considered the guidance redundant. This aligns with research showing that scaffolding must be contingent, adaptive, and clearly connected with students' current level of understanding to be effective [29,81]. However, it could also reflect a lack of affective scaffolds, which are needed to prevent students from becoming frustrated over time; without such support, disengagement may occur, possibly reducing the effectiveness of other forms of scaffolding.

Additionally, in the Insect Hotel project, an attempt was made to connect subject-matter content with the creation of the product, thereby scaffolding students' understanding beyond the practical task itself. However, students did not see this connection; hence, they did not experience it as support. So, besides the possibility that this is a problem of transfer from one subject to another, providing relevant knowledge without showing its connection with practice does not always scaffold student learning. A possible explanation is that the scaffolds did not directly contribute to the task at hand, which was the successful

completion of making the hotel. For instance, scaffolding was found to be most effective when it was clearly tied to the actual project task and problem-solving [82,83].

However, it should be noted that students differ in prior knowledge, motivation, and learning skills, all of which can influence how they interpret and use scaffolds in open-ended learning environments [29,84–86]. For instance, students with stronger self-regulation skills or greater confidence in navigating ambiguity may experience loosely structured scaffolds as supportive, whereas others may perceive the same scaffolds as insufficient or unclear. Similarly, differences in prior knowledge may shape whether students recognize the relevance of conceptual input for the task at hand. Although this study did not systematically measure these factors, the variation in student responses across the cases suggests that readiness for self-directed learning likely mediates how scaffolding is experienced in CBL environments.

Finally, and perhaps unsurprisingly, the nature and frequency of scaffolding appeared to be related to teachers' confidence and comfort in working within a student-centered pedagogy such as CBL. For example, in EcoKino, the teacher emphasized the value of students struggling as part of the learning process, even if this meant some risk to success. In Save the Planet, in contrast, the teacher appeared to find it more difficult to refrain from helping students extensively, seemingly aiming to reduce such risks. Research shows that scaffolding approaches are influenced by teachers' beliefs, experiences, confidence in navigating student-centered and open-ended learning environments, and their perspectives on what constitutes "good education" [87]. For example, if a teacher favors more directive approaches, this will be reflected in their scaffolding, which will provide more structure and take fewer risks. Furthermore, the shift in a teacher's pedagogical role from expert to coach does not happen overnight and requires practice [17,21,22]. Thus, not only do students need to learn and adapt to taking ownership in a self-directed and open-ended environment such as CBL [39,49], but teachers also undergo a parallel learning process [88], taking risks and stepping outside their comfort zones to find the right balance between student autonomy and structure, and to maximize learning by providing appropriate scaffolds at the right time.

Building on this, the findings indicate that teachers' comfort and confidence also shape how they approach sustainability education. While teachers often connect their projects to broader sustainability competences, these competences are neither explicitly taught nor formally assessed. Sustainability education is not part of the standard Dutch curriculum, which may partially explain this gap. Moreover, even though teachers recognize the value of sustainability education, they struggle with implementation [89], as sustainability education requires dealing with climate emotions [90] and managing their own feelings toward sustainability issues, from hopelessness to apathy [91,92]. As such, targeted professional development, either within school-based or cross-school professional learning communities, could support teachers in addressing these challenges, while also providing strategies to design CBL environments that resonate with the holistic, pluralistic, and action-oriented nature of sustainability education, and that incorporate appropriate scaffolding to guide and support students' engagement and competence development [46,47].

4.1. Practical Implications

Results from this study provide insights into the implementation of hard and soft scaffolding instances in three diverse CBL projects, each with distinct strategies, objectives, and student participants. These insights can inform both educators and researchers, providing better understanding of how scaffolding practices can be aligned with the demands of authentic, complex sustainability challenges in secondary education.

First, teachers, in collaboration with school leadership, should decide where to position CBL within the school and curricula. As this study shows, whether CBL is implemented primarily for conceptual knowledge gains or for broader goals such as sustainability competences affects scaffolding approaches. Regarding sustainability education, CBL is likely to function best where there is sufficient curricular space and freedom to support open-ended, authentic challenges. To go beyond everyday learning, schools should dedicate time and effort through workgroups or professional learning communities to formulate clear objectives for sustainability competences, for instance as framed by the GreenComp framework [3]. This makes student learning and scaffolding more explicit, measurable, and effective.

Although this study did not measure the direct effectiveness of scaffolding, tentative implications can be drawn from student and teacher experiences. First, instances of scaffolding, particularly hard scaffolds, should be clearly connected with the overall goal of the project, to help students understand how they support progress toward this goal. When this connection is absent, students may not see the purpose or benefit of the scaffold and may perceive it as additional work. This was evident in the Insect Hotel project, where scaffolds aimed at fostering sustainability awareness did not resonate with students whose primary focus was on completing the product. Moreover, scaffolds need to be offered at the right moment to have their intended effect. In the EcoKino project, the optional nature of the scaffolds worked well for students with strong self-directed skills, yet students who struggled did not always recognize when or how to use the available scaffolds, leading them to experience the support as redundant or irrelevant. Making the purpose and timing of certain scaffolds more explicit, or in some cases embedding them as shared project milestones, may help students structure their work in a timely manner, while still leaving room for students to make their own choices in regulating their work.

In addition, we recommend starting with smaller CBL projects, such as nano-challenges, to gradually build students' readiness for self-directed environments and to help them become more comfortable with autonomy. This gradual approach is equally important for teachers. Large, abstract projects that require students to take ownership can feel daunting for teachers, which may lead them to take back control or avoid risk, potentially limiting student ownership and reducing the authenticity of the project. Professional development can therefore play an important role in supporting teachers in providing contingent scaffolds, recognizing when to step back rather than step in, and managing uncertainty in open tasks.

Last, across all cases we observed predominantly cognitive scaffolding. We therefore recommend also using affective scaffolding, as students must navigate unfamiliar learning environments, make difficult decisions, and are expected to figure out many aspects independently. When students struggle, support should address not only cognitive or metacognitive aspects, such as helping them refocus on their goals, but also the affective dimension [29]. This includes preventing frustration, maintaining engagement, and helping students persist in ill-defined problem spaces, as well as supporting students in recognizing the value and real-world relevance of the challenge, for instance by fostering empathy for those affected by the issue being addressed.

4.2. Limitations and Future Research

Some limitations of this study should be acknowledged. The study focused primarily on how scaffolding was implemented by teachers and experienced by students within CBL projects. As a result, the analysis provides insight into scaffolding practices and the ways in which teachers supported students' thinking processes, such as structuring problem framing, encouraging multiple perspectives, and guiding students toward feasible

solutions. However, the study did not systematically examine how these scaffolding practices influenced students' learning outcomes.

In particular, the study did not directly measure the development of disciplinary knowledge, sustainability competences, or self-directed learning skills. While the projects were analyzed in relation to sustainability competences, for example through the GreenComp framework, the data do not allow conclusions about the extent to which students actually developed these competences during the projects. Similarly, the study does not provide a detailed analysis of students' cognitive processes or knowledge construction throughout the projects.

Future research could address these limitations by combining analyses of scaffolding practices with measures of student learning. For example, studies could examine how specific scaffolding strategies influence students' conceptual understanding, sustainability competences, or problem-framing abilities over time. Future research could, for instance, adopt a mixed-method design using pre- and post-project questionnaires to assess potential changes in students' competences or understanding, complemented by more in-depth student interviews to further explore and contextualize these developments. In addition, analyzing student artifacts, project products, or learning trajectories could provide deeper insight into how students construct knowledge and how their understanding of sustainability challenges evolves within CBL environments.

It should also be noted that this study examined only three cases. While this provides rich contextual insights into scaffolding in CBL environments, the findings are not intended to be generalizable. Rather, the purpose of the multiple-case design was to identify patterns and explore how scaffolding functions across different contexts. Future research could expand the number of cases to examine the applicability of these patterns in other settings.

Furthermore, the three projects involved students who may have varied in their readiness for self-directed and open-ended learning, including differences in prior knowledge, motivation, and learning skills, which likely influenced how scaffolding was perceived and used. Students with more developed self-regulatory skills and confidence in navigating ambiguity were better able to engage with optional or minimally structured scaffolds, whereas others struggled to recognize when and how support could be helpful. Because student readiness was not measured or controlled for, it is difficult to determine whether differences in scaffolding experiences stemmed from the scaffolds themselves or from students' varying ability to operate effectively in a CBL environment. This variability may therefore have shaped the findings in ways that cannot be fully disentangled. Future research could incorporate longitudinal assessments of students' self-directed learning readiness to better understand how evolving readiness levels interact with scaffolding use and shape students' experiences in CBL over time.

5. Conclusions

In bringing real-life sustainability issues into the classroom, CBL serves the goal of confronting students with authentic, complex problems. However, we cannot expect students to tackle these challenges head-on without proper support. At the same time, providing too much support or scaffolding in the form of predetermined structures can detract from the real-life and meaningful nature of the challenge, thereby defeating its purpose. This study investigated both the designed (hard) scaffolds and the just-in-time (soft) scaffolding implemented by teachers across three diverse CBL projects on sustainability issues in secondary education. The results highlight generalizable points: for scaffolding to be effective, it should be closely connected with the goals of the project, aligned with students' readiness for self-directed learning, and responsive to the affective domain to prevent disengagement and frustration. Furthermore, both students and teachers require support

in a broader sense: students in learning to navigate open and self-directed environments, and teachers in becoming comfortable with their role as coach while monitoring the need for scaffolding and levels of student frustration. At the same time, some findings are context-dependent. For instance, the effectiveness of scaffolding may vary depending on the degree of curricular freedom, the positioning of the project within the school, and students' prior experience with autonomy. Teachers' confidence in facilitating open-ended, sustainability-focused projects also influenced how scaffolding was implemented, highlighting the need for professional development and school-level support when adopting CBL in new contexts.

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Abbreviations

The following abbreviations are used in this manuscript:

CBL	Challenge-based learning
PBL	Problem-based learning
DBL	Design-based learning
PLC	Professional learning community
SDG	Sustainable development goal
PHE	Physical health education
BWI	Construction, living, interior (Dutch for Bouwen, wonen, interieur)
PIE	Produce, install, energy

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