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Designing for Digital Education Futures: Design Thinking for Fostering Higher Education Students' Sustainability Competencies

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Abstract: This study explores how design thinking (DT) for sustainable futures fosters higher education (HE) students' sustainability competencies. By analysing the DT process of two teams of HE students co-designing digital educational technologies to address sustainability challenges (namely, children's nature connection and their engagements with fast fashion), we identify how sustainability competencies defined by the GreenComp framework emerge temporally, across the DT phases, and which DT practices foster or hinder their development. Our findings identify three specific DT practices—and three ways to enact those practices effectively—that unlock the transformative potential of DT and enable HE students to embody sustainability values, embrace complexity in sustainability, and envision sustainable futures. Our work contributes to the field of Education for Sustainability (EfS) by demonstrating how design-based learning can promote challenge-centred, collaborative sustainability learning within HE. Drawing on our findings, we also raise the need for new pedagogical interventions that can strengthen the emergence of sustainability competencies in the process of DT.

Keywords: education for sustainability; design thinking; sustainability competencies; design-based learning; higher education (HE); educational technologies

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1. Introduction

As the United Nations [1] points out, climate change is having a profound impact on people's lives, spanning health, food security, housing, and work. There is a global recognition that the many challenges emerging from climate change must be met with sustainable practices and innovation [2]. Environmental sustainability, hereafter referred to as 'sustainability' for brevity, is a critical concept with a problem- and process-oriented application. In this work, we follow Bianchi et al. [3], who define it as "prioritising the needs of all life forms and the planet by ensuring that human activity does not exceed planetary boundaries".

As human activity is the primary driver of climate change, education about and for sustainability has emerged as an imperative to engage individuals and communities in addressing these issues [4]. Education for Sustainability (EfS) has been identified as a catalyst for change by raising students' awareness, fostering their understanding, and developing critical, as well as practical, skills to foster sustainable behaviours [5]. Seeking to inform EfS, previous work has emphasised the importance of recognising students as social and public actors continuously engaged with their context [6]. Other work has advocated new learning frameworks to support a shift from knowledge-based learning towards constructivist and social learning approaches in EfS [3,7,8]. Moreover, the importance of introducing an interdisciplinary and transdisciplinary lens within EfS has also been recognised [9]. The present research is concerned with EfS within higher education (HE), which is a critical pathway for engaging future professionals, policymakers, and educators in sustainability challenges [10–12]. We focus on design-based learning (DBL), which combines the aforementioned pedagogical considerations by presenting HE students with authentic real-life challenges that they must work through using design approaches [13], such as design thinking.

As a DBL approach to EfS, design thinking has been shown to promote creativity, critical reflection, and user-centred problem-solving [14]. Building upon previous research showing DBL's potential, more broadly, to foster sustainability competencies [13,15], we contend that embedding design thinking into EfS could enable HE students to respond to the complexities of sustainability challenges whilst also fostering their sustainability competencies at the same time, such as their systems thinking, futures literacy, and collective action [3]. Nonetheless, since design is a socially constructed practice, the pedagogical value of DBL in developing sustainability competencies will depend on how HE students engage in design thinking. Previous research has not taken a process-oriented approach to understand how HE students practice design thinking and its impact on the emergence of these competencies. Addressing this, our research advances a temporal perspective to examine how a group of HE students, enlisted with designing digital sustainable futures, participate in design thinking processes. Guided by this focus, we ask the following research questions: *What sustainability competencies are fostered through DT for HE students designing for sustainable futures*, and *what are the practices of the DT process that foster or hinder these sustainability competencies?*

To investigate these questions, we carried out a reflective case study concerning two teams of HE students enrolled in a "design thinking and making" module forming part of an Education and Technology postgraduate master's programme at a London-based university. As part of the module, the students designed an educational technology for young children that addressed a specific sustainability challenge in their lives. In line with case study research, we documented the unfolding design decisions students took as part of their design thinking practices and the contextual factors that shaped them. Combined with inductive thematic analysis of students' design practices, we used the GreenComp framework proposed by Bianchi et al. [3] as an analytic tool to identify the emergence of sustainability competencies in this specific educational setting. Contextualised in this case study, we provide insights into how DBL approaches, grounded in design thinking, can promote collaborative sustainability learning within HE.

2. Background

2.1. Challenge-Driven Education for Sustainability in Higher Education

Challenges arising from human-induced harms to the environment, or 'sustainability challenges', are recognised as wicked, systems-level problems [6,9]. Wicked problems involve interlinked complex systems, such as natural and social systems, with the latter including technological, political, and economic systems [3]. As such, sustainability challenges require an interdisciplinary approach that accounts for the complexity and interdependence arising from biological, ethical, social, cultural, and economic factors [6,16].

Wicked problems are difficult to mitigate because they entail incomplete, intractable, controversial, contested, and evolving requirements. These requirements are difficult to recognise or intertwine as they can be conflicting or incomplete, and often do not lead to a single solution to the sustainability challenge [3]. For instance, the rise of fast fashion is associated with complex economic (e.g., capitalist business models, removal of trade barriers), environmental (e.g., use of toxic elements, solid waste accumulation), and social (e.g., poor/unethical labour conditions, consumerism and social signing via clothing, low price expectations) aspects, which could lead to multiple possible mitigations depending on the perspective one takes [17].

To our current interest, higher education (HE) institutions have the potential to develop their graduates' competencies through interdisciplinary learning, as well as transdisciplinary co-creation with non-academic stakeholders, that actively engages them in the process of tackling these complex sustainability challenges [9]. HE's role is critical because universities shape and nurture future citizens, teachers, researchers, and leaders, who can directly affect sustainable futures [10–12]. HE institutions can lead in questioning paradigms and practising new thinking, teaching, learning, and living [14]. Therefore, there is a growing urgency to promote learning practices aligned with such problems through EfS in HE [12].

EfS should aim to empower students and increase their agency to assume responsibility for creating sustainable futures, regardless of their chosen field of study [18]. EfS is a potential catalyst for change in the climate crisis, for instance, by raising students' awareness and developing the skills and, more broadly, the competencies necessary to engage in the crisis [5]. Recognising the need for active climate citizenship, since the early 2000s, there has been a shift away from a knowledge-centric approach to a competence-based approach in EfS. Several sustainability competencies frameworks have been proposed to facilitate this shift, including those by various authors [3,7,8,14]. In this work, we use GreenComp framework [3], which defines sustainability competencies as a set of knowledge, skills, and attitudes that together support students to become agents of change by contributing individually and collectively to shaping futures within planetary boundaries. This framework was developed from the consensus of approximately 75 sustainability education experts and stakeholders, providing educators with "a common reference basis for dialogue, exchange of practices, and peer learning" [3]. It consists of four competence areas: embodying sustainability values, embracing complexity in sustainability, envisioning sustainable futures, and acting for sustainability (see Table 1).

Table 1. GreenComp framework sustainability areas, competencies, and descriptors. Reprinted from Bianchi et al. [3].

Area	Sustainability Competences
1. Embodying sustainability **values**	1. Valuing sustainability (reflection on personal and societal values) 2. Supporting fairness (support equity and justice for current and future generations) 3. Promoting nature (respect the needs and rights of other species and nature)
2. Embracing **complexity** in sustainability	1. Systems thinking (approach a sustainability problem from multiple perspectives) 2. Critical thinking (assess information, identify assumptions and challenge the status quo) 3. Problem framing (formulate current or potential challenges as a sustainability problem to identify suitable approaches to prevent, mitigate and adapt)
3. Envisioning sustainable **futures**	1. Futures literacy (develop alternative sustainable scenarios and steps to achieve it) 2. Adaptability (manage transitions and challenges in complexity) 3. Exploratory thinking (interdisciplinarity and experimentation with novel ideas and methods)
4. **Acting** for sustainability	1. Political agency (responsibility and accountability) 2. Collective action (act in collaboration with others) 3. Individual initiative (agency and active contribution to sustainability)

The GreenComp framework [3] can offer a way to design learning opportunities that develop relevant sustainability competencies for both formal and informal learning. Within HE, this calls for closing the gap between theory and practice, a challenge that can be addressed by educators' application of holistic, project-oriented learning approaches to EfS [19]. Expanding on this, the GreenComp framework [3] argues that transformative, problem-based learning can be an effective approach to developing sustainability competencies. The following section explores how design-based learning aligns with these views, detailing how it can support EfS in HE.

2.2. Design-Based Learning and Design Thinking for EfS

Previous work carried out by Guaman-Quintanilla et al. [13] shows that design-based learning (DBL) can inspire HE students to reflect on their learning process and create their own meanings as they work on mitigating real-life challenges through design, including identifying constraints, generating possible ideas, and testing prototypes. In line with its constructivist underpinnings, research reported that DBL engaged students to apply their prior knowledge [20]. Additionally, students learned problem-solving skills while their creativity was enhanced through the design activities, a finding also observed in the work by Guaman-Quintanilla et al. [13].

Looking at the intersection of DBL and EfS, Huang et al. [15] introduced DBL to teach sustainability within engineering education. They reported that students perceived their sustainability competencies to increase when exposed to DBL as compared to traditional lecturing. Other work found that DBL improved design students' understanding of a specific sustainability challenge, i.e., the circularity of plastic in Taiwan [15]. While fostering their collaborative problem-solving skills, DBL also elicited an intrinsic interdisciplinary connection between the sustainability domain and the design practice, steering the students to explore new pathways in their hands-on learning, e.g., weaving with plastic materials [21]. In a different case study, Taimur and Onuki [14] found that students from two different programmes (a graduate programme in Sustainability Science—Global Leadership Initiative and an undergraduate Design Thinking for Sustainability module) critically examined their assumptions, values, and beliefs and deconstructed ways of knowing and understanding. For example, students' prior assumptions were challenged upon conducting research with the people they were designing for.

Taken together, this past research shows that the constructivist and transformative learning underpinning DBL offers a pathway to cultivate sustainability competencies. Constructivist learning approaches and active learning strategies in EfS involve the learner's participation in a generative and action-oriented learning, fostering responsibility and their willingness to contribute to a sustainable environment [22]. Transformative learning experiences in EfS aim to deconstruct existing ways of knowing and understanding, critically reflect on the values, beliefs, and worldviews underpinning them, and co-construct new shared meanings that can contribute to sustainability [23]. As Taimur et al. [14] argue, transformative learning aims to construct learning environments that expose learners to examine their assumptions critically, grapple with social issues, and engage in social action, usually structured around action-oriented projects and problem-oriented approaches. Demonstrating the transformative potential of such approaches, Taimur et al.'s study revealed students' intention to continue engaging with communities and implementing collective action even after completion of the course [14].

In our research, we propose design thinking (DT) as one approach to foster DBL. DT engages with a problem or challenge to create different "solutions" that place future target users and the context's requirements at the centre [2,24–27]. It is underpinned by constant iteration and interaction with multiple sources of information. DT was originally developed as a framework to guide design practitioners. However, when used in an education context as part of DBL, it can support constructivist learning through participation and engagement with abstract knowledge that gets connected with concrete applications and actions [28]. Similarly, it is well documented that DT can also foster the development of HE students' skills, including problem-solving, teamwork, collaboration, and communication [13,29–31].

This research uses the 'Double Diamond' model of DT, proposed by the UK Design Council in 2003 [32] and later extended by Liu in 2016 [33] to represent the five phases of the design process (see Figure 1). As Figure 1 exemplifies, design is not always linear, and it can be iterative as each phase introduces insights that may prompt the designer to return to an earlier point in time [27,34]. The first diamond represents the 'problem' space, which starts with a trigger, or a challenge, that needs to be addressed [34–36]. It involves literature reviews and user research with the target user group, drawing from a range of design methods intended to enrich the designer's understanding and inquiry of the problem situation (empathise phase) [37,38]. This is followed by a critical analysis that narrows down the information from the previous phase to frame the design problem (define phase) [39].

Upon entering the second diamond, the 'solution' space, the problem situation is transformed into a prospective 'solution'. Following a divergent ideation process with the aid of creative methods (ideate phase) [40], those ideas that are most aligned with the problem situation are turned into functional prototypes using a range of representation techniques (prototype phase) that are evaluated with the target user group (test phase). Evaluation allows to explore if/how the prototype addresses the initial challenge and to uncover unforeseen challenges or unintended consequences to achieve its long-term success. While the design methods and techniques used can vary based on the aim of each phase, the choice and design of methods also depend on the context, user group and design purpose. For example, in designing technologies for learning, previous work has proposed that testing might evaluate the technological (is it intuitive?), pedagogical (does it support users' acquisition of knowledge/skills?), and sociocultural (does it align with users' values?) usability of a digital prototype [41].

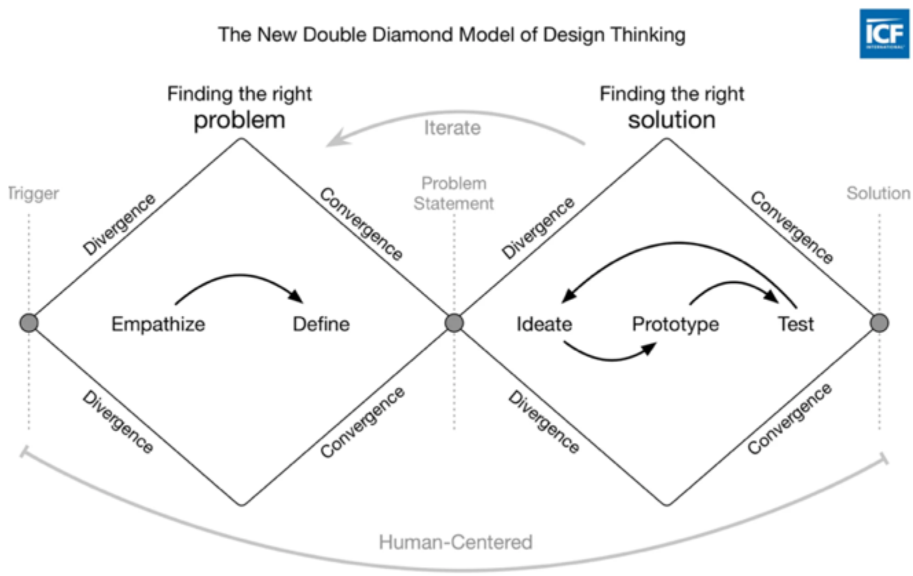


Figure 1. Double Diamond model of design thinking adapted by Liu in 2016 [33].

2.3. Research Motivation: Design Thinking for Sustainability Competencies

This paper builds upon the opportunities introduced by DBL for EfS, and the potential of DT to foster HE students' sustainability competencies. DT calls on students to critically examine their own assumptions, values, and beliefs, and to place target users, as well as their practices and concerns, at the centre of design [2,14,23–27]. When designing for sustainability, DT can thus provide a forum for students to develop sustainability competencies related to values (e.g., by comparing their own to other people's values) and grapple with complexity (e.g., by considering sustainability from a critical systems-thinking lens that negotiates different perspectives). Moreover, because DT catalyses students' creative, action-oriented skills, and willingness to take responsibility [22,42], it can support students to envision sustainable futures (e.g., through exploratory and anticipatory design actions), whilst taking sustainable actions (e.g., through design artefacts designed within teams). Since DT is orchestrated as an interdisciplinary and transdisciplinary co-creation, in alignment with Horn et al. [9], we postulate that it also stimulates the communication and negotiation skills necessary to navigate wicked problems, e.g., [13,43]. Drawing from Birdman et al.'s work [44], these social skills are foundational to the emergence of the GreenComp framework's sustainability competencies informing our work.

As discussed in Section 2.2, the role of DT in fostering sustainability learning amongst HE students has been empirically explored [14,21]. Consistent with its constructivist foundations, past studies indicate that students experience the DT process in diverse ways. For example, when students have positively interacted with target users and stakeholders, this has increased their perceived sustainability competencies, such as their ability to analyse complex issues and develop informed strategies for future sustainable scenarios [44]. Conversely, research has also highlighted how conflicts with peers can hinder the same competencies, underscoring the need for conflict resolution as an integral part of DBL pedagogy [44].

These findings align with the understanding of design as a socially constructed activity, shaped by designers' experiences, team dynamics, and the cascading decisions made throughout the process [39]. As illustrated in Figure 1, DT follows a temporal flow, whereby each design move creates new possibilities while simultaneously constraining others. Existing literature has not taken a process-oriented, temporal lens to analyse the emergence of sustainability competencies *during* the DT process. To address this gap, we examine the design practices of two HE student teams as they designed an educational technology prototype to support primary school children to learn about and engage with sustainability. In line with this, we ask (i) *What sustainability competencies are fostered through DT for HE students designing for sustainable futures (RQ1)*, and (ii) *what are the practices of the DT process that foster or hinder these sustainability competencies? (RQ2).*

3. Methodology

3.1. Student Designers

This research involved HE student designers enrolled in a 'design thinking and making' module offered in an Education and Technology postgraduate master's degree at a London-based University in 2023. From the 32 students participating in the module, this paper focuses on two five-member student design teams (*n* = 10 total) who worked with children on the topic of nature connection or fast fashion. All ten students provided informed consent to participate in this research following an institutionally approved ethics process. Of the ten student designers, eight were female and two were male (one male per group). The students came from Asia, South Asia, the Middle East, Latin America, Africa, and Eastern Europe.

The module, which was led by two of the authors (A.V. and A.G.) with the involvement of a third visiting researcher (H.H.), aimed to develop students' design practice and bridge this with theories from critical studies, pedagogy, and digital learning, with an application to environmental sustainability. Within both teams, there was a diversity of relevant interdisciplinary skills, representing the different domains of expertise necessary when developing new digital prototypes [45]. Each team had members with creative and technology design skills, balanced with team members experienced in education and designing learning materials. All reported being confident in exploring new digital technologies, which was deemed to be important in exploring a wider design space. None of the students were familiar with sustainability and its application to technology design before taking the module.

Table 2 presents the relevant expertise team members reported at the start of the module, alongside their countries of origin.

Table 2. Design teams' relevant knowledge and skills.

Nature Connection	Fast Fashion
Ying (China; teacher, experience with children)	**Angelina** (Colombia; humanities, design skills)
Melanie (Indonesia; teacher, experience with children, learning design, drawing)	**Stefania** (Georgia; teaching)
Hamzah (South Korea; education)	**Barack** (Malawi; computer science)
Rihana (Saudi Arabia; education)	**Sabine** (Switzerland; teaching, experience with children)
Daksha (India; education, design skills)	**Xinbei** *(*China*;* no experience reported*)*

3.2. Design-Based Learning Context

The DT practice we report on took place during a ten-week period in the Spring of 2023, over which the students were tasked to create a digital technology that could offer new pathways to foster environmental sustainability learning. By design, and in line with the constructivist lens guiding DBL, the module left the scope open to allow the teams to develop and pursue their own critical direction.

The first part of the module aimed to develop the conceptual and practical foundation for the design project. This included lectures on:

1. Environmental sustainability, learning, and design.
2. Interaction design approaches and traditions for involving users, such as participatory and co-design.
3. Hybrid artefacts and their digital-physical materials, countering the designers' natural inclination to seek out screen-based technologies, as evidenced in previous years of teaching the module.

To introduce an engagement with past theory, using a structured board in Miro, the teams developed and presented a literature review of their focal domain (i.e., children's nature connection; children and fast fashion) that would inform their technology design, and an analysis of how relevant theories have been applied to the design of existing technology. Ensuring the designers were exposed to a range of theories, we provided curated lists of literature that students could engage with and extend through their research. This initial period also served to develop the teams' collaborative dynamics, for example, through engaging in joint moments of reflection on the collaborative process or participating in low-stake collaborative tasks that allowed students to develop trust within their team.

Having had this foundational learning, the teams embarked on a design project to create a functional prototype that would engender children's nature connection or support a balanced relationship with fashion. Following a DT process (see Figure 2), there were weekly workshops advancing through the design process: (1) exploration and framing the design problem (empathise/define phase), (2) creative ideation (ideate phase), (3) prototyping (prototype phase), (4) formative evaluation/testing (test phase). Within each week, relevant design methods were introduced for the students to use in their projects. In between class times, the teams worked on advancing their projects. This practice-based focus was supported by digital prototyping skills introduced throughout the term, consisting of wireframing techniques with Figma, creating openings for screen-based interactions, and physical computing activities with the BBC micro:bit, in alignment with a hybrid-artefact focus.

The module used the Double Diamond model of DT as a guide to orchestrate the ten weeks (see Figure 2). There was an initial exploratory phase to understand current child practices and position the potential role of technology, followed by conceptual design and making practices that generated the prototype. Children were involved during this design process, first to inform the design challenge in the 'define' phase and then to improve it during the 'test' phase. Table 3 presents the student outputs associated with each phase.

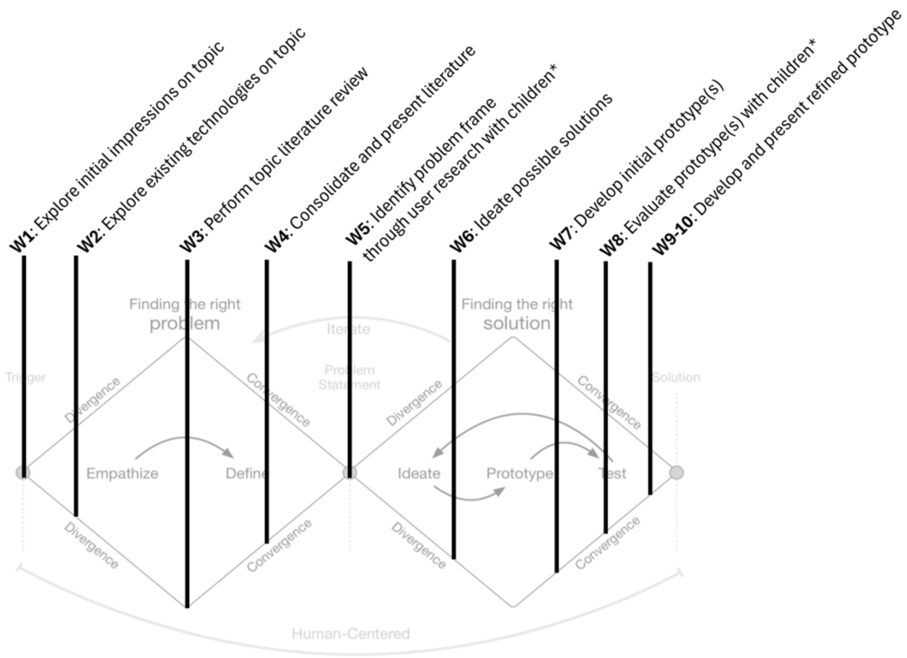


Figure 2. Design thinking activities over ten weeks (W), overlaid on Double Diamond model [33]. * = children involved in the design process in the define phase (W5) and test phase (W8).

Table 3. Student-designer outputs from DT process.

DT Phase	
Empathise/define	1. Literature review based on curated article lists and self-identified readings. 2. Devise research questions to guide user research with children. 3. Use a curated toolkit of framing methods, select and adapt a method to explore the design problem. 4. Carry out user research with children to develop a design frame and iterate upon a design question to give direction to the project.
Ideate	1. Use a curated toolkit of creative ideation methods, select and adapt a method to generate novel and useful ideas that support the design question.
Prototype	1. Use a curated toolkit of prototyping methods, select and adapt methods to develop the chosen ideas into a low-fidelity paper prototype.
Test	1. Devise research questions for user research with children. 2. Use a curated toolkit of testing methods, select and adapt a method to test the prototype. 3. Carry out user research with children to identify improvements and create a high-fidelity prototype.

3.3. Co-Designing with Children in Rural Oxfordshire

Children's involvement was facilitated through a partnership the teaching team had established with a primary school in rural Oxfordshire. The school was based in a remote area accessible by car/bus, with some cycling routes from neighbouring villages. On the school grounds, there were four separate playgrounds, several sports courts, and key areas of green space, including an orchard with apple trees and hedges, a tended garden with mature trees, and a forest school.

Ethics approval was granted by the university ethics board, allowing the involvement of children insofar as it was for teaching purposes. The collection of field notes and visual artefacts was allowed, but no audio recordings or verbatim quotes were obtained from children.

Following a process of informed consent with the children, two classes of thirty 9–10-year-old children each were involved in the two design projects. To ensure the design teams' workload over the design period remained manageable, the tutors determined that children would be involved in the design process twice. In the 'empathise' phase, children shaped the direction of the project in a co-design workshop, and in the 'test' phase, they tried out and gave feedback on the digital prototype the design team had developed.

Each session lasted 45 min, took place in a quiet space in the school library, and involved 15 children at a time. Alongside a teaching assistant who was present in the sessions, there were four facilitators (two designers and two tutors), allowing for smaller group work with the children. In addition to the core participants, the tutors arranged for two children aged 10–11 (one female, one male) to act as advisors to the designers before the first workshop, providing input to try out and improve the methods and topics they planned to explore.

3.4. Pedagogical Support Embedded in the Design Thinking Process

During each week, the HE students were supported by tutors to plan and analyse their design activity, as well as document reflections stemming from their design practice at the end of each week, with the help of structured guides (see Table 4). Alongside the requirement for all the teams to capture each week's work in a PowerPoint presentation, weekly oral presentations were given by two teams using their slides. This provided an opportunity for tutors and peers to observe and comment on the teams' design practices, identifying areas for improvement.

In addition to feedback on the design phase just completed, during each class, tutors and sometimes peers provided critical feedback to improve each team's planning. Taking a mentorship role, the tutors shadowed each team, listening to their discussions. Careful not to guide the students' decision-making, they offered prompts to ensure the teams maintained a critical approach. Examples of such interventions included prompting the students to question prior assumptions embedded in their design questions, scrutinising the alignment between their design frame and creative ideas, and encouraging design through making. Peers, on the other hand, were tasked to provide constructive feedback to each other's prototypes at the end of a session.

Table 4. Pedagogical support across DT process.

	Empathise/Define *		Ideate	Prototype	Test *
	Weeks 1–4	Week 5-Reading week	Week 6	Week 7	Week 8–9
Scaffolds					
Pre-defined structured Miro board	x				
Preparation sheet for planning design research and activities		x	x	x	x

Reflective design thinking prompts bringing attention to insights generated, methodological reflections, and critical design decisions.		x		x	x	x
Tutor and Peer Feedback						
Tutors comment on the Miro board to clarify ideas and comment on promising directions.	x					
Tutors and peers provide oral and written feedback on rotating weekly presentations reporting on design outputs and process.	x	x		x	x	x
Tutors and peers providing feedback during class, whilst the teams prepared their design research and activity.		x		x	x	x

* User research weeks with children.

3.5. Data Collection and Analysis

Over the ten weeks of the module, a range of material artefacts and other visual communication outputs were produced by the design team and formed part of the data collection. For each team, this included:

1. A visual Miro board summarising the themes from their literature review;
2. Four design PowerPoint presentations were created during the design process (for empathise/define, ideate, prototype, and test phases), inclusive of their design methods and visual outputs;
3. An interactive prototype developed within Figma and/or BBC micro:bit.

Besides the visual outputs, acting as participant-observers, each of the three members of the research team took field notes of their ongoing interactions with the design teams and observations of the designers' practice within the class, alongside field notes of the co-design sessions with the children.

Finally, during the weeks following the literature review, 15 min weekly reflective discussions were held online with each design team. Except for a final hour-long discussion, which was scheduled after the term had ended, the remaining ones were hosted by the visiting researcher. While the module leads were careful to avoid a hierarchical dynamic with their students, nonetheless, this step was taken to ensure the design teams could freely share their views without any fear of judgment.

Within each discussion, open-ended prompts were presented to trigger the teams' reflections on their ongoing design decisions and to thus capture critical insights guiding their work (e.g., *What did you learn from the user research you carried out? How does it align/extend/challenge the literature you are using to inform your case?).* The prompts were pasted within the chat window by the facilitator, and the team nominated a member who subsequently orchestrated a group discussion. Audio transcription was enabled to capture these conversations. Overall, 29 data files were collected and analysed.

Thematic analysis was undertaken using the NVivo 14.23.2 Mac software (https://help-nv.qsrinternational.com/14/win/Content/about-nvivo/whats-new.htm). Data triangulation was employed to cross-reference the case study's different data sources (visual presentations, transcriptions of focus groups and reflections, and written field notes), allowing us to widen our field of vision and cross-validate findings [46]. First, we developed a temporal narrative of each design project to capture the evolution of each team's DT. Once this was done, a thematic analysis was carried out, starting with data familiarisation and followed by inductive coding in NVivo. This resulted in 53 preliminary codes across both case studies that were grouped into themes characterising each design phase. The codes were repeatedly discussed within the team and grounded in the data sources to maintain a rigorous coding approach. Based on the thematic coding and the temporal narrative, a description of each design case was developed.

Following this, one of the authors used the sustainability competence framework (see Table 1) to code the emergent competencies. The framework was chosen as it offered a structured methodological tool to analyse and track how individual competencies emerge and interrelate in the designers' learning process. It should be noted, however, that this deductive coding is based on the data available to us, and we acknowledge that competencies may have arisen outside of our data collection. Applying a collaborative coding approach, the codes were validated by a second member of the research team, leading to further refinements.

4. Findings

This section narratively explores the two design student teams' reflections throughout the DT process and the sustainability competencies that emerged [in square brackets; refer to Table 1]. First, we present each team's final prototype to contextualise how they conceptualised their sustainability challenge throughout the design process. This is followed by an analysis of the reflections from their DT process, divided into the problem diamond (how students made sense of the sustainability challenge) and the solution diamond (how students designed an educational technology to address the challenge).

4.1. Team 1: Children's Nature Affective Connection

Team 1 (henceforth, the 'Nature team') were tasked to design a digital approach to fostering children's affective connection to nature. The outcome of their DT process was "Pet Plant" (see Section 4.1.1).

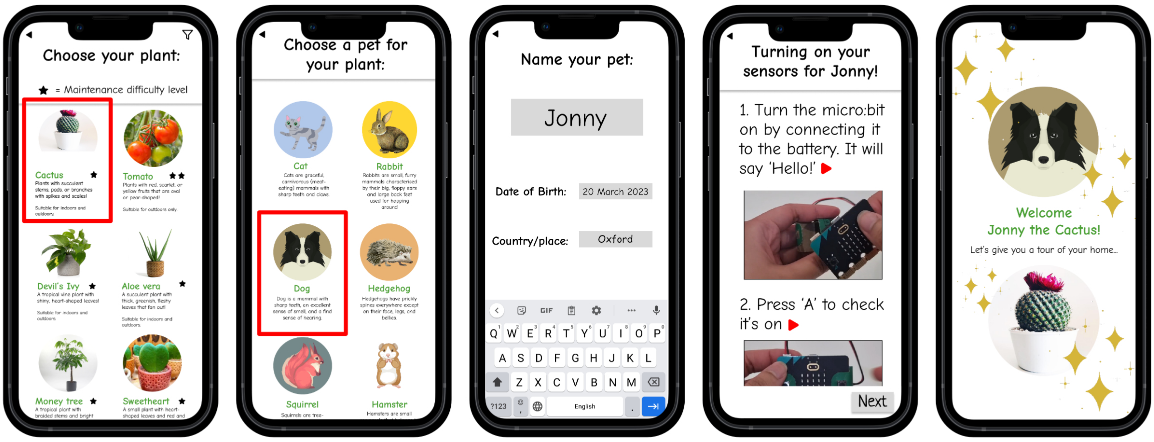
4.1.1. Introducing the Pet Plant Prototype

Pet Plant (Figure 3) is a tangible artefact involving the BBC micro:bit plant sensing (e.g., temperature, sunlight, water, etc.) and a mobile app. Children are guided to the app which introduces the challenge of taking care of plants and explains how to install the micro:bit in the plant pot, so that it monitors the plant's status (Figure 3A). The child is prompted to identify their plant in a catalogue and can choose a digital 'guardian pet' for the plant (Figure 3B). Acting as an avatar for the plant, the digital pet helps the child identify and take care of the plant's needs. In Figure 3B, the child has selected a cactus represented by a pet dog who communicates to the child the plant's needs during the day.

Once the pet avatar is paired with the child's plant, the plant's main needs (soil, sun, water, temperature) are monitored and displayed in the avatar pet's digital environment within the app (Figure 3C). The sensing data are visualised in the bottom menu and are highlighted with a traffic-like colour scheme. Green indicates that the plant is healthy and red indicates that the plant needs care, thus encouraging children to take the required action. For example, the pet dog, in this case, indicates to the child that the plant needs more sunlight (Figure 3C, left, middle), prompting the child to take the plant to a physical location with sunlight, thus triggering the display to change as a result (Figure 3C, right). In addition to this, children can also access information about their plant and its care in the top left menu, as well as tips on how to meet the plant's needs, through a "fun facts" page.

While the visualisation of the plant's environmental conditions is seen as a key factor to informing children's instrumental plant care actions, in Pet Plant, the child's love for pets is mobilised as a mechanism for affective connection, enabling children to *transfer their positive affect for their pet to the plant*. Over time, it is speculated that this affective transference creates a long-term connection with the plant.

A. Pet Plant introduction



B. Pairing with Pet Plant

C. Pet avatar indicates that the plant needs sunlight

Figure 3. Pet Plant final prototype, developed in Figma by the Nature Team. Created by the Nature Team, based on their final prototype presentation (2023).

4.1.2. Problem Diamond: Bringing the Children's Sociocultural Context in Conversation with the Literature

To empathise with the topic of nature dis/connection and define the design challenge, the Nature team kicked off the design process with a targeted literature review of their sustainability challenge related to their target users, i.e., children. For example, alongside the module's pre-curated reading lists (see Table 3), they identified literature that explores how nature and sustainability are linked, focusing on children [47–49]. The team's exploration of the broad domain—nature and sustainability—narrowed to a specific population allowed them to consider the sustainability challenge from the lens of the child [values: 1.1]:

> *Today's children risk experiencing alienation due to urbanisation […] [47], which causes a lack of understanding of nature and our relationship towards it, which is responsible for current severe sustainability issues [49]. Therefore, there is a need for […] an increased exposure to nature and positive experiences in the natural world to improve one's connectedness to nature [48]* (empathise/define phase, PowerPoint slides).

By exploring the specific literature that linked their sustainability challenge to children, the Nature team identified key concepts related to childhood, such as alienation and urbanisation. For instance, ref. [47] introduces ideas of young people in the U.S. and other technologically advanced countries experiencing nature "*so close, and yet so far*", where urban areas offer fewer natural play spaces. These concepts resonated with the team's own assumptions about children's connection with nature, since they had grown up in urban environments and felt disconnected from nature due to a lack of nature interaction [values: 1.1, complexity: 2.3]. The literature and their personal assumptions were reflected in an initial design question that framed how the team viewed children's nature connection from a deficit perspective:

> *"How might we encourage children to change how they view and interact with nature?"* (empathise/define phase, PowerPoint slides)

However, this design question was challenged when the Nature team engaged children in user research in the "define" phase of design thinking. Following their literature review, the Nature team implemented two user-research strategies to explore the children's sociocultural context and to question their initial assumptions about them. First, inspired by the focus group method, they created an initial activity using visual nature props (e.g., images of pristine landscapes, deforestation, animals) and emotion sticks (displaying happy, unsure, and sad faces) to ask children about their understanding and feelings towards nature. The team noted that children clearly articulated their understanding about how the natural world was threatened by human activity, and how they were being affected by this emotionally [values: 1.1, 1.3; complexity: 2.2].

> **Melanie:** *I assumed [children] would be similar to how I was as a kid and how it was aligned with the literature, but they were the opposite of what I assumed they would be. They were aware of their emotions and very articulate*. (empathise/define phase, weekly group chat)

Secondly, inspired by the cultural probes design method that seeks to tap into people's everyday experiences [50], the Nature team led the children in a multi-sensory activity where they distributed little baggies of natural materials (soil, leaves, sticks, pebbles, etc.), as well as drawing templates, and asked children to tell a story about their past experiences in nature, primed by the natural materials. They observed how children interacted with the natural materials, noting that some children did not want to touch the soil, while others played freely with it, making miniature mountains and forests from these resources or simply passing it through their fingers. The team reflected that, while a couple of children reported engaging *with* nature (e.g., through gardening with parents), most children drew stories about being *in* nature (e.g., playing with their pets, playing hide-and-seek with friends, playing sports, and camping in Europe), noting that these experiences did not involve direct sensory experiences with nature, which the team speculated affected the quality of their nature connections [values: 1.1, 1.3; complexity: 2.1, 2.2]:

Melanie: *Their connection with nature is limited to the aesthetic aspect of it, instead of actually going into it.*

Rihana: *Yeah, […] they are interacting in nature, but not with nature… with others in nature, but not with nature.*

Further, the user research also made the team aware of unacknowledged assumptions that they developed because of their own cultural heritage, such as how children in rural England interacted with nature differently from their experiences in their home countries [values: 1.1; complexity: 2.2]:

Ying: *I had an assumption that kids in the UK always interact with nature, unlike kids in my hometown, but it turns out that they would only "appreciate" nature. Like: "Ohh, nature is beautiful, and nature is good", but they would also think that our soil is dirty… that was out of my expectation.* (empathise/define phase, weekly group chat)

The user research provided more contextual detail that enabled the team to become aware of the sociocultural aspects relevant to children's nature connection. For example, another unexpected finding revealed by children's stories was the mediating role of parents in children's relationship with nature. Based on children's contributions, the team reported that "*They [children] want to spend more time in nature, but are not allowed by their parents as it is deemed 'unsafe' and 'dirty'*" (empathise/define phase, PowerPoint presentation) [values: 1.1, 1.3; complexity: 2.1, 2.2]. Upon uncovering this finding, the team faced division:

Melanie: *We were conflicted. Half of our group was like, "Include parents!", and half was like, "No, don't include parents!" […] So, we wanted to look at literature, like, evidence on it.* (empathise/define phase, weekly group chat)

The team returned to the literature to see if this finding had empirical backing, noting several other papers with similar themes [47,51,52] (Empathise/Define phase, PowerPoint presentation) and determined that the parents were an important factor to consider. Furthermore, they noted how bringing parent–child collaboration into their design would align with a recommendation from Vasalou and Gauthier [53] that future technologies for children's engagement with environmental sustainability should seek to foster intergenerational and community collaborations [values: 1.1, 1.3; complexity: 2.1, 2.2, 2.3]. As such, this particular finding about parents redirected the course of their design, shifting their design question from

"How might we encourage children to change how they view and interact with nature?"…

to

"How might we encourage parents and children to understand nature better and their interactions with it to nurture an affective relationship?" (empathise/define phase, PowerPoint presentation).

However, coming to this reframing of their design question was experienced by the team as a challenge, and was possible because of the team's social dynamics, characterised by collaboration and negotiation. Daksha reflected on how they worked together to reframe their design question following their user research [complexity: 2.2; 2.3]

Daksha: *I do remember all of us just [discussing] and me going down that rabbit hole and then just taking that question in different directions, but I don't think it was an issue. I think it was just all of us thinking, and me being the person who would read it like a lot more. I was going into my rabbit hole, but I think it really helped when we all just talked about what exactly we meant by certain things, so that we could have worded it better, which is where asking and following up with questions, no matter how* *annoying that entire 10 min was, it really did help for us to understand what we're not talking about and what we need to focus on*. (empathise/define phase, weekly team chat).

4.1.3. Solution Diamond: Embracing Three Design Dilemmas

Once the Nature team framed their sustainability challenge and defined their design question, they entered the solution diamond of DT to develop a digital prototype that responded to this challenge. During the ideation phase, the Nature team employed two creative methods to generate ideas: (1) embodied ideation, a method that examines the relationship between the human, materials, and context to broaden the design space [54] and (2) brainstorming, a method supporting the generation of divergent and convergent ideas [55]. For embodied ideation, the team tried to take on the role of children, going to a local park where they hugged trees and played with natural found-materials. They reflected on the strengths of how they conducted their embodied ideation (e.g., how they were able to re-learn about nature, use their senses to gain first-hand knowledge of natural materials, become aware of possible hazards that would be of concern to parents), and also on the weaknesses of their approach (e.g., lack of preparation of sensory probes a priori), connecting these to the literature [54] [values: 1.1, 1.3; complexity: 2.1; 2.2]. Based on their findings from the embodied ideation, they then engaged in more traditional brainstorming using a digital whiteboard to generate ideas.

Three design dilemmas emerged during their ideation, which made this phase particularly challenging for the Nature team. In their weekly discussion, Melanie said, "*It was like ridiculously hard. I wanted to cry*". Daksha elaborated, "*I think, unanimously, none of us really enjoyed the ideation phase [because] we did face some bottlenecks*", referring to design dilemmas. The first dilemma related to the "abstract nature" of nature connection. Melanie explained, "*I think the problem is because our design question is very abstract. I feel like it's not that technical cause it has to do with supporting affective relationships, which is not something we can really see and it's not something tangible. I guess it's like, you know, compared to other teams like in fashion who would just like, 'Ohh what can [kids] do', it's very close, it's a bit more straightforward*". To overcome this dilemma, the team attempted to anchor their ideas in the sociocultural playful activities that children reported already doing in nature [values: 1.1, 1.3; complexity: 2.2; futures: 3.1, 3.3]:

Rihana: *Most of the activities the children did in nature were passive, like cycling or playing football […] After Ideation, we got an idea about […] allowing them to go into nature and interact using an app to guide them.*

Melanie: *We wanted to focus on the natural activities they're already doing, but […] adding more meaning to them*. (ideation phase, weekly team chat)

The second dilemma related to integrating technology as an opportunity for nature connection, an idea they found incompatible with their previous literature review and personal experiences of how screens tend to pull people away from nature/outdoors to indoors. Daksha explained how they "*struggled to relate technology with nature*" because they "*wanted children to spend more time in nature, but without [using] the technology*". To tackle this apparent incompatibility between nature and technology, the team diversified how they thought about *when* technology could foster nature interaction, i.e., using technology *before* nature interaction (e.g., for planning or incentivising activities in nature) or using technology *after* nature interaction (e.g., to document activities in nature), rather than *during* nature interaction [values: 1.1, 1.3; complexity: 2.1, 2.2; futures: 3.3].

The Nature team addressed these two dilemmas by developing two ideas that introduce technology as an intermediary to children's current activities happening in an outdoor setting [54]. Namely, an interactive map, where children could document stories about their nature interactions in those areas to share with other children, and a gardening app, where children could use a digital platform to interact with plants in outdoor settings, scanning plants and getting real-time information about them. These initial ideas illustrate how the team used the sociocultural context unveiled during their user research to explore different approaches that fostered technology as a mediator to enhance children's connection to nature.

However, a third dilemma arose when the team realised that these technologies did not address parents' reluctance to allow children to spend time outdoors due to safety concerns, as revealed in the workshop with the children. To overcome this challenge, the team broadened their consideration of nature from constituting only outdoor spaces to a relational lens of nature as all living things and spaces created by living things (i.e., including indoor spaces shared by humans and non-humans) [values: 1.1, 1.3; complexity: 2.1, 2.2, 2.3; futures: 3.1]:

> **Rihana:** *[We] realised it is possible to include technology and make children go outdoors and interact with each other […], but it is easier to bring nature inside and include technology at the same time*. (Final focus group)

Whereas these critical dilemmas informed how the Nature team developed the initial Pet Plant prototype (see Section 4.1.1), the team continued to build on findings from previous research, e.g., [48,56,57]:

> *When children interact with plants more, they learn how to problem-solve and care for their plants. This increases [children's] exposure to nature and their interest in environmental protection and pro-conservation behaviours [48,56,57].* (ideation phase, PowerPoint presentation)

At each turn of designing Pet Plant, the Nature team used new literature to negotiate and justify the design decisions they made, e.g., whether to allow manual or automated plant-animal pairings, the level of detail to show for the plant's statistics, the way educational information about plants was integrated, as evidenced in their reflective slides from the prototyping week. For example, as Figure 4 shows, concepts from children's agency and self-determination were used to compare and ultimately critically inform the design choice for children's manual pet avatar selection e.g., [58], expecting it to foster children's perceived responsibility towards their plant [values: 1.1, 1.3; complexity: 2.2; futures: 3.1].

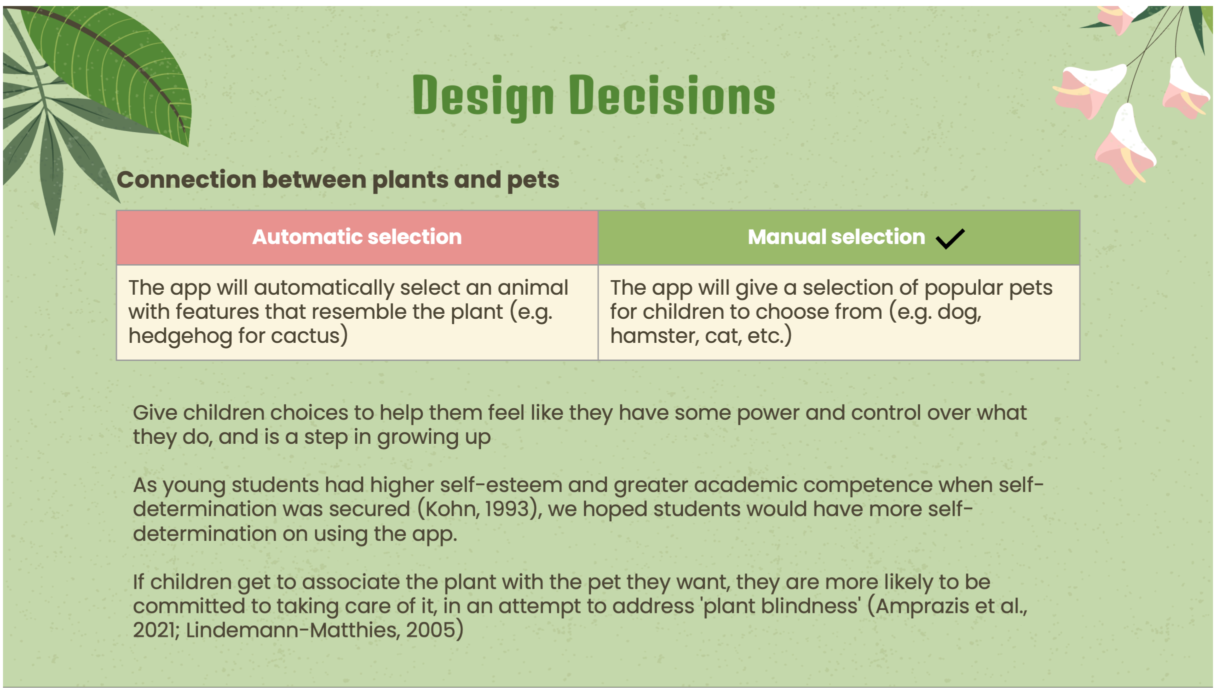


Figure 4. Prototype phase: Pet avatar design decisions informed by literature. Created by the Nature Team, based on their prototype phase PowerPoint presentation (2023) [58].

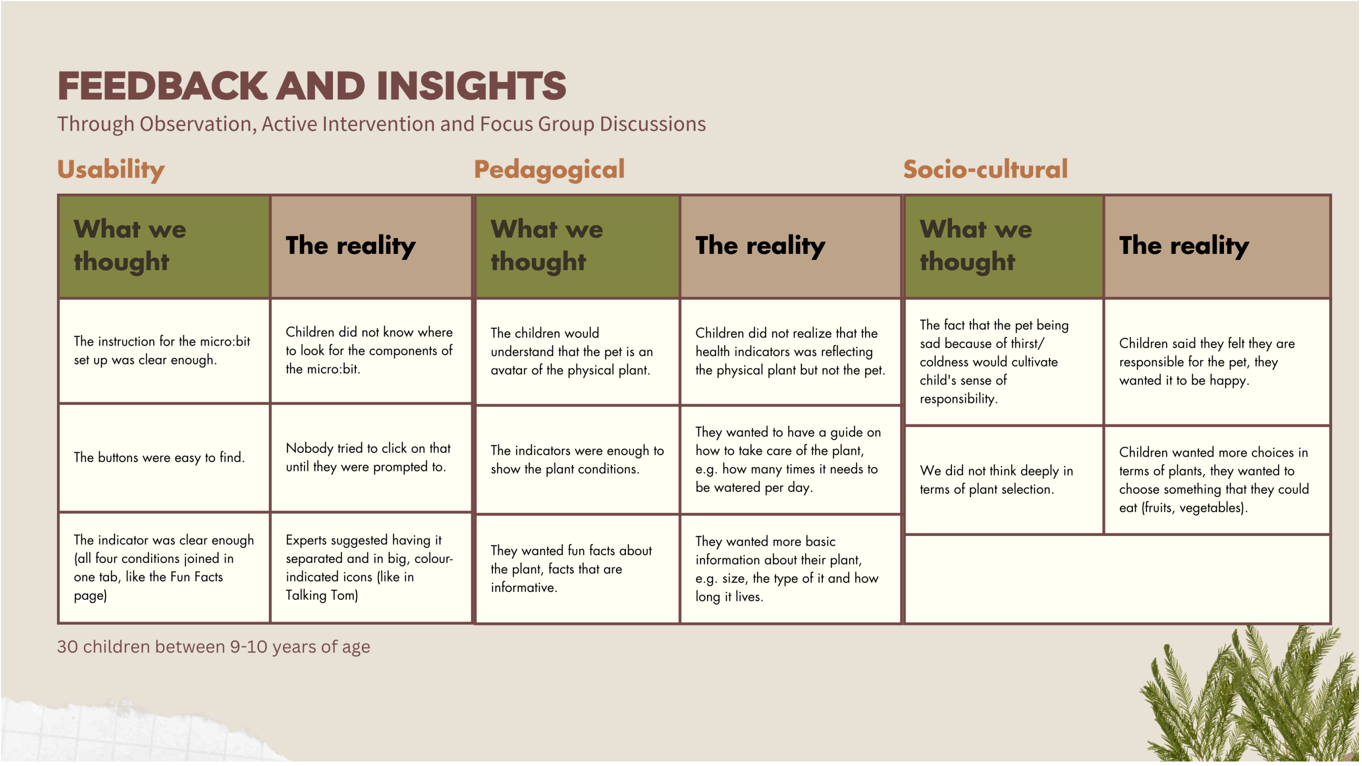
In addition to developing an interactive prototype of the Pet Plant app and the micro:bit, the team created a video narrative that enacted a child interacting with Pet Plant in their home. Pet Plant was tested with the same class of thirty in small groups of 4-5 children, similar to the "define" phase, with children watching the video and interacting with Pet Plant freely. Guided by the module's materials, they probed into usability, pedagogical and sociocultural issues, intending to improve their prototype. Many children showed excitement toward Pet Plant, connecting it to previous, unsuccessful experiences they had in caring for plants, which Pet Plant could assist with. On the whole, the "test" phase allowed the Nature team to consider both how Pet Plant nurtured children's affect with plants and to identify improvements to the design features used to cultivate this affect [values: 1.1; complexity: 2.2; futures: 3.1, 3.3]. One of these improvements stemmed from the finding that children were not always able to relate the physical plant to the pet avatar:

> **Ying**: *They didn't make the association between the pet and the cactus. They just simply forgot about the plant*. (Final focus group)

Besides this comprehensibility issue, children had affinity with specific animals and some failed to relate with the dog avatar included in the mock prototype. Children introduced ideas for new pet avatars, ranging from including other favoured pets to animals that represented the qualities of the plant. Further extending the affective connection, they proposed new plants they wished to care for. These ideas enriched the team's prototype, though members of the Nature team continued to ask whether the pet avatar forged the pathway toward the child's affective connection with the plant, or whether this was established by the quantitative plant indicators that visualised its health [complexity 2.2; futures: 3.1].

> **Melanie**: *How does the app support children to form an affective relationship with their plants, and like if they would feel more responsible…? They all said yes, but we don't know if it's because of the dog. If the dog had any role in it, or was just because they knew what was going on through the (plant) indicators.* (Final focus group)

Following an approach similar to their initial user research, the Nature team continued to draw critical comparisons, this time between the design assumptions embedded in their prototyping design decisions and the research findings generated from involving children, contributing to targeted improvements in their prototype (see Figure 5) [complexity 2.2; futures: 3.1, 3.3].



FEEDBACK AND INSIGHTS
Through Observation, Active Intervention and Focus Group Discussions

Usability: What we thought	Usability: The reality	Pedagogical: What we thought	Pedagogical: The reality	Socio-cultural: What we thought	Socio-cultural: The reality
The instruction for the micro:bit set up was clear enough.	Children did not know where to look for the components of the micro:bit.	The children would understand that the pet is an avatar of the physical plant.	Children did not realize that the health indicators was reflecting the physical plant but not the pet.	The fact that the pet being sad because of thirst/ coldness would cultivate child's sense of responsibility.	Children said they felt they are responsible for the pet, they wanted it to be happy.
The buttons were easy to find.	Nobody tried to click on that until they were prompted to.	The indicators were enough to show the plant conditions.	They wanted to have a guide on how to take care of the plant, e.g. how many times it needs to be watered per day.	We did not think deeply in terms of plant selection.	Children wanted more choices in terms of plants, they wanted to choose something that they could eat (fruits, vegetables).
The indicator was clear enough (all four conditions joined in one tab, like the Fun Facts page)	Experts suggested having it separated and in big, colour-indicated icons (like in Talking Tom)	They wanted fun facts about the plant, facts that are informative.	They wanted more basic information about their plant, e.g. size, the type of it and how long it lives.		

30 children between 9-10 years of age

Figure 5. Testing phase: Contrasts between team assumptions and user research findings. Created by the Nature Team, based on their testing phase, PowerPoint presentation (2023).

4.2. Team 2: Children's Fashion

Team 2 (henceforth, the 'Fashion team') were tasked to design a digital approach for children to learn and engage with fast fashion as a sustainability issue. The result of their DT process was a game called Fashion Turtles (see Section 4.2.1).

4.2.1. Introducing the Fashion Turtles Prototype

Fashion Turtles is a mobile game for children that aims to develop their knowledge about the lifecycle of clothing through game-based learning. Representing a circular fashion approach, the game first introduces children to the clothing lifecycle, with each level representing a single stage of the lifecycle, starting with the materials used to make clothes, through to clothes manufacturing, and disposal (see Figure 6A). Approaching each stage of the lifecycle as a game level, the Fashion team developed 'materials', i.e., the first level of the game for their prototype, as an archetype for all future levels. Upon selecting a level, children are presented with three types of minigames to choose from: trivia (true/false questions, single answer questions), match (pairing questions), and organise (classification questions) (see Figure 6B). If the child answers correctly, points are awarded; otherwise, a corrective explanation is given. Once the child has correctly answered all the questions within the minigames, the app unlocks a challenge aimed at supporting children's fashion-related sustainability skills, such as repairing (see Figure 6C), as well as opening the next level in the fashion lifecycle.

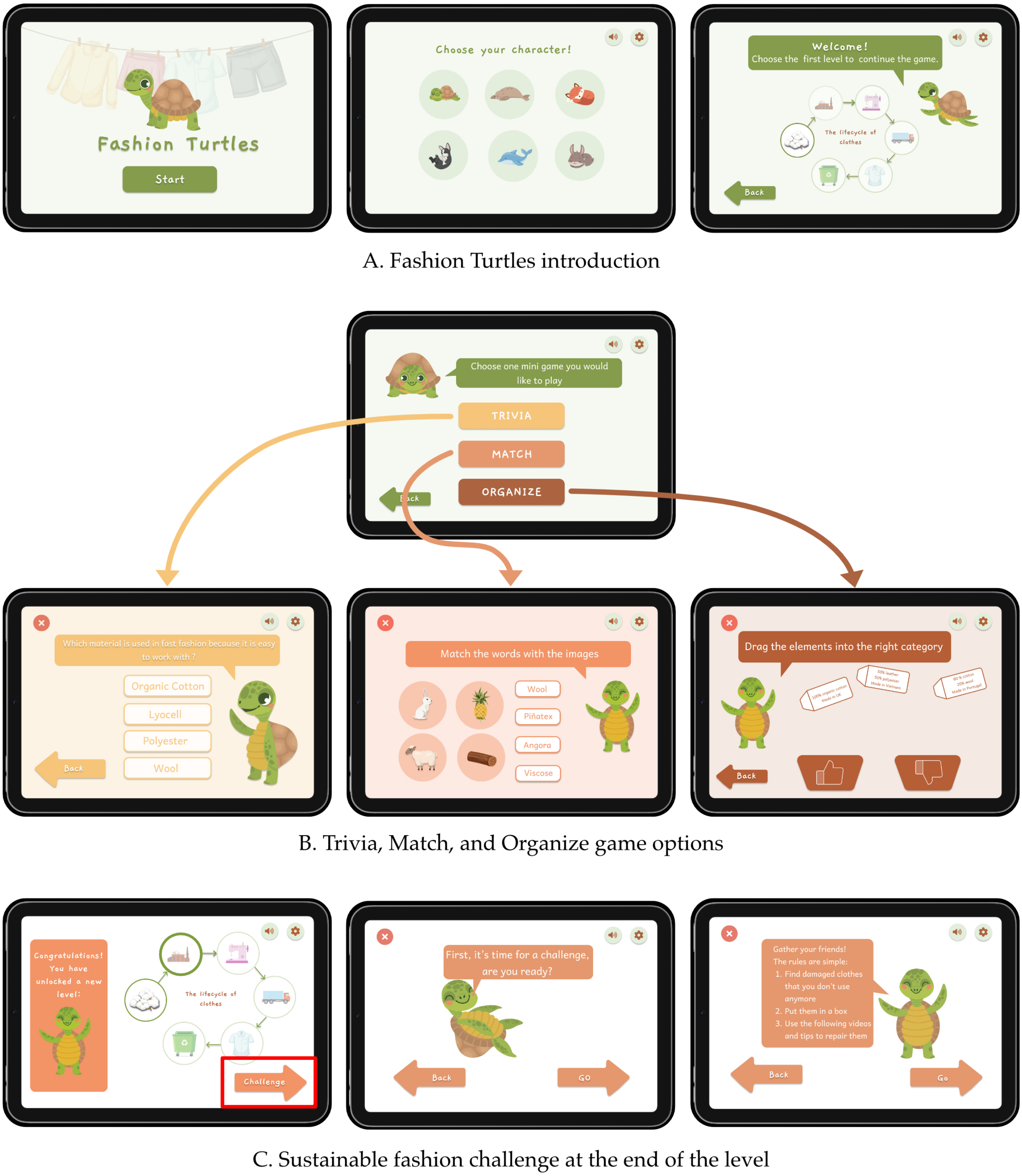


Figure 6. Fashion Turtles game prototype, developed in Figma by the Fashion team. Created by the Fashion team, final prototype presentation (2023).

4.2.2. Problem Diamond: Non-Specific Literature Review Before User Research Derails Design Goals

The Fashion team started by exploring fast fashion through a systems-thinking lens, which allowed them to develop their joint understanding [complexity: 2.1]:

> *People throw them away instead of repairing them [clothes] (habits). [Clothing] contains toxic substances, and [fast fashion] leads to pollution (environmental impact), and there*

are bad working conditions for producing cheap [fast fashion] products (social impacts). (empathise/define phase, Miro board).

These initial directions were elaborated with a concept map (see Figure 7) that further expanded on the importance of just and fair labour [values: 1.2; complexity: 2.1].

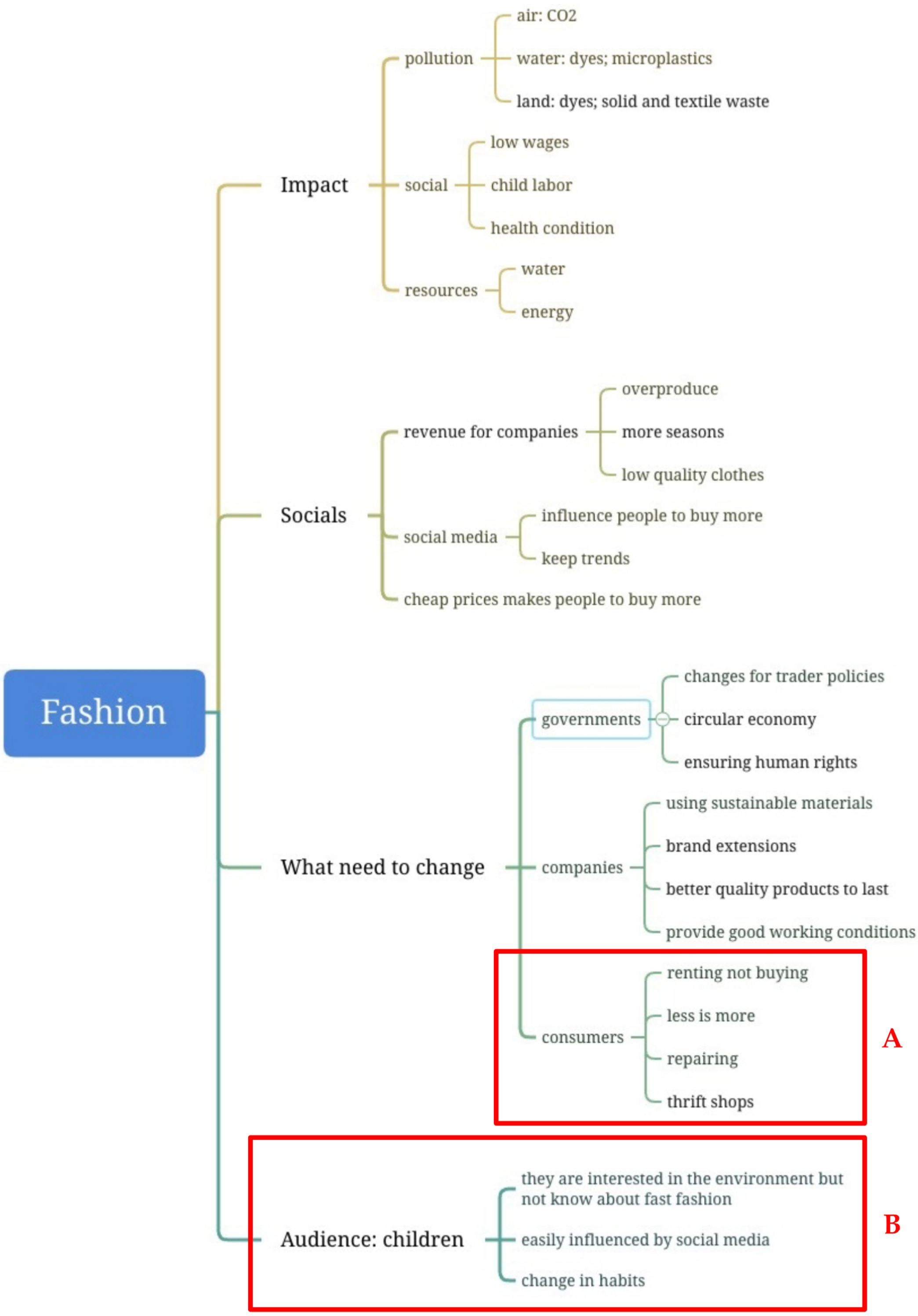


Figure 7. Empathize/define phase: Conceptualization of a sustainability problem in fashion (Miro board). Created by the Fashion team using a Miro board developed by tutors (2023).

Despite these elaborations, however, as the map indicates, on the whole, the Fashion team did not incorporate how fast fashion affects children; e.g., the team identified "*what needs to change*" from the consumer's perspective without contextualizing this to children

(Figure 7A). Where the analysis highlighted that children could have a potential knowledge gap when it comes to fast fashion, it did not consider how children engage with the clothing lifecycle and if their knowledge is influenced by peers or adults in their lives (e.g., friends, parents) (Figure 7B). In addition to lacking a child perspective, there were few academic sources (only six) supporting and extending each of the ideas included in the map.

In a departure away from a consumerist mindset, the Fashion team's analysis of fast fashion identified examples of positive actions that consumers could be undertaking to decrease their fashion footprint, namely renting, repairing, or buying second-hand clothes (Figure 7A). Anchoring their ideas in this part of their analysis, the team pre-determined the sustainability challenge as a need to increase children's positive action and formulated the following design question "*How might students develop their awareness of environmental protection through recycling/upcycling activities?*" [complexity: 2.3]. Framing the problem around recycling and upcycling skills, the Fashion team developed related research questions they wished to answer in their user research with children:

> *"What are the children's experiences with upcycling and repairing? What do they do with clothes that cannot be worn anymore?"* (empathise/define phase, PowerPoint slides).

Applying this convergent approach to the design question at the very start of the DT process also introduced constraints to the team's opportunity to explore children's fast fashion. Moreover, an examination of their initial questions illustrated incongruencies between the *design question* developed to frame the sustainability problem on the one hand and the *research questions* devised by the team to explore and better understand the design problem on the other. To this end, whereas 'recycling' and 'upcycling' appeared within the design question, the research questions identified 'repair' and 'upcycling' as the focus. Whilst repair was the only concept identified in the initial literature review (Figure 7A), using these terms indicated that the team lacked clear definitions in their design project. Taking the literature review and the design question as their point of departure, the team engaged children in user research through two activities: (i) an icebreaker discussion with the whole group, followed by (ii) a crafting activity where children were asked to create their own superhero costume.

Taking a focus group format, during the icebreaker, the team asked children to reflect on their favourite piece of clothing and the reasons for this preference. Children discussed how they liked comfy and warm clothing but showed little interest in fashion trends reflected in social media. In another line of questioning focusing on how clothes may damage the environment, children shared their concerns about animal welfare and byproducts (e.g., cows for leather produce methane, animals are poached for materials, silkworms die in the process of making silk), as well as other processes (e.g., deforestation for cotton fields, factories that make clothing running on fossil fuels, animals getting caught in discarded materials). This icebreaker activity invited the Fashion team to realise prior assumptions they had held about children's knowledge and interests for the first time [values: 1.1; complexity: 2.2]:

> **Angelina**: *"I think that it's surprised me how much they knew about a subject that I thought they did not know about".*
>
> **Sabine**: *"I think that one challenging thing is that we thought that the kids would be more interested in fashion. Like they had an actual interest, which they didn't. But it was based on our experiences, it wasn't from the literature".* (empathise/define phase, weekly group chat).

In the crafting activity inspired by the cultural probes [50], children used a template and a range of materials (pencils, markers, stickers, and paper cut-outs) to design their own superhero costume. The context of this activity provided the Fashion team with an opportunity to probe children about whether they enjoyed crafting and what kinds of making they did with their parents to upcycle, what they/their parents did with clothes they had outgrown or were damaged (e.g., bin it, repair it, donate it), what they would do if their favourite superhero costume got damaged (e.g., would they fix it themselves or ask for help?), and if they would want to learn how to fix it themselves. This revealed that "*children are not necessarily interested in repairing clothes, partly because they have an adult at home who can do it for them*" (empathise/define phase, PowerPoint presentation) [values: 1.1; complexity: 2.1].

Following the research with the children, the Fashion team recognised that their literature review had not provided them with strong theoretical and empirical concepts to influence their user research. During the weekly group chat, Stefania and Angelina both reflected on how they had spent effort looking at the general domain of fast fashion without connecting these broader themes to children's values and practices:

> **Stefania**: *"Our literature review consisted of so many comprehensive different parts. We talked about economy, for instance, and circular economy, and stuff like that. And none of these were relevant for [the children] because they had no idea, because they have never mentioned anything beyond the production of the material [for clothing]".*
>
> **Angelina**: *"…the literature review about how kids and parents use their time… We didn't look into that and, when we got to [user] research, we saw that they didn't spend that much together and doing these kinds of things [repairing, upcycling, recycling]".* (empathise/define phase, weekly group chat)

Despite these reflections, the Fashion team did not appear to return to the literature after the user research to understand how children have engaged in positive environmental actions as it relates to fast fashion and juxtapose previous research to their own findings. For some group members, the user research illustrated an apparent incompatibility between their initial design question and children's interests [values: 1.1; complexity: 2.2]:

> *Stefania: "For me, I was surprised that whatever we thought before that would work with [the children]—repairing, upcycling, and recycling—none of these can straightforwardly work for us anymore, and the data [we] gathered were quite different from what we expected in general. I thought there would be some corrections, but it was quite astonishing that everything was quite different from what we expected".*

This perceived incompatibility—alongside the limited literature concepts guiding the project and the few insights gleaned from the user research with children—led the Fashion team to reconsider their direction. Abandoning their focus to foster children's positive actions, they opted to pivot to a new, knowledge-centric goal for their project: "*[We decided] not to follow upcycling, repairing paths, and deepen their <u>theoretical knowledge rather than practical skills for repairing</u>*". Drawing on children's affinity toward animals identified in the icebreaker activity, they proposed: "*Children have an awareness about how clothing impacts animals and the environment, but less about social impact. They know where the materials used to make clothes come from but do not understand the process through which it goes to make the garment*" (framing phase, PowerPoint presentation) [values: 1.1; complexity: 2.1, 2.2]. Consequently, the Fashion team shifted its focus from *directly* fostering hands-on sustainability skills to knowledge transfer about the environmental impact of fashion, which they proposed might *indirectly* promote sustainable actions, as captured in a revised design question [complexity: 2.3]:

> *How might we <u>inform</u> 9-10-year-old children about the process of making clothes to promote sustainability actions?* (ideation phase, PowerPoint presentation).

Social dynamics played a pivotal role in shaping how the Fashion team approached their project. Despite their ongoing communication and engagement in the project, team dynamics were marked by the dominance of certain members during decision-making. Additionally, despite the team recognising how their engagement in decisive tasks (e.g., the literature review) hindered their progress, this awareness was not sufficient to mobilise them to improve their strategy:

Angelina: *We did get stuck with recycling and…*

Stefania: *[Interruption] We had the discussion.*

Sabine: *Exactly, I think…*

Angelina: *[Interruption] We had a lot of resistance on your part […].*

Sabine: *We all had a gut feeling that it wasn't it, but we couldn't find the right answer.* (empathise/define phase, weekly group chat).

In summary, the Fashion team's transition from supporting skills that will slow down fashion habits, to fostering children's knowledge acquisition about fashion, seemed to be driven by the desire to *move on* in the design process. The children's "partial knowledge" about the clothing lifecycle provided them with a tangible problem, leading them to revise their design question.

4.2.3. Solution Diamond: General Criteria Informing Design Choices

After re-framing their sustainability challenge, the Fashion team transitioned into the 'solution diamond' where they began to envision and develop a digital prototype. When ideating, the team generated a range of ideas to facilitate children's knowledge acquisition (see Figure 8). This included search engines, infographics, games, and interactive books. As the quotes below illustrate, the team evaluated their ideas based on the perceived difficulty they posed for children's understanding, the child engagement they were expected to engender, and the feasibility of the idea given the team's expertise. Ideas were not appraised based on the Fashion team's original intention to foster children's multidimensional understanding of the material process or the social impact of fast fashion, nor were they informed by their future vision over how digital technology could impact children's learning within this domain. Instead, general criteria about learning, engagement, feasibility and technology informed their discussions.

Sabine: *We rejected the ideas, such as the search engine, because we thought it would be hard for the kids [to understand]. We also rejected the idea of only visualising data or displaying information because they wouldn't be engaged with it.*

Barack: *I wasn't necessarily enthusiastic about the digital book, [but] I was more worried about the complexity of prototyping a game, so I thought the book was simpler and easier* (ideation phase, weekly group chat).

These criteria led the Fashion team to converge on a games-based learning idea. They envisioned a game that would present information about the lifecycle of clothes to support children's knowledge acquisition and foster their memorisation through behaviourist-driven minigames (i.e., reward for correct answers to trivia-style questions).

Angelina: *Here is the welcome page for the trivia you start, and you have these different questions […] If you answer it wrong […], you can get a hint and try again until you get it right. […] Then you move to the next level […]. The learning part is not only like the questions but also facts they can learn from [the activities].* (prototyping phase, weekly group chat)

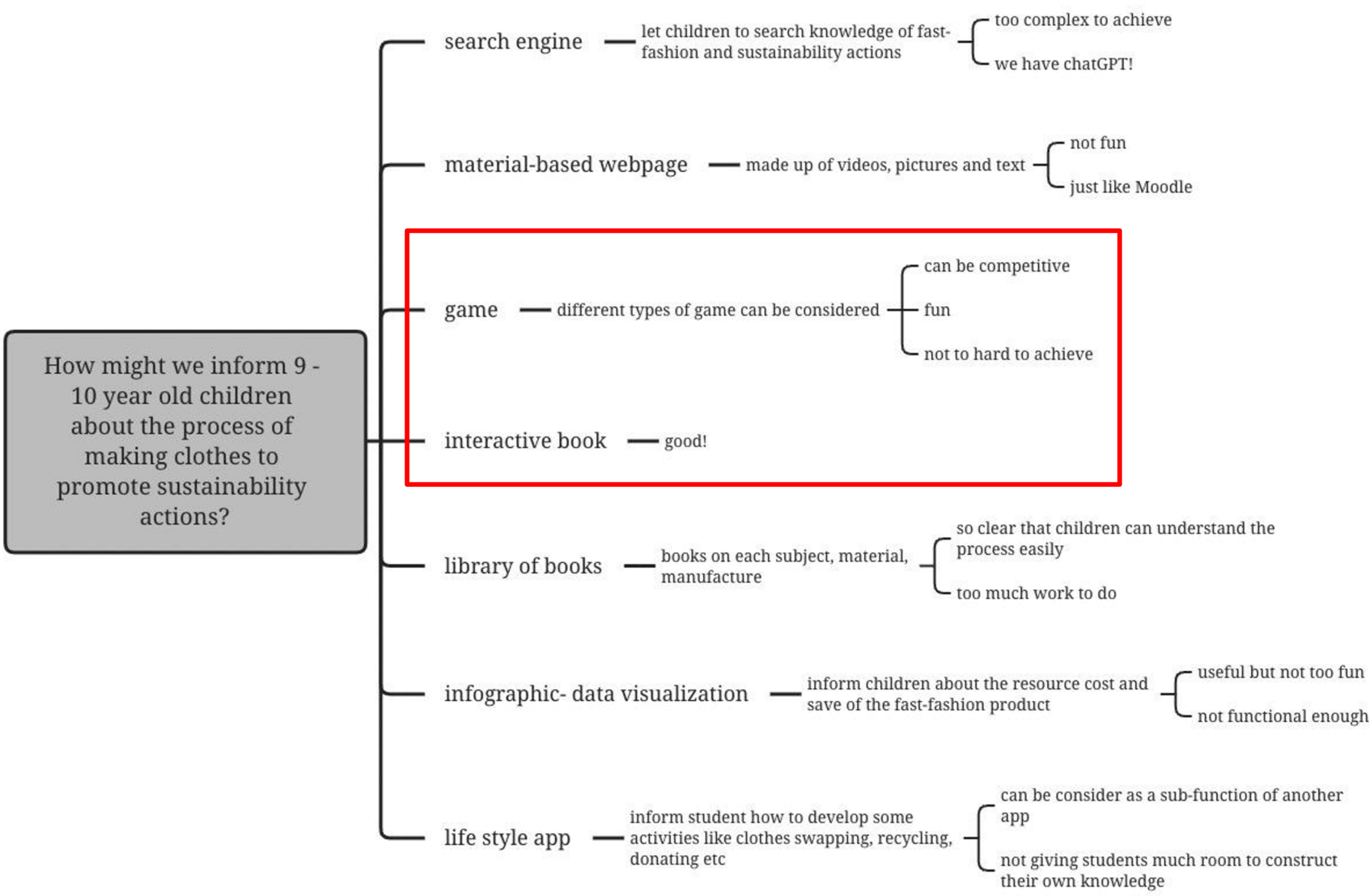


Figure 8. Ideation phase: Outcomes of brainstorming and evaluation criteria. The elements in the red box represent the chosen ideas and criteria used by the Fashion team to develop a prototype. Created by the Fashion team, ideation phase PowerPoint presentation (2023).

When prototyping the game, the team's design decisions continued to be dominated by general considerations, this time at the juncture of games and learning, such as whether their game should foster competition or collaboration, how many hints to integrate and when to time them, or how to design levels (see Figure 8, red box). Notably, as Figure 9 indicates, not only were these decisions not concerning children's understanding of fast fashion, but they were also not anchored in academic sources in alignment with the practices observed in the problem diamond.

Some connections with fast fashion were nonetheless made. Building on children's concern about animal welfare when making and discarding clothes [values: 1.1], it was deemed important to represent animals. Even so, the game did little to support systems thinking so that children could grapple with how animals may be affected by their fashion practices, and those of others, across the lifecycle of clothes. Moreover, despite their earlier decision to focus on knowledge, the team reintroduced their original interest in repair by incorporating game challenges, inviting children to repair their clothes upon completion of game levels (see Figure 6C). While this change was not explicitly recognized, members of the team justified the introduction of challenges based on how they fostered children's sensorial experiences of their clothes. Sabine explained: "*We wanted the kids to, like, do something with their hands because I think that, like, like they said, like the materials are important to them. So, we also want to encourage them to use their senses and to feel the materials and to interact with the materials, kind of it's not like they're going to be behind their screens the whole time*". Overall, however, the Fashion team's most substantive engagement with the fashion domain came from the game content they designed and embedded in the minigames. Reliant on desk research, they created content about different materials (e.g., hemp, polyester) and their environmental impact (see Figure 6B).

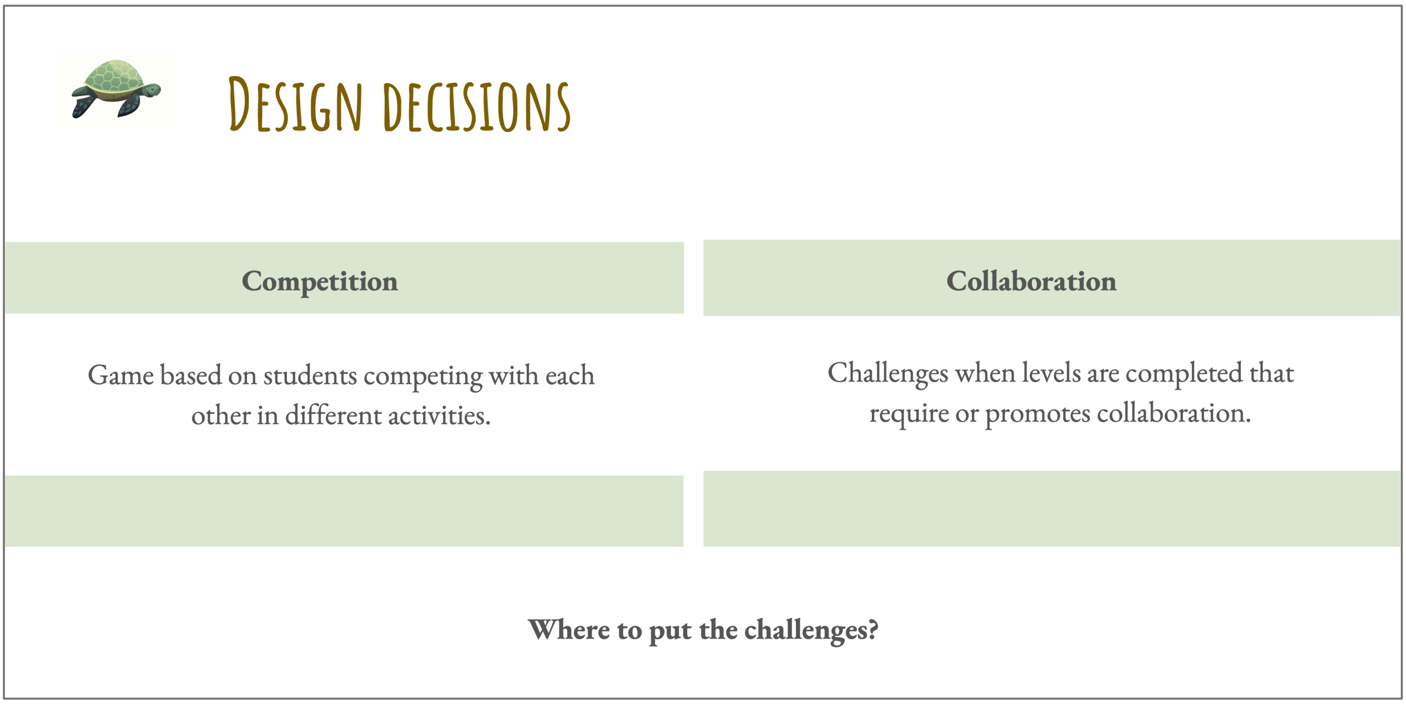


Figure 9. Prototyping phase: Competition vs. collaboration dilemma. Created by the Fashion team, prototyping phase PowerPoint presentation (2023).

Upon designing a low-resolution game Prototype, the Fashion team re-engaged the same class of children to test it, aiming to gain insights that could improve their game. As children interacted with each minigame, the team were able to observe children's understanding of the game content. Xinbei explained how the children's lack of prior knowledge supported the importance of the game hints: *"We have the assumption that the children know the materials very well, like we have the assumption they know what hemp is and what is polyester. But in the formative evaluation, we find that they didn't know much about the materials"* (testing phase, weekly group chat) [values: 1.1]. Inviting children's general feedback on the game design, the Fashion team additionally identified new ideas originating in prominent game tropes that children wished to see, e.g., tokens, leaderboards, and characters. Owing to this feedback, several members of the team concluded that the Fashion Turtles game was not "fun" as designed. Therefore, the testing session with the children did not lead to critical reflections on original design intentions, despite the team's continued aspiration to foster child advocacy in the context of fast fashion [action: 4.2].

> **Stefania**: *You [child] know it [fast fashion] more and you are able to explain to the other people more and it also helps, you know, influencing others. That's how we try to… that's where our political values that we tried to put into this* (Final focus group).

Mirroring the social dynamics observed within the problem diamond, it continued to be challenging to resolve differences in opinion between members. For instance, whilst one member raised the lack of games expertise in the team in favour of pursuing the e-book idea, others were drawn to the appeal of a game for children, deprioritising this concern. Even after the design project had finished, members continued to negotiate design decisions within the Fashion Turtle game. For instance, in the final focus group, one member advocated for linking game challenges with the game content encountered, despite the team having taken a different direction by focusing on repair challenges that departed from the content's focus on material qualities.

5. Discussion

In the context of HE, DBL and DT have been touted for their potential to increase students' knowledge of sustainability challenges [15], support their development of problem-solving and interdisciplinary skills [21], transform their perspectives, and empower students to engage in collective action after the DBL experience is completed [14]. The current research extends these past studies by taking a temporal lens that recognises DT as a socially constructed practice. We examined in detail the DT practices of two collaborative teams of HE students in pursuit of designing technologies for children's sustainable futures. The discussion draws on the case studies presented in Section 4 to evidence the types of sustainability competencies engendered across different moments of the DT process (Section 5.1). Building upon these trends, we go on to analyse how sustainability competencies are mediated by DT practices performed by the HE students (Section 5.2).

5.1. Sustainability Competencies Fostered During DT

The GreenComp framework [3] includes 12 sustainability competencies, organised under four overarching areas: (1) embodying sustainability values, (2) embracing complexity in sustainability, (3) envisioning sustainable futures, and (4) acting for sustainability. In the context of this case study, we note that action competencies are intrinsic to DT; in other words, designing for children's sustainable education futures enabled the HE students to exercise collective action. Drawing on our findings, in Table 5 we summarise the frequency of the 12 sustainability competencies experienced by the two student teams, within the problem and solution diamonds. Summarising the findings this way allows us to identify several distinctive patterns. These patterns evidence how and when sustainability competencies may develop within the DT process, providing HE educators with an understanding of how to best embed and reinforce them in their teaching. A first pattern suggests that certain competencies align with specific phases of DT. For instance, as Table 5 indicates, the three competencies under envisioning sustainable futures (futures), which were forward-looking and idea-oriented, emerged only in the solution diamond.

A second pattern illustrates that there were also transversal sustainability competencies that spanned both diamonds. These included competencies under *embodying sustainable values* (values) and *embracing complexity in sustainability* (complexity), both of which involve questioning and critically engaging in multiple perspectives and information sources, relevant to all phases of DT. The importance of transversal competencies raises implications for how DT may be taught in HE, particularly when the learning objectives include the acquisition of time-intensive, practical skills that can emphasise the later ideation/prototyping DT phases. Our findings suggest that not only should HE practitioners give equal focus to the earlier empathise/define phase, where transversal sustainability competencies begin to develop, but also scaffold their development across the unfolding DT process. More tools are thus required to properly facilitate HE students' competency development with particular attention to the transitions between DT phases, supporting similar conclusions by Taimur and Onuki [14].

In addition to these general patterns, Table 5 suggests that the topic of the design case (i.e., the chosen sustainability challenge) can shape which 'value' competencies are developed. The Nature team sought to foster children's nature connection and, perhaps unsurprisingly, exercised their value of *promoting nature* [1.3] throughout the design process. Contrastingly, the Fashion team's choice of designing for children's understanding and engagement with fast fashion brought into focus issues of social justice and unfair labour, thereby *supporting fairness* [1.2] in their early conceptualisations of the problem space. Depending on the learning aims of the HE module, we argue that it is possible to cultivate *both* competencies independently of the chosen topic. For instance, the Nature team could have been encouraged to explore children's access to nature in different places of the world (supporting fairness; see [59]), or the Fashion team could have been supported to position nature as an active beneficiary in the design of their fast fashion intervention (promoting nature; see [60]).

Table 5. Sustainability competencies fostered during design process for Nature and Fashion teams. "∞" = collective action is inherent to the design process. "?" = unclear if these competencies may have emerged outside the DT process.

Sustainability Competence	Nature Team Problem Diamond	Nature Team Solution Diamond	Fashion Team Problem Diamond	Fashion Team Solution Diamond
Values total	**11**	**11**	**5**	**2**
Values 1.1	*7*	*6*	*3*	*2*
Values 1.2	*0*	*0*	*2*	*0*
Values 1.3	*4*	*5*	*0*	*0*
Complexity total	**12**	**12**	**9**	**0**
Complexity 2.1	*3*	*3*	*4*	*0*
Complexity 2.2	*6*	*8*	*3*	*0*
Complexity 2.3	*3*	*1*	*2*	*0*
Futures total	**0**	**11**	**0**	**0**
Futures 3.1	*0*	*6*	*0*	*0*
Futures 3.2	*0*	*0*	*0*	*0*
Futures 3.3	*0*	*4*	*0*	*0*
Actions total	**-**	**-**	**-**	**-**
Actions 4.1	*?*	*?*	*?*	*?*
Actions 4.2	*∞*	*∞*	*∞*	*∞*
Actions 4.3	*?*	*?*	*?*	*?*

5.2. DT Practices that Fostered or Hindered Sustainability Competencies

An inspection of Table 5 shows notable differences in the sustainability competencies developed within each team. Why did the DT undertaken by the Nature team elicit more competencies as compared to the Fashion team? And how did the Nature team sustain transversal competencies across both diamonds, whereas the Fashion team did not achieve this? Moreover, why was the Fashion team not able to engage in *envisioning sustainable futures* competencies? To address these questions, we turn to RQ2, which asks: *"what are the practices of the DT process that foster or hinder sustainability competencies?"* Inspecting the temporal DT practices across the two teams reveals three key practices that supported, or prevented, the development of the four competence areas:

1. Undertaking a broad and user-centred (i.e., specific to children) review of the sustainability literature to shape the project;
2. Performing research with target users to inform and motivate design decisions that are intrinsic to the sustainability challenge;
3. Engaging in self-questioning of one's sustainability values, assumptions, and design dilemmas that impact design for sustainability.

Grounded in our findings, as reported within Section 4, Table 6 demonstrates the presence/absence of these practices for each team across the four DT phases. In what follows, we illustrate how each practice enabled sustainability competencies or, when neglected, hindered them. We contend that all three practices need to be (1) critically developed on their own (Section 5.2.1), (2) carried over time, threaded across DT phases (Section

5.2.2), and (3) interconnected with each other (Section 5.2.3) before HE students' sustainability competencies can develop across the DT process.

Table 6. Key DT practices that foster sustainability competencies used by Nature (🍃) and Fashion (👕) teams.

DT Practice	Empathise and Define	Ideate	Prototype	Test
Sustainability literature and children	🍃👕	🍃	🍃👕	🍃
User research with children driving sustainability design	🍃👕	🍃	🍃	🍃
Questioning about sustainability values and design decisions	🍃👕	🍃	🍃	🍃

5.2.1. Each Practice Should Be Deeply and Critically Developed

Our findings show that deep and critical engagements with the sustainability literature, user research, as well as self-reflection on assumptions, can enable HE students to embody *sustainability values* and *embrace complexity in sustainability*. Certain tasks embedded in DT—particularly the literature reviews and user research—fostered multiple competencies at once. For example, the Fashion team created a literature review that engaged with *systems thinking* and *inequalities (values)* persistent in the fashion industry (Section 4.2.2). During their user research in the empathise/define phase, both teams recognised the roles of parents in repair activities and nature connection, *increasing an appreciation of child-parent values* and, as such, *multi-perspective systems thinking* (Sections 4.1.2 and 4.2.2). To this end, Section 3 offers a detailed account of the pedagogical approach taken to inform future practice.

However, the extent to which teams engaged deeply and critically in these DT practices had implications for their competence development. For example, compared to the Nature team who engaged in both broad *and* child-specific literature perspectives to frame the problem (Section 4.1.2), the Fashion team did not contextualise their literature review to their target child users during the empathise/define phase, leading to a missed opportunity to deeply understand the issues of fast fashion from the child's perspective (Section 4.2.2). In another contrasting example, the Fashion team made no effort to acknowledge their assumptions from the start of the project, thereby limiting their recognition of their peers' sustainability values and assumptions, compared to the Nature team, who put them front and centre of their DT (Sections 4.1.2 and 4.2.2). While this lack of recognition influenced the Fashion team's development of the *values* competency, it also negatively impacted their DT process, since making one's individual assumptions (or frames) explicit early in the design process is a crucial step toward evolving a shared frame that appropriately scopes a collaborative design project [39], something that the Fashion team struggled with.

5.2.2. Practices Are Temporal and Cutting Across DT Phases

Our research suggests that when HE students use insights generated from all three DT practices to inform subsequent DT phases, sustainability competencies can become transversal whilst also enabling competencies related to *envisioning sustainable futures*.

For example, except for using literature for content development during their prototyping, the Fashion team stopped engaging with the fast fashion literature and their initial user research after progressing to the solution diamond. Consequently, the rest of their design process became decontextualised from fast fashion, affecting the temporal development of competencies in the solution diamond, as also evidenced by the absence of *envisioning sustainable futures* (Section 4.2.3). Contrastingly, the Nature team continued to thread the three practices across each of the DT phases. An example of this was observed during the ideation/prototyping phase, where they referred to past user research findings and chose ideation methods that continued to provoke their empathy with the children (Section 4.1.3). This fostered the development of *complexity* competencies in the form of a range of design dilemmas that the team had to negotiate before progressing with their prototype. Halskov and Hansen [61] have discussed the importance of bridging the gaps *between DT phases* so that user voices are not lost. Whilst experienced designers may be able to draw these links, in HE-teaching contexts, where there may also not be time to involve users in all phases of DT, this intentional threading across phases is vital to connect the problem and solution diamonds. As also proposed in Section 5.1, pedagogical scaffolds to support this could be the focus of future work.

5.2.3. Interconnecting the DT Practices

Alongside the multiple sustainability competencies fostered when individual DT practices were deeply and critically applied (Section 5.2.1), multiple competencies also emerged when HE students strategically connected all three practices within their DT process. For example, during the test phase, the Nature team synthesised insights from both user research with children and literature. In tandem, they critically examined how features of the Pet Plant prototype (e.g., pet avatar, data visualisation) promoted children's nature connection (Section 4.1.3). This approach demonstrated their ability to *envision sustainable futures* whilst actively engaging in *complexity* and *critical thinking*.

In contrast, the Fashion team struggled to effectively integrate the three DT practices. Although they attempted to link their literature and user research, their generalist literature review of fast fashion lacked a childhood perspective. As a result, they failed to align concepts from the literature with the insights gathered from the children (Section 4.2.2). Despite recognising this gap, they did not seek out new literature to inform the interpretation of their user research findings. Consequently, their *complexity* competency remained limited in the problem diamond, and the same gap persisted in the solution diamond. Lacking the ability to synthesise new information sources, the students were unable to forge a new sustainability-centred direction for their design. This ultimately hindered their engagement with *envisioning sustainable futures* competencies (Section 4.2.3).

Alongside the importance of all three DT practices, the way these practices were performed across the DT phases was influenced by the social dynamics within the teams. Even though DT is known for harnessing students' ability to collaborate and communicate in teamwork [13,29–31], research has also documented how conflicts within teams can negatively influence the DT process [35,44]. Whilst the DT process within the Nature team was characterised by strong collaboration and negotiation, thus facilitating their establishment of shared values, visions, and strategies, the Fashion team often struggled to find common ground, hindering their progress and pushing them to make decisions that would enable them to 'move on' in the design process. Determining the extent to which these social dynamics facilitated or hindered their development of sustainability competencies, however, is outside of the scope of this research.

6. Conclusions

The urgency of the climate crisis has called for a shift from knowledge-centric learning approaches in Education for Sustainability (EfS) towards more constructivist and social learning approaches that imbue students with the competencies needed to tackle the environmental challenges, e.g., [3,7,8]. This study focuses on design-based learning and, more specifically, design thinking (DT), as one such approach. We analysed the temporal DT practices of two teams of postgraduate students who designed digital educational technologies to address a chosen sustainability challenge. Leveraging the GreenComp framework [3] and the Double Diamond model of DT [32,33], we aimed to explore what sustainability competencies emerged during the DT process (RQ1) and what DT practices supported or hindered the development of these competencies (RQ2).

Our findings indicate that, whilst *collective action* is inherent to the entire design process, *embodying sustainable values* and *embracing complexity in sustainability* are traversal competencies that emerge across both problem and solution diamonds, and *envisioning sustainable futures* arises through the activities specific to the solution diamond. Some *values* competencies were specific to the chosen design case. Furthermore, our findings suggest that three specific DT practices can foster (or, when neglected, hinder) the emergence of sustainability competencies: (i) undertaking a broad and user-specific literature review, (ii) performing research with target users, and (iii) engaging in self-reflection and team reflection practices around the sustainability values and design decisions. Our research shows that sustainability competencies emerge when each practice is deeply and critically developed, threaded across DT phases, and when the practices are explicitly connected to each other.

These findings have several implications for other HE practitioners seeking to implement DT for EfS in their teaching, suggesting specific areas for future education research and development:

1. Ensuring sustainability competencies are cultivated from the early stages of DT by placing equal emphasis on activities in the problem diamond in comparison to the solution diamond.
2. Embedding pedagogical scaffolding to help HE students synthesise and connect the above-listed DT practices, and thread them across the DT phases.
3. Supporting the development of all *values* competencies, particularly critically engaging with value tensions amongst the different perspectives (e.g., within the design team, between designers and users).

We hope future education researchers will explore the transferability of these findings to other education contexts and cohorts. Moreover, paying attention to the scope of our data collection raises avenues for future research. For instance, we did not seek to observe how HE students' sustainability competencies manifested outside the context of our module and, thus, do not know if they developed *individual action* and *political agency* action competencies. Furthermore, we do not know if the competencies exhibited by students during the design process persisted beyond the module or if these transferred to other academic, work, or life contexts. Future research could apply a more holistic perspective that looks beyond the teaching context to better understand these aspects.

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