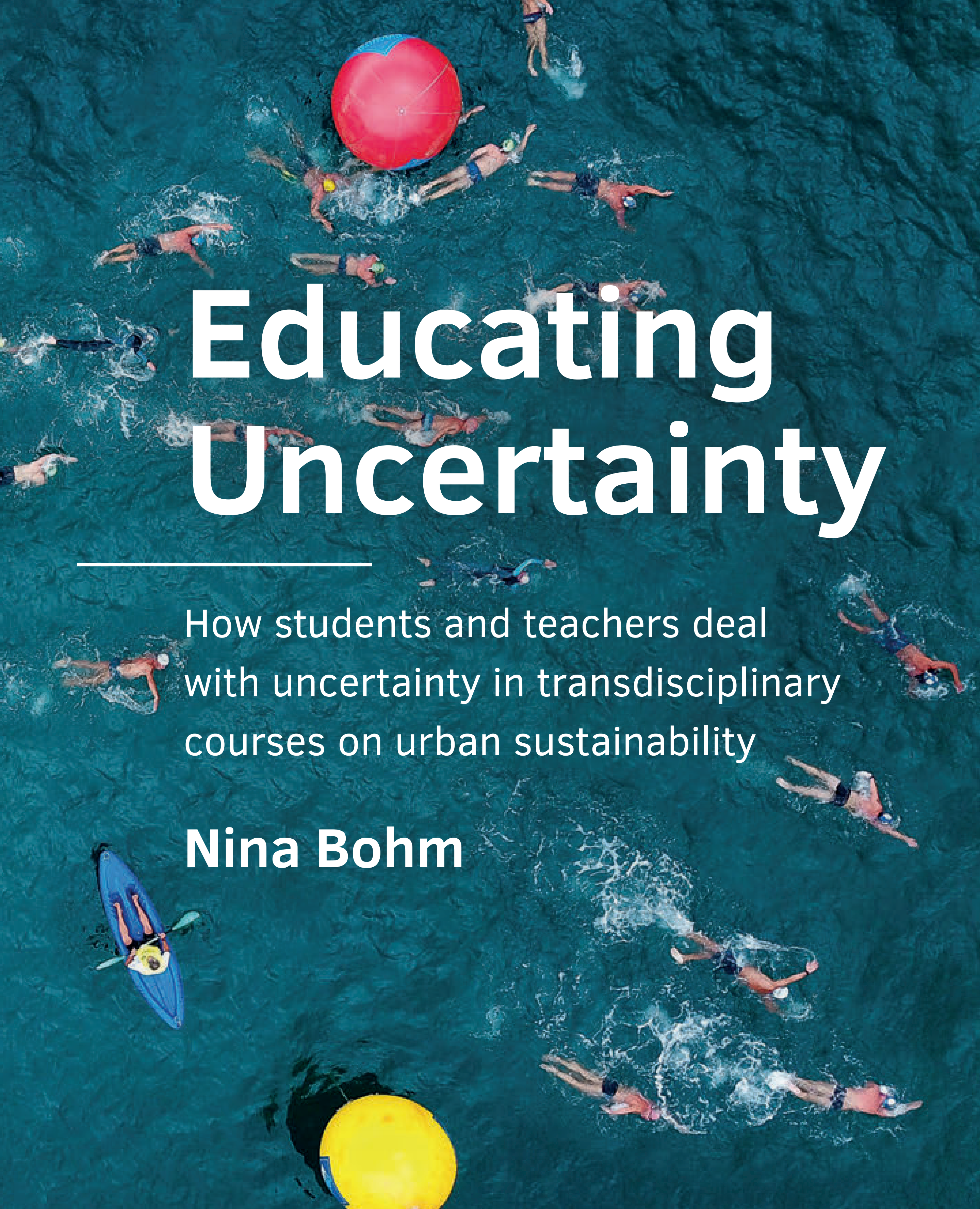

Educating Uncertainty

How students and teachers deal with uncertainty in transdisciplinary courses on urban sustainability

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TOC

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TOC

Educating Uncertainty

How students and teachers deal with uncertainty in transdisciplinary courses on urban sustainability

Dissertation

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at Delft University of Technology
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chair of the Board for Doctorates
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by

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And what is the point of learning facts within the school system when
the most important facts given by the finest science of that same school system
clearly mean nothing to our politicians and our society?

Greta Thunberg

Contents

List of Tables

List of Figures

Summary

Higher education institutions have increasingly turned to transdisciplinary approaches within their curricula. These approaches aim to tackle real-world challenges and engage with the actors of these challenges. These challenges often are *sustainability* challenges that depend on unpredictable decisions; knowledge of how to balance environmental and social boundaries is lacking, and perspectives on the problems and solutions differ among the people considered experts in their fields. These dimensions of uncertainty became an inescapable part of education as courses began to incorporate sustainability challenges and the multiple perspectives of the actors involved. Therefore, students and teachers had to figure out how to deal with uncertainty as part of transdisciplinary education.

However, uncertainty had not been studied as a part of transdisciplinary education, and little research informed teachers and students about how to deal with it. The purpose of this dissertation was twofold: (1) to contribute to a further theoretical understanding of what uncertainty is in transdisciplinary education and how to learn to deal with it, and (2) to highlight principles for designing education that empowers both students and teachers to navigate these uncertainties effectively. The central research question in this research was: **How can transdisciplinary education be designed so that students learn to deal with uncertainty in sustainability challenges?**

The research approach of this dissertation was based on Educational Design Research (EDR). EDR systematically investigates the design of educational interventions. This research consisted of four empirical studies examining the intended, implemented, and attained curriculum, and a design intervention in transdisciplinary course design.

The first study took a broader look at the aims and ideals for transdisciplinary courses taught at Delft University of Technology and AMS Institute in Amsterdam. The following three studies zoomed in on one specific course: the Living Lab course, which is part of the master program MSc MADE (Metropolitan Analysis, Design, and Engineering). In the 16-week Living Lab course (24 ECTS) in the second year of the MSc MADE, students worked on an urban sustainability challenge commissioned by an extra-academic actor. In groups of 3, 4, or 5, students co-creatively explored the problems that the challenge consisted of and designed a solution that the commissioner could continue to use or develop after the course ended.

The research questions further specified the EDR approach: (1) How are learning objectives described in transdisciplinary courses concerning urban sustainability challenges and how does this relate to the aims of the teachers? (2) What are the characteristics of uncertainty in urban sustainability challenges implemented in the Living Lab course? (3) What uncertainty do students encounter when working on urban sustainability challenges (metacognitive awareness) in the Living Lab course and how do they deal with it (metacognitive regulation)? (4) What scaffolding strategies do teachers use over time in the Living Lab course to guide students toward problem-solving in uncertainty?

Chapter 1 motivated and explained the rationale for and approach to the research in this dissertation. Additionally, it included a reading guide that helps navigate the dissertation.

Chapter 2 answered research question 1 and investigated the intended learning in eight transdisciplinary courses at Delft University of Technology and AMS Institute. The study aimed to get a better understanding of what students were meant to learn from working on real-world challenges and to what extent extra-academic actors participated in these courses. In the analysis, the formal intentions in 8 courses descriptions were compared with the aims and ideals that teachers described in 7 interviews.

The study revealed that teachers used transdisciplinary courses to teach problem-solving in an integrative manner, centered on authentic issues relevant to students' lives. The teachers also described intentions that were not written down clearly in the course descriptions and those misalignments were visible in the learning objectives related to analysis and metacognition, and at the level of active participation with actors in the course.

Chapter 3 answered research question 2 and focused on uncertainty in the Living Lab course's challenge descriptions. The Living Lab course was one of the eight transdisciplinary courses in Chapter 2 that showed a high level of active participation with extra-academic actors. The challenge descriptions were formulated by the extra-academic actor who commissioned the challenge, also called a 'commissioner' in this context. Through document analysis of 48 documents that each contained a challenge from a commissioner, we evaluated which of the three dimensions of uncertainty—unpredictability, knowledge incompleteness, and knowledge frame multiplicity—were present in the challenges at the start of the course on three difficulty levels: clear, complicated, and complex. Furthermore, we analyzed how commissioners expected students to address these uncertainties through the methods they described in the challenge descriptions.

Although almost all challenges included all three uncertainty dimensions, they did not all describe them at the same difficulty level. Most challenges dealt with knowledge incompleteness on a complicated level and, on a complex difficulty level, students in the course most frequently encountered knowledge frame multiplicity. To work on the complicated issues, commissioners suggested conventional research methods, yet for the complex issues they expected students to be able to experiment with transformative approaches to research. Transformative research approaches, such as co-creation, aim to rethink the values, norms, and responsibilities of scientific research and if necessary, transform them. Students were likely to experience tensions in the course due to the commissioners' mixed expectations of using such transformative approaches to research in combination with conventional approaches.

Chapter 4 answered research question 3 and aimed to further specify the kind of metacognitive learning that was necessary to deal with uncertainty. To this end, we interviewed 9 students at 3 different moments in the Living Lab course (after 4, 10, and 16 weeks).

Throughout the 21 interviews, students most often were aware of the uncertainty of multiplicity in the challenge and to a lesser extent knowledge incompleteness. During the course, students became increasingly aware of the unpredictability of the challenge. Students used three types of metacognitive regulation to deal with uncertainty: seeking social assistance, employing small coping mechanisms, and changing their attitude toward uncertainty.

Chapter 5 answered research question 4 and examined teachers' scaffolding strategies at 3 different moments in the Living Lab course (after 5, 10, and 14 weeks) to support students in problem-solving amidst uncertainty. In this design-based study, we monitored how 10 teachers developed scaffolding strategies based on a workshop they received before the course began. In 3 qualitative surveys and 3 focus groups, teachers reflected on their teaching practices and coaching strategies.

Teachers found knowledge incompleteness most challenging. Especially, they struggled to guide students in developing the theoretical grounding in the transformative approaches they were required to use in the Living Lab. Overall, the main scaffolding strategies teachers used to guide students in the Living Lab were intended to mark critical features, maintain the direction of learning within the project, and manage frustrations but teachers also adapted their focus during the course.

In **Chapter 6**, the main findings contributed to three key insights into uncertainty in transdisciplinary education:

The dimensions of uncertainty change during transdisciplinary courses. This dissertation approaches uncertainty through three key dimensions of uncertainty in sustainability challenges within transdisciplinary courses: unpredictability, knowledge incompleteness, and knowledge frame multiplicity. Generally, these dimensions were consistently present in the challenges students faced yet the extent to which these dimensions of uncertainty were experienced by students and teachers in the course fluctuated over time. Particularly, the dimension of knowledge frame multiplicity emerged during the course as a prominent uncertainty dimension experienced by students and teachers, as well as in the challenge descriptions of commissioners. In line with the aims of transdisciplinary education, this reflected how difficult it was to integrate diverse perspectives and values. Additionally, teachers and commissioners saw knowledge incompleteness as a prominent uncertainty dimension. For teachers this was specifically related to the theoretical grounding of the projects at the start and middle of the course. Furthermore, students experienced the uncertainty dimension unpredictability more prominently toward the end of the course, when it became clearer to them what the unexpected changes during the project were.

Behind transformative approaches lies an uncomfortable and unpredictable struggle to develop attitudes that embrace uncertainty. This dissertation revealed that uncertainty fostered a form of constructive friction, where students struggled with what they did not know and then resolved this in creating a new integrated understanding. This enabled students to grow their self-awareness and to self-regulate their learning processes. To do so, students attained three main types of metacognitive behavior in response to uncertainty: seeking social assistance, employing coping mechanisms, and changing their attitude toward uncertainty. Notably, changing attitudes, from initial discomfort to embracing uncertainty, might have been a significant outcome of transdisciplinary education, because attitudes are difficult to change. These attitude shifts were crucial to develop integrative problem-solving approaches and to navigate the complexities of sustainability challenges effectively. At the same time, the feeling of discomfort that came with the reconsideration of attitudes toward uncertainty needs further support in transdisciplinary courses in the future.

Teachers support learning in uncertainty by offering social assistance, also, on individual learning objectives. Teachers played a pivotal role in supporting student learning in uncertainty by providing social assistance and scaffolding, particularly regarding individual learning objectives. However, the personalized nature of uncertainty awareness and attitudes presented a challenge for teachers because students in transdisciplinary courses often have diverse disciplinary backgrounds and learning styles. The integration of diagnostic strategies and clearer guidance on individually formulated learning objectives could enhance teacher support and facilitate students' self-regulated learning paths in transdisciplinary education. Additionally, broader recognition of personal development goals and explicit support for diverse learning trajectories within these courses might be necessary to support learning in uncertainty.

The key insights and main findings of this dissertation should be viewed in the light of two limitations. First, the qualitative research methods focused on small groups of participants and should therefore be considered a first exploration of the global themes of uncertainty. Second, the EDR approach has predominantly focused on the Living Lab course as a single case study. Hence, the findings need to be further contextualized, beyond the constructivist and engineering environment of this course in the Netherlands, and also beyond its Western-European context.

Future research could deepen the understanding of uncertainty by using more quantitative methods in addition to the qualitative approach in this research. For instance, attitudes toward uncertainty could be studied more longitudinally, beyond the boundaries of one course, and with larger groups of students to further develop the first understanding of uncertainty in this dissertation. Furthermore, future research might investigate how commissioners perceive and deal with uncertainty and how this is effected by their active participation in education. Additionally, specific studies on goal setting in personal development or the way students self-regulate frustration might help teachers to advance their role as coaches and could be further researched in collaboration with students and teachers. Overall, this dissertation underlined the importance of ongoing design research to systematically investigate and critically evaluate educational interventions in their complex context.

This dissertation concluded by presenting six design principles for educating uncertainty that were based on a combination of the main findings of the research and the practical insights from the people involved. Design principles A and B dealt with the initial stages of the course design where it is important to pay attention to the (cognitive, metacognitive, and affective) learning objectives and the way extra-academic actors will be involved in relation to uncertainty (Chapters 2 and 3). Then, design principles C and D were based on the findings that showed how uncertainty changes during the course and how students' attitudes towards uncertainty can be made more explicit (Chapters 3 and 4). Lastly, design principles E and F suggested how course design might better facilitate learning to deal with uncertainty by paying attention to personal development and emotions (Chapters 2, 4, and 5). These design principles can be used by teachers, students, and other people involved in the design of transdisciplinary courses:

A **Activate the participation of extra-academic actors:** Involvement of extra-academic actors, for instance as commissioners, is crucial in transdisciplinary education. There are different ways participation can be shaped. The framework in Chapter 2 presents three levels of involvement of participants, ranging from low to high involvement: distant, client, and partner. This framework could be used to consider the level of participation from other actors involved in the course, especially in relation to the aims and ideals of the course. Not every transdisciplinary course needs active participation from actors as partners, but such participation will most probably involve more dimensions of uncertainty in the course.

B **Balance conventional and transformative approaches in the learning objectives:** Formulate learning objectives that describe the analytical skills students need to learn from dealing with the uncertainty in the challenge and clarify the expectations of theoretical grounding in the project. Such analysis might be applied to conventional data collection methods, such as interviews and observations, but they can also be part of transformative approaches to research, such as systems thinking, experimenting, mapping, and co-creating. Additionally, formulate learning objectives that describe metacognition as the knowledge object that students attain during the course, for instance, by reflecting on uncertainty with peers or setting personal learning objectives.

C **Explore the dimensions of uncertainty (unpredictability, knowledge incompleteness, and knowledge frame multiplicity):** The framework in Chapter 3 presents the three dimensions of uncertainty on different difficulty levels: clear, complicated, and complex. This framework allows students and teachers to recognize which uncertainties are most prominent in a sustainability challenge at different moments in the course. Additionally, the framework could be used to define the complexity and uncertainty in the challenge with potential commissioners before the start of the course.

D **Reflect on attitude shifts:** Make time for the discussion and development of attitudes toward uncertainty. Students can develop attitudes such as flexibility, empathy, and relativism. These could be strengthened and regulated when they become a more explicit part of the course.

E **Scaffold self-regulation for frustration control:** Develop support mechanisms, such as scaffolding (adaptive guidance) throughout the course for frustration control. Especially at the start of the course, there is a need for such support mechanisms. In general, support mechanisms can be offered by teachers, but also by peers, because students have their small coping mechanisms for uncertainty and they might be willing to share those if the right atmosphere is created for that exchange.

F **Set personal development goals:** Integrate goal setting regarding personal development to increase self-awareness and self-knowledge. Only if you know what you know can you become aware of what you do not know. By clarifying the way that goal setting happens, teachers can become more involved in guiding personal development throughout the course. This way learning and teaching of metacognition will go beyond the common reflection report at the end of the course and can start to support dealing with uncertainty during the course as well.

Samenvatting

Hogescholen en universiteiten gebruiken steeds vaker transdisciplinaire benaderingen in het onderwijs. Transdisciplinariteit in onderzoek en onderwijs richt zich op het aanpakken van maatschappelijke vraagstukken, zoals de transitie naar een duurzamere samenleving, in samenwerking met maatschappelijke partners. In duurzaamheidsvraagstukken speelt onzekerheid een belangrijke rol. Hoe de grenzen van de planeet in balans kunnen worden gebracht met sociale ambities en economische doelen is vaak een omstreden kwestie, met uiteenlopende perspectieven op de problemen en oplossingen, zelfs onder experts. Die verschillende perspectieven, het gebrek aan kennis en een onvoorspelbare toekomst zijn onvermijdelijk een onderdeel geworden van het onderwijs over duurzaamheidsvraagstukken. In de afgelopen jaren ontstond daarom bij studenten en docenten een behoefte aan meer begrip over hoe met die onzekerheid om te gaan.

Er is nog weinig onderzoek gedaan naar onzekerheid als onderdeel van transdisciplinair onderwijs, noch naar hoe docenten en studenten ermee omgaan. Het doel van dit proefschrift is daarom tweeledig: (1) bijdragen aan een verder theoretisch begrip van wat onzekerheid in transdisciplinair onderwijs is en hoe men ermee kan omgaan, en (2) ontwerpprincipes ontwikkelen voor het onderwijs dat zowel studenten als docenten in staat stelt om met onzekerheid om te gaan. De centrale onderzoeksvraag in dit onderzoek was: **Hoe kan transdisciplinair onderwijs zo worden vormgegeven dat studenten die te maken krijgen met duurzaamheidsvraagstukken leren omgaan met onzekerheid?**

De onderzoeksaanpak van dit proefschrift is gebaseerd op Educational Design Research (EDR). EDR is een manier om systematisch (het ontwerp van) veranderingen (ook wel ‘interventies’) in het onderwijs te onderzoeken. Dit onderzoek bestaat uit vier empirische studies, waarbij de eerste drie studies ieder een eigen perspectief op het ontwerp van transdisciplinair onderwijs onderzoeken (het beoogde, uitgevoerde en geleerde curriculum) en de laatste studie onderzoekt een onderwijsinterventie in een transdisciplinair vak in de praktijk.

De eerste studie kijkt naar de doelen en idealen voor transdisciplinaire vakken aan de Technische Universiteit Delft en het AMS Institute in Amsterdam. De daarop volgende drie studies zoomen in op één specifiek vak: het Living Lab vak dat deel uitmaakt van het masterprogramma MSc MADE (Metropolitan Analysis, Design, and Engineering).

In dit vak met een looptijd van 16 weken (24 ECTS) in het tweede jaar van de MSc MADE, werkten studenten aan een stedelijke duurzaamheidsvraagstuk van een opdrachtgever uit de metropoolregio Amsterdam. In groepen van 3, 4 of 5 studenten onderzochten zij, vaak participatief of co-creatief, de achterliggende problemen van het vraagstuk en ontwierpen zij een oplossing die de opdrachtgever na afloop van het vak verder kon gebruiken of ontwikkelen.

De vier empirische studies beantwoorden ieder een onderzoeksvraag:
(1) Hoe worden leerdoelen beschreven in transdisciplinaire vakken over duurzaamheidsvraagstukken in de stad en hoe verhoudt dit zich tot de doelen van de docenten? (2) Wat zijn de vormen van onzekerheid in de duurzaamheidsvraagstukken in de stad die in het Living Lab vak voorkomen? (3) Met welke onzekerheid worden studenten geconfronteerd wanneer ze werken aan duurzaamheidsvraagstukken in de stad (metacognitief bewustzijn[1]) en hoe gaan ze hiermee om (metacognitieve regulatie) in het Living Lab vak? (4) Welke scaffolding[2] strategieën gebruiken docenten op verschillende momenten in het Living Lab vak om studenten te begeleiden in onzekerheid?

Hoofdstuk 1 motiveert de aanleiding en onderbouwt de aanpak van het onderzoek in dit proefschrift. De leeswijzer aan het einde van dit hoofdstuk helpt specifieke onderdelen van het proefschrift te vinden.

Hoofdstuk 2 beantwoordt onderzoeksvraag 1 en onderzoekt het beoogde curriculum in acht transdisciplinaire vakken aan de Technische Universiteit Delft en AMS Institute. De studie was erop gericht in beeld te brengen wat studenten zouden moeten leren (de leerdoelen van de vakken) door te werken aan authentieke vraagstukken uit de stad. En in hoeverre er in dit vak is samengewerkt met maatschappelijke actoren (mensen van buiten de academische wereld). De analyse baseert zich op de formele doelen in het vakbeschrijvingen van 8 vakken en vergelijkt die met de doelen en idealen die docenten van die vakken in 7 interviews beschreven.

1 Metacognitie is het bewustzijn van eigen kennis en het ontwikkelen van strategieën om te leren. In dit proefschrift speelt metacognitie een belangrijke rol, omdat het ontwikkelen van zelfkennis nodig is om inzicht te krijgen in wat nog onzeker of onbekend is.

2 'Scaffolding,' letterlijk 'steigers' in het Nederlands, is een vorm van begeleiding die docenten kunnen inzetten om studenten complexe vaardigheden, zoals probleemoplossend vermogen, te leren. Scaffolding is adaptief, de steigers worden alleen gebouwd als ze nodig zijn, en persoonlijk, iedere student worstelt op een eigen manier en de steiger past bij wat zij op dat moment aan ondersteuning nodig hebben.

Deze studie laat zien dat docenten transdisciplinaire vakken gebruiken om probleemoplossend vermogen van studenten te vergroten. Ze richten zich daarbij op de authentieke en reële vraagstukken die aansluiten bij de interesses van de studenten. De docenten benoemden ook doelen die in de vakbeschrijvingen niet duidelijk zijn vastgelegd. Juist de leerdoelen over analyseren en metacognitie, en de actieve participatie met maatschappelijke actoren, geven docenten aan als belangrijke leeropbrengsten van de vakken, maar deze stonden niet als leerdoel in de vakbeschrijvingen.

Hoofdstuk 3 beantwoordt onderzoeksvraag 2 en richt zich op onzekerheid in de beschrijvingen van de vraagstukken in het Living Lab-vak. Het Living Lab was één van de acht transdisciplinaire vakken in Hoofdstuk 2 die duidelijke actieve participatie met maatschappelijke actoren beoogde. De 48 vraagstukken werden geformuleerd door een 'opdrachtgever', een maatschappelijke actor die actief betrokken is bij het vraagstuk tijdens het vak. In een documentanalyse van 48 documenten, elk met een vraagstuk van een opdrachtgever, evalueerden we welke van de drie vormen van onzekerheid – onvoorspelbaarheid, onvolledigheid van kennis, en meervoudigheid van kennis[3] – aanwezig waren in de vraagstukken aan het begin van het vak. We categoriseerden vervolgens de vormen van onzekerheid op drie moeilijkheidsniveaus: simpel, ingewikkeld en complex. Verder analyseerden we hoe opdrachtgevers verwachtten dat studenten deze onzekerheden zouden aanpakken via de methoden die ze beschreven in de documenten.

Hoewel bijna in alle vraagstukken alle drie de vormen van onzekerheid voorkwamen, waren er wel verschillen in hoe complex ze waren. De meeste vraagstukken bevatten onvolledigheid van kennis op een ingewikkeld niveau. Meervoudigheid kwam het meeste voor op het hoogste, complexe moeilijkheidsniveau. Als de onzekerheid zich op een ingewikkeld niveau bevond, stelden opdrachtgevers conventionele onderzoeksmethoden voor, zoals een literatuurstudie. Maar voor de complexe vormen van onzekerheid, verwachtten ze dat studenten zouden experimenteren met transformatieve onderzoeksmethoden. Transformatieve onderzoeksmethoden, zoals co-creatie, zijn erop gericht de waarden, normen en verantwoordelijkheden van wetenschappelijk onderzoek te heroverwegen en waar nodig te transformeren. In het vak ontstaat daardoor een spanning tussen de conventionele en transformatieve benaderingen, die de opdrachtgevers verwachtten van studenten.

3 Onvoorspelbaarheid is onzekerheid over hoe de toekomst eruit zal zien. Onvolledigheid van kennis gaat over een gebrek of de onvolmaaktheid van kennis die leidt tot onzekerheid. Meervoudigheid van kennis is de onzekerheid die voortkomt uit complexe problemen, waarbij verschillende experts niet tot hetzelfde antwoord op een vraagstuk kunnen komen.

Hoofdstuk 4 beantwoordt onderzoeksvraag 3 en heeft tot doel het soort metacognitief leren dat nodig is om met onzekerheid om te gaan beter te begrijpen. We interviewden 9 studenten op 3 verschillende momenten in het Living Lab-vak (na 4, 10 en 16 weken) om inzichtelijk te maken hoe zij omgingen met onzekerheid en te horen tot welke keuzes ze dat bracht.

Studenten waren zich in de 21 interviews het vaakst bewust van onzekerheid als een meervoudigheid in het vraagstuk en, in mindere mate, zagen zij de onvolledigheid van kennis. Tijdens het vak werden studenten zich steeds meer bewust van de onvoorspelbaarheid van de uitdaging. Studenten gebruikten drie soorten metacognitieve regulatie om met onzekerheid om te gaan: het zoeken van sociale hulp, het toepassen van kleine coping mechanismen, en het veranderen van hun houding ten opzichte van onzekerheid.

Hoofdstuk 5 beantwoordt onderzoeksvraag 4 en onderzoekt de scaffolding-strategieën waarmee docenten studenten ondersteunen bij het ontwikkelen van probleemoplossend vermogen om met onzekerheid om te gaan. Op 3 verschillende momenten in het Living Lab-vak (na 5, 10 en 14 weken) volgden we hoe 10 docenten scaffolding-strategieën ontwikkelden op basis van een workshop die ze kregen voordat het vak begon. In 3 kwalitatieve enquêtes en 3 focusgroepen reflecteerden docenten op hun lespraktijk en coaching.

Docenten vonden onvolledigheid van kennis het meest uitdagend. Ze worstelden met het begeleiden van studenten bij het ontwikkelen van de theoretische onderbouwing bij de transformatieve benaderingen die ze in het Living Lab moesten gebruiken. Over het algemeen waren de belangrijkste scaffolding-strategieën die docenten ontwikkelden om studenten in het Living Lab te begeleiden gericht op feedback geven, focus houden, en het beperken van frustraties. Daarnaast pasten docenten hun coaching aan tijdens het vak afhankelijk van wat zij inschatten dat de studenten nodig hadden.

Hoofdstuk 6 voegt de belangrijkste bevindingen uit de empirische studies samen tot drie kerninzichten over onzekerheid in transdisciplinair onderwijs:

De vorm van onzekerheid verandert tijdens transdisciplinaire vakken. Dit proefschrift benadert onzekerheid in transdisciplinair duurzaamheidsonderwijs als een concept dat drie vormen aanneemt: onvoorspelbaarheid, onvolledigheid van kennis en meervoudigheid. Over het algemeen waren deze vormen van onzekerheid consequent aanwezig in de vraagstukken waaraan studenten werkten, maar de mate waarin deze vormen van onzekerheid door studenten en docenten in het vak werden ervaren, fluctueerde in de loop van de tijd. Vooral meervoudigheid, de verschillende perspectieven op het vraagstuk en de oplossingen, was een grote uitdaging die zowel door studenten en docenten, als ook door de opdrachtgevers, werd omschreven. In lijn met de doelen van transdisciplinair onderwijs, weerspiegelde dit hoe moeilijk het was om diverse perspectieven en waarden te integreren. Daarnaast zagen docenten en opdrachtgevers onvolledigheid van kennis bijdragen aan onzekerheid. Voor docenten was dit specifiek gerelateerd aan de theoretische onderbouwing van de projecten aan het begin en in het midden van het vak. Verder ervoeren studenten onvoorspelbaarheid als onzekere factor vaker tegen het einde van het vak, wanneer het voor hen duidelijker werd wat de onverwachte veranderingen tijdens het project waren geweest.

Het is een onvoorspelbare en ongemakkelijke worsteling om onzekerheid te leren omarmen. Dit proefschrift liet zien hoe onzekerheid een vorm van constructieve frictie stimuleerde in het vak. Studenten worstelden met wat ze niet wisten en zij losten dit op door op een nieuwe manier naar kennis en onzekerheid te kijken. Onzekerheid in het vak gaf studenten gelegenheid hun zelfbewustzijn te vergroten en hun leerprocessen zelf te reguleren. Om dit te bereiken, ontwikkelden studenten drie belangrijke soorten metacognitief gedrag in reactie op onzekerheid: ze zochten hulp bij anderen, ze gebruikten eigen copingmechanismen voor het gevoel van onzekerheid en ze veranderden hun houding ten opzichte van onzekerheid. Houdingen zijn moeilijk te veranderen. Het is daarom opmerkelijk dat het veranderen van de grondhouding tegenover onzekerheid (van aanvankelijke ongemakkelijkheid naar het omarmen van onzekerheid) een mogelijke leeropbrengst is van transdisciplinair onderwijs. De houding tegenover onzekerheid is belangrijk onderdeel van het komen tot oplossingen voor de complexe uitdagingen van duurzaamheid in de stad. Tegelijkertijd moet het gevoel van ongemak dat gepaard gaat met het heroverwegen van een houding ten opzichte van onzekerheid in de toekomst verder worden ondersteund in transdisciplinaire vakken.

Leren van onzekerheid wordt ondersteund door docenten die ook aandacht hebben voor persoonlijke leerdoelen. Docenten speelden een cruciale rol in het ondersteunen van leren omgaan met onzekerheid door hulp te bieden aan studenten, met name met betrekking tot de persoonlijke leerdoelen. Persoonlijke leerdoelen zijn doelen die studenten zelf formuleren in het vak. Voor docenten is het een uitdaging dat de houdingen en ervaringen met onzekerheid zo persoonlijk zijn, omdat studenten in transdisciplinaire vakken vaak diverse disciplinaire achtergronden en leerstrategieën hebben. Docenten kunnen studenten daarbij begeleiden door gedurende het vak steeds opnieuw te diagnosticeren waar studenten staan ten opzichte van hun eigen geformuleerde doelen. Om leren in onzekerheid te ondersteunen is het belangrijk dat persoonlijke ontwikkelingsdoelen een expliciete plek krijgen in het leertraject binnen een vak.

De belangrijkste inzichten en bevindingen van dit proefschrift moeten worden bekeken in het licht van twee beperkingen. Ten eerste waren de kwalitatieve onderzoeksmethoden gericht op kleine groepen deelnemers. Ze zijn daarmee bedoeld als eerste verkenning van de globale thema's die belangrijk zijn bij het leren omgaan met onzekerheid. Ten tweede was de EDR-aanpak voornamelijk gericht op het Living Lab-vak als een alleenstaande casestudie. Deze bevindingen moeten verder worden geconcretiseerd, buiten de specifieke omgeving van dit vak in Nederland en ook buiten de West-Europese context.

Toekomstig onderzoek zou het begrip van onzekerheid kunnen verdiepen door naast de kwalitatieve aanpak in dit onderzoek ook meer kwantitatieve methoden te gebruiken. Zo zouden houdingen ten opzichte van onzekerheid over een langere periode van tijd kunnen worden bestudeerd, buiten de kaders van één vak, om een beter beeld te krijgen van wat ten grondslag ligt aan een houding tegenover onzekerheid. Daarnaast kan onderzoek onder grotere groepen studenten dit eerste begrip van onzekerheid in dit proefschrift verder contextualiseren. Toekomstig onderzoek zou ook verder aandacht kunnen besteden aan hoe opdrachtgevers onzekerheid waarnemen en ermee omgaan en hoe dit wordt beïnvloed door hun actieve deelname aan het onderwijs. Daarnaast zouden specifieke studies naar het stellen van doelen in persoonlijke ontwikkeling of de manier waarop studenten frustratie zelf reguleren, docenten kunnen helpen hun rol als coach beter te begrijpen. Zulk onderzoek wordt bij voorkeur gedaan in een samenwerking tussen studenten en docenten. In het algemeen moedigt dit proefschrift aan tot meer ontwerpend onderzoek, met een EDR aanpak, in het onderwijs. Door veranderingen in het onderwijs systematisch te onderzoeken en kritisch te evalueren in hun complexe context kan innovatie in het klaslokaal een veel bredere impact hebben op de kwaliteit van onderwijs.

Dit proefschrift sluit af met het presenteren van zes ontwerprichtlijnen voor onderwijs in onzekerheid, die gebaseerd zijn op een combinatie van de belangrijkste bevindingen van het onderzoek en de praktische inzichten van de betrokken studenten, docenten, opdrachtgevers en onderzoekers. Ontwerprichtlijnen A en B behandelden de beginfasen van het vakontwerp, waarbij het belangrijk is om aandacht te besteden aan de (cognitieve, metacognitieve en affectieve) leerdoelen en de manier waarop maatschappelijke actoren worden betrokken met betrekking tot onzekerheid (Hoofdstukken 2 en 3). Vervolgens waren ontwerprichtlijnen C en D gebaseerd op de bevindingen die aantoonden hoe onzekerheid verandert tijdens het vak en hoe de houding van studenten ten opzichte van onzekerheid explicieter kan worden gemaakt (Hoofdstukken 3 en 4). Ten slotte suggereerden ontwerprichtlijnen E en F hoe het vakontwerp het leren omgaan met onzekerheid beter kan faciliteren door aandacht te besteden aan persoonlijke ontwikkeling en emoties (Hoofdstukken 2, 4 en 5). Deze ontwerprichtlijnen kunnen worden gebruikt door docenten, studenten en andere betrokkenen bij het ontwerp van transdisciplinaire vakken:

A **Activeer de participatie van maatschappelijke actoren:** Betrokkenheid van maatschappelijke actoren, bijvoorbeeld als opdrachtgevers, is cruciaal in transdisciplinair onderwijs. Er zijn verschillende manieren waarop participatie vorm kan krijgen. Het kader in Hoofdstuk 2 presenteert drie niveaus van betrokkenheid van deelnemers, variërend van lage tot hoge betrokkenheid: afstandelijk, cliënt en partner. Dit kader kan worden gebruikt om het niveau van participatie van andere actoren in het vak te overwegen, vooral in relatie tot de doelen en idealen van het vak. Niet elk transdisciplinair vak vereist actieve participatie van actoren als partners, maar een dergelijke participatie zal hoogstwaarschijnlijk meer vormen van onzekerheid in het vak met zich meebrengen.

B **Balanseer conventionele en transformatieve benaderingen in de leerdoelen:** Formuleer leerdoelen die de analytische vaardigheden beschrijven die studenten moeten leren om met de onzekerheid in het vraagstuk om te gaan en verduidelijk de verwachtingen van theoretische onderbouwing in het project. Welke analysevaardigheden studenten moeten leren in transdisciplinair onderwijs is afhankelijk van de beoogde doelen van de docent. Het kan gaan om conventionele dataverzamelingsmethoden, zoals interviews en observaties, maar ook om transformatieve benaderingen van onderzoek doen, zoals systeemdenken, experimenteren, mapping en co-creatie. Formuleer daarnaast leerdoelen die het soort metacognitieve vaardigheden of kennis die studenten verwerven tijdens het vak, bijvoorbeeld door te reflecteren op onzekerheid met medestudenten of door persoonlijke leerdoelen te stellen.

C **Verken de vormen van onzekerheid (onvoorspelbaarheid, onvolledigheid en meervoudigheid):** Het kader in Hoofdstuk 3 presenteert de drie vormen van onzekerheid op verschillende moeilijkheidsniveaus: simpel, ingewikkeld en complex. Dit kader stelt studenten en docenten in staat om te herkennen welke onzekerheden het meest urgent zijn in een duurzaamheidsuitdaging op verschillende momenten in het vak. Daarnaast kan het kader worden gebruikt om de complexiteit en onzekerheid in de uitdaging te bespreken samen met potentiële opdrachtgevers voordat het vak begint.

D **Reflecteer op veranderingen van houding:** Maak tijd vrij om de ontwikkeling van houdingen ten opzichte van onzekerheid te bespreken. Studenten kunnen houdingen ontwikkelen zoals flexibiliteit, empathie en relativisme. Deze kunnen worden versterkt en gereguleerd wanneer ze een explicieter onderdeel van het vak worden.

E **Ondersteun zelfregulering om frustraties te managen:** Ontwikkel ondersteuning, zoals scaffolding (adaptieve begeleiding) gedurende het vak voor het leren omgaan met frustratie. Vooral aan het begin van het vak is er behoefte aan die ondersteuning. Docenten, maar ook door medestudenten, kunnen die ondersteuning bieden, omdat studenten hun eigen coping mechanismen hebben om met onzekerheid om te gaan en deze wellicht bereid zijn te delen als de juiste sfeer voor uitwisseling wordt gecreëerd.

F **Stel doelen voor persoonlijke ontwikkeling:** Integreer het stellen van doelen met betrekking tot persoonlijke ontwikkeling om zelfbewustzijn en zelfkennis te vergroten. Alleen als je weet wat je weet, kun je je bewust worden van wat je niet weet. Door de manier waarop doelen worden gesteld te verduidelijken, kunnen docenten meer betrokken worden bij het begeleiden van persoonlijke ontwikkeling gedurende het vak. Op deze manier gaat het leren en onderwijzen van metacognitie verder dan het gebruikelijke reflectieverslag aan het einde van het vak en kan het ook het omgaan met onzekerheid tijdens het vak ondersteunen.

1 Introduction

‘I’m quick in thinking: oh, I don’t know things, well, then all of it is nonsense.’

This is how one of the students interviewed in this research explained what uncertainty meant to them: a lack of knowledge that is nonetheless inevitable when studying the complexities of the world. In my own words, uncertainty is the uneasy space between knowing and not knowing that can lead to an uncomfortable feeling. For this student, uncertainty leads to relativism, as doubts arise regarding the validity of knowledge and the credibility of authorities in the field (Perry, 1970). Such uncertainty could become an obstacle in the learning process when it hampers the self-confidence of students (Bandura, 1986) and their ability to decide what to do next (Pearce et al., 2018).

The Living Lab course[4] in which this student was a participant is an educational innovation that is increasingly part of higher education programs in the Netherlands: transdisciplinary education. Transdisciplinary courses strive to make real-world challenges, such as the energy retrofitting of social housing or the design of climate-adaptive streets, a central part of education, including the diverse perspectives of actors involved in these challenges (Gibbs, 2017). Particularly for engineering education, teaching scientific research and the design of new technologies to societal questions is crucial to avoid a mismatch between technological advancements and societal needs. Additionally, student motivation in transdisciplinary courses is expected to be higher (Bohm et al., 2020) because students can relate to the societal concerns that make this kind of education feel much more real (Ryan & Deci, 2000).

4 The Living Lab course is a 16-week challenge-based course where students work in teams of 3, 4, or 5 students on an urban sustainability challenge together with actors from the metropolitan region of Amsterdam. The course is part of the final year of the MSc MADE (Metropolitan, Analysis, Design and Engineering), a joint degree of Delft University of Technology and Wageningen University hosted at AMS Institute (Amsterdam Institute for Advanced Metropolitan Solutions) in Amsterdam.

Currently, societal concerns focus on the challenges of climate change and transdisciplinary courses are evolving to confront students with the complex set of interrelated problems that together can be characterized as being unsustainable (Kelly et al., 2023). The interrelatedness of the problems demand an integration of viewpoints of the solutions that will aid the transition to a sustainable society that can function within planetary boundaries (Raworth, 2017). Transdisciplinary education focuses on teaching such integration but may therefore also evoke uncertainty about how to come to analytical clarity or how to make decisions on possible solutions when different, conflicting perspectives are involved (Baumber, 2022).

The increased use of sustainability challenges in transdisciplinary education confronts students and teachers with uncertainty. Students need to learn how to navigate uncertainty in and beyond the course. Consequently, teachers must be able to guide the process of becoming competent in dealing with uncertainty, without the mere presence of uncertainty leading to too much discomfort for the students. However, empirical studies on transdisciplinary courses are limited (Horn et al., 2022), and dealing with uncertainty as a competence remains relatively unexplored (Diwekar et al., 2021). This dissertation is motivated by the simple question of how to educate uncertainty.

In the next section, I describe the theoretical background of transdisciplinary education and the knowledge gaps about uncertainty in such courses in more detail. These knowledge gaps will focus the research problem, aims, and research question, that I present in Section 1.2. Section 1.3 explains the research approach and methods for each of the four empirical studies. In Section 1.4, the background of the Living Lab course is discussed in more detail as the central case study in this dissertation. In Section 1.5, the outline of this thesis provides a reading guide that helps navigate the research.

1.1 Theoretical background

1.1.1 The two characteristics of transdisciplinary courses

Transdisciplinary courses have two main characteristics. The first characteristic is that transdisciplinarity centers around a complex challenge (Nicolescu, 2005). Complex challenges are problems in a dynamic, ill-structured problem space where it is hard to distinguish cause and effect (Simon, 1973). The challenges of city planning, for example, are complex, because there is not one person in control of how a city develops and it is very difficult to predict what the effect of new urban developments will be on social interaction in a neighborhood or the local economy (Stolk, 2015). With increased complexity comes also more uncertainty about what the right decisions are (Alexander et al., 2018). There is no definitive or objective answer to the questions such complex challenges pose, but several solutions directions (Dorst, 2015).

Increasingly, the challenges in transdisciplinary courses often focus on sustainability (Horn et al., 2022). At the time of writing, global surface temperatures have reached 1.1 °C warming compared to pre-industrial levels (in 1850-1900) (IPCC, 2023). The currently implemented policies to limit greenhouse gas emissions are projected to lead to 3.2 °C global warming before the end of the century. With some planetary boundaries being trespassed and others near trespassing, those challenges are increasingly framed from a sustainability perspective, which focuses on the continued balance between human activity and needs and sustained planetary carrying capacity for human and non-human activity. As such, climate change instigates educational changes across higher education to prepare students for an age of climate change and transdisciplinary education provides one of the methods to do so (Leal Filho et al., 2018).

As the complexity of sustainability challenges is difficult to replicate in traditional pedagogies, such as seminars, students need to experience the uncertainty in real-world and outside of the classroom. Therefore, transdisciplinary course design uses pedagogies and educational concepts that put a real-world challenge at the heart of the course, for instance through project-based, experiential, or inquiry learning (Gallagher & Savage, 2020). Recently, challenge-based learning (CBL) has gained attention as a transdisciplinary educational concept, where students can experience complexity (Malmqvist et al., 2015). In CBL courses, students engage, investigate, and act on a real-world challenge that is introduced by a 'commissioner' (Kasch et al., 2022). A commissioner is someone from outside of the university, an extra-academic actor[5], who brings a challenge from their daily practice for students to work on in the course (O'Sullivan, 2023).

The involvement of extra-academic actors as commissioners is the second defining characteristic of transdisciplinary education (Piaget, 1972). Transdisciplinary approaches require a way of working that seeks collaboration with both academic (peers with different disciplinary backgrounds) as well as extra-academic actors (people from outside of the university). A complex challenge crosses disciplinary boundaries and in teams, students from different disciplinary backgrounds can learn to integrate expertise and research approaches leading to interdisciplinary research (Ryser et al., 2008). Furthermore, transdisciplinary research considers local knowledge from actors outside of the field of academic inquiry (Bernstein, 2015).

Figure 1.1 shows how problems are positioned differently in academic research (Jaeger, 1998). Similarly, in disciplinary education, problem and approach are aligned and isolated. In multidisciplinary education, several disciplinary problems are considered part of a shared problem space, yet students will work on disciplinary approaches for each of those problems. In interdisciplinary education, students will need to create a shared understanding of the problem and work on it by merging several disciplinary approaches. In transdisciplinary education, students will work on a problem defined outside of the university not tied to any specific discipline beforehand. Furthermore, also in their approach they need involve the perspectives of extra-academic actors.

Hence, transdisciplinary courses expose students to theoretical and practical approaches from a range of perspectives both in- and outside of disciplines. Such courses offer an opportunity for students to learn to integrate these perspectives into actionable solutions for society (Roux et al., 2017). At the same time, the multiple perspectives present in a course interfere with the focus of students (Pearce et al., 2018) or might lead to a confusion about what is certain (Perry, 1970).

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5 I gratefully make use of the term 'extra-academic actors' to describe those involved in transdisciplinary education that are not usually involved in the university but do have a variety of stakes and resources, including power, in the societal challenges. O'Sullivan (2023) first proposed to use this term instead of societal actor or external stakeholder, as she argues: 'The word external suggests that some are on the outside while others are on the inside. In grand societal challenges, everyone is a stakeholder. Academic actors and extra-academic actors are all actors in society. Knowledge produced outside the university is of no greater or lesser importance than knowledge produced within the university.' (p.32)

Throughout this dissertation, I use these two characteristics to recognize transdisciplinary education: courses with a complex challenge and participation of extra-academic actors. However, creating transdisciplinary circumstances is not enough for transdisciplinary education to succeed (Oonk, 2016). Additionally, it must be clear what students should learn in these courses and how they are supported by teachers and others in that process (Biggs & Tang, 2011).

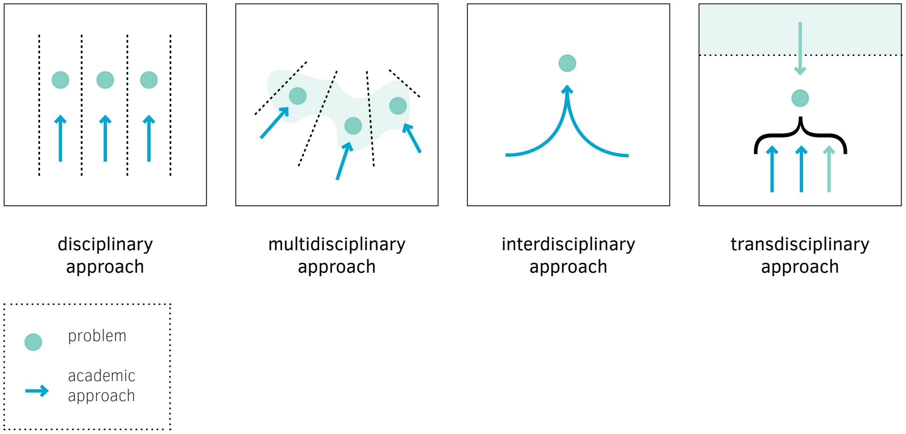

FIG. 1.1 The different approaches toward problems of a disciplinary, multidisciplinary, interdisciplinary, or transdisciplinary nature (adapted from Jaeger, 1998).

1.1.2 Learning to deal with uncertainty as a competence

Several frameworks for sustainability education mention that students need to learn to deal with uncertainty in the context of complex problems (Bianchi et al., 2022; UNESCO, 2017) and that transdisciplinary education would be a useful method to do so (Remington-Doucette et al., 2013). Additionally, other frameworks for sustainability education mention transdisciplinary education as a method for learning collaborative problem-solving. For example, the interpersonal competencies in the framework of Wiek et al. (2011) refer to the ability to 'motivate, enable, and facilitate collaborative and participatory sustainability research and problem solving'. Brundiers et al. (2020) propose to add intrapersonal competencies to the framework of Wiek et al. (2011) to account for the growth of self-awareness of one's knowledge, values, and emotions through transdisciplinary education. Furthermore, students value the competence of constructive communication most in the transdisciplinary course that Roy et al. (2019) studied. Although these frameworks do not always explicitly mention dealing with uncertainty as a learning outcome, they refer to communication and integration of perspectives that might lead to uncertainty (Pearce et al., 2018).

The concept of uncertainty is difficult to grasp (Funtowicz & Ravetz, 1990). The Merriam-Webster dictionary attributes two meanings to the word 'uncertainty' ("Uncertainty," n.d.):

1 the quality or state of being uncertain (doubt)
2 something that is uncertain

This research initially focuses on the second meaning of the word, namely the complex, sustainability challenges that are uncertain but it will show that encountering uncertain problems will inevitably lead to feelings of doubt as well.

Uncertainty in those challenges is not only due to a lack of knowledge but can also be contested by different actors having different perceptions of the problem (Koppenjan & Klijn, 2004). Both the dynamic and networked nature of sustainability challenges (Ingold et al., 2018) and a lack of agreement on what the problem is, cause uncertainty (Lang et al., 2012). Brugnach et al. (2008) define uncertainty as having three dimensions: unpredictability (accepting not to know), knowledge incompleteness (knowing too little), and knowledge frame multiplicity (knowing too differently). Such uncertainty dimensions are part of sustainability challenges in practice (Raadgever et al., 2011). In transdisciplinary education, students might also encounter these dimensions of uncertainty, yet this has not been studied in detail before and dealing with uncertainty as a competence[6] it has not yet been concretely operationalized.

Dealing with uncertainty will at least require awareness of one's knowledge to understand what knowledge might still be missing. From that awareness of uncertainty, one can start to regulate the thinking and learning that is necessary to deal with the unknown. Such awareness of knowledge and regulation of one's thinking is called 'metacognition' (Stanton et al., 2021). Metacognitive behavior is not only related to cognition and thinking but can also be used to regulate feelings (Tobias & Everson, 1997). Finding uncertainty in a sustainability challenge might lead to 'epistemic emotions' such as feeling uncertain or doubtful, the first meaning

6 Based on the recommendation of the European Commission on Lifelong Learning (2018), we understand competence as "a dynamic combination of knowledge, skills, and attitudes" (p. 12).

of the word in the dictionary (Carruthers, 2016). Therefore, dealing with uncertainty might not only relate to cognitive but also to affective behavior. In this dissertation, I will approach dealing with uncertainty as a metacognitive competence to allow operationalization in transdisciplinary education.

It is an open question how students learn to deal with uncertainty in a transdisciplinary course. Although the effectiveness of teaching metacognition is well-established in educational research (Perry et al., 2019), little is known about dealing with uncertainty as a specific competence. Kirschner et al. (2006) warn that without clear guidance learning environments that rely on students' self-directed learning, such as transdisciplinary education, will most likely fail. When learning complex competencies, such as problem solving and dealing with uncertainty, the guidance of teachers is an important enabler for learning (van Merriënboer & Kirschner, 2007). The next section further elaborates on how uncertainty in a course poses several challenges to the design of transdisciplinary courses.

1.1.3 The impact of uncertainty on the design of transdisciplinary courses in the city

To design transdisciplinary education, the perspective of at least three main characters is always considered: students, commissioners, and teachers. The previous section elaborated on what students need to learn to deal with uncertainty and what is yet unknown about dealing with uncertainty as a competence. Additionally, the position of the commissioner in the course and the changing role of the teacher shape transdisciplinary education (Oonk et al., 2020).

The participation of extra-academic actors is crucial to account for the real-world complexity of a challenge. Without the active participation of actors students will not have the opportunity to engage with different perspectives (Klein, 2010). Between transdisciplinary courses, the levels of participation might be different, as they are also considered to be different in participatory research and design (Gaete Cruz et al., 2022). For example, a commissioner from the municipality might present their experiences in the energy transition during a guest lecture, and in another course, students co-create ideas for retrofitting the façade of a building block with its inhabitants. It is unclear how the levels of participation of commissioners might differ between transdisciplinary courses. Therefore, it is unclear what kind of uncertainty arises from them, as the complexity and uncertainty both depend on the way extra-academic actors and their challenges are participating in the course.

Due to the involvement of a commissioner, and maybe even more actors, in transdisciplinary courses the role of teachers[7] changes. In disciplinary-oriented lectures and working groups, teachers often are perceived as the central authority in a certain subject but in transdisciplinary courses teachers become the 'coach' of an inquiry that students lead by themselves (Kasch et al., 2022). Although this is not unique to transdisciplinary courses – for instance, also in project-based learning teachers are positioned as coaches (Fleming, 2000) – in transdisciplinary education, the uncertainty of working on complex challenges with different people requires teachers to develop new competencies (Oonk et al., 2020). At the start of a transdisciplinary course, also the teachers do not know what the correct solutions are or even which integrative research approach the students might come up with (Savin-Baden, 2014). Therefore, effective coaches are willing to let go of some of their control and find an adaptive, non-directive way of supporting students' learning (Pearce et al., 2018). Scaffolding is a teaching model that aims to provide such adaptive guidance to students who learn to problem solve (van de Pol et al., 2010). Some studies have started to develop scaffolding within the context of sustainability education (e.g. Lönngren et al., 2017; Peng et al., 2022), yet scaffolding for uncertainty has not yet been investigated in this context.

As another central character in the process, teachers lack concrete implementation guidance for transdisciplinary education (Daneshpour & Kwegyir-Afful, 2022), despite the international discourse urging to develop such courses in practice (Frodeman, 2010; Jantsch, 1972; Max-Neef, 2005; Nicolescu, 2005; Nowotny et al., 2001). In the Netherlands, transdisciplinary ambitions in higher education are part of all recent educational strategies for universities of technology, either specifically called transdisciplinary education (University of Technology Delft, 2023; Wageningen University & Research, 2017) or challenge-based learning (Eindhoven University of Technology, 2018; University Twente, 2020). The challenge that these universities have formulated for themselves is to find a further engaged position in society and to operationalize this engagement in their curriculum. However, not many authors have investigated how to do this. The empirical investigation of transdisciplinary courses is limited and it is unclear how to the design of transdisciplinary courses can be supported based on educational research (Gallagher & Savage, 2020; Gibbs, 2017; Malmqvist et al., 2015). Hence, there is a need for inquiry of how such courses are designed in practice.

7 The roles of teachers in the design of transdisciplinary education are diverse. For instance, teachers develop and coordinate a course, or they can be the coaches that guide a student team in transdisciplinary work. In this dissertation, I broadly define teachers as the academics responsible for (a part of) the teaching and learning in transdisciplinary course design.

At the onset of this research, the MSc MADE program was a newly initiated master degree from the TU Delft and Wageningen University and Research that offered an opportunity to investigate transdisciplinary education in practice. MSc MADE is an acronym for Metropolitan Analysis, Design, and Engineering and the program is hosted at a research institute co-founded by the City of Amsterdam that aims to connect engineering expertise to the challenges of sustainability in the city and wider metropolitan region. In an urbanizing world, the city is not only an accumulation of complex challenges, but it also provides a knowledge network that forms as breeding ground for ideas, innovations, and knowledge development (Goddard & Vallance, 2013). To use the advantages of the city and contribute to solutions for complex challenges, universities create physical spaces for educational innovation with the city , such as MSc MADE, and discover new ways of delivering their core tasks of research, education, and valorization within society (van der Zwaan, 2017).

Specifically, in the transdisciplinary course called the Living Lab in MSc MADE, students co-create solutions to complex challenges of commissioners in Amsterdam. Horn et al. (2022) argue that there is a high probability that transdisciplinary courses, such as the Living Lab course in the MSc MADE program, are understudied and that many of the transdisciplinary courses in practice are not critically evaluated or deeply investigated. Therefore, the research in this dissertation aims to contribute to a further understanding of transdisciplinary courses from the perspective of all those involved: commissioners, teachers, and students.

1.2 Problem, aims, and research question

1.2.1 Problem statement and knowledge gaps

The previous sections showed how sustainability challenges increasingly enter engineering education through transdisciplinary courses. Those transdisciplinary courses center around a complex challenge and engage with the extra-academic actors of the challenge. The unpredictable nature of sustainability challenges, the knowledge gaps, and the multiple viewpoints of the people involved lead to more uncertainty. That increased uncertainty requires a course design that can effectively support learning to deal with the unknown in transdisciplinary education.

However, many aspects of transdisciplinary course design are understudied. For teachers, it is unclear what their aims and ideals are for teaching transdisciplinary courses. Although transdisciplinary education is expected to confront students with uncertainty through authentic challenges from a commissioner, there is no framework to identify uncertainty within sustainability challenges, nor is it clear to what extent students are aware of uncertainty or how they deal with it in the course. If teachers need to guide students through the uncertainty in sustainability challenges, all these aspects of the course design need to be better understood to be able to effectively support learning to deal with uncertainty in transdisciplinary education. Without such clear guidance this kind of education will most likely fail.

1.2.2 Research aims and research questions

This research aims to understand how to design transdisciplinary education where students learn to deal with uncertainty by answering the central research question and four sub-questions. Figure 1.2 illustrates how the research questions are connected to the perspectives of the people involved in the design of a transdisciplinary course.

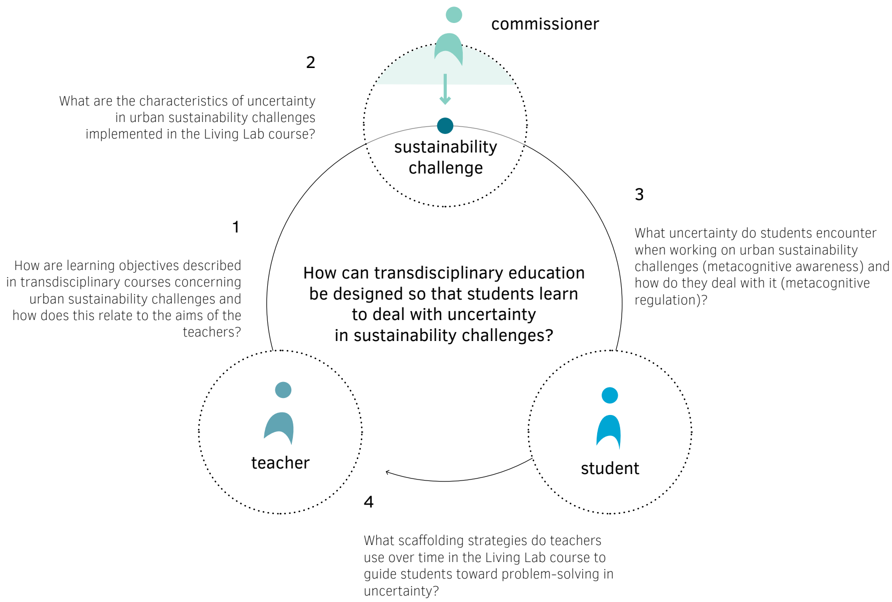

FIG. 1.2 The three main characters in transdisciplinary education are the student, teacher, and commissioner that introduces the sustainability challenge. This research aims to understand how uncertainty affects them by asking four sub-questions.

Central research question

How can transdisciplinary education be designed so that students learn to deal with uncertainty in sustainability challenges?

Sub-questions

1. How are learning objectives described in transdisciplinary courses concerning urban sustainability challenges and how does this relate to the aims of the teachers?
2. What are the characteristics of uncertainty in urban sustainability challenges implemented in the Living Lab course?
3. What uncertainty do students encounter when working on urban sustainability challenges (metacognitive awareness) in the Living Lab course and how do they deal with it (metacognitive regulation)?
4. What scaffolding strategies do teachers use over time in the Living Lab course to guide students toward problem-solving in uncertainty?

1.3 Research approach and methods

1.3.1 Educational Design Research (EDR)

This research deals with recently implemented educational innovation and a central research question aimed at further understanding and developing the course design. Therefore, this research is methodologically approached as an Educational Design Research (EDR). EDR focuses on the design of an educational intervention to better understand the intervention or the environment it was implemented in (McKenney & Reeves, 2012). The design of a course has many interrelated aspects and one of the benefits of EDR is that it allows for studying the design in an information-rich environment, because the researcher is closely involved in the course design and therefore has a detailed understanding of the decision-making process that led to the actual implementation of the course.

Due to its deep investigation with one or a few specific local interventions, this research is limited in its replicability but gains validity of the studies as they allow for an investigation of course design within the complexities of a specific context (Hutjes & Buuren, 1992). Additionally, this kind of qualitative research also has clear criteria to ensure rigorous investigation (Le Roux, 2017). In this research, I worked if possible, with a second coder that was not embedded in the research context and used multiple methods for triangulation. Additionally, I actively involved participants in collecting, analyzing, and interpreting data to be able to critically reflect in all stages of the research on the findings.

Nonetheless, the generalizability of EDR remains limited. Therefore, it is common to formulate 'design principles' as one of the final outcomes of the research (McKenney & Reeves, 2012; Plomp & Nieveen, 2014) and as a practical way of answering the open 'how can…' questions in EDR (Dorst, 2015). Design principles are a combination of the main findings of the study and the practical experiences or tools developed during the research (Kali et al., 2009). This dissertation answers the main research question with such design principles that allow for a case-to-case generalizability, where abstractions of the key findings might lead to a better informed course design in a new context outside of the research (McKenney & Reeves, 2012).

TOC

1.3.2 The intended, implemented, and attained curriculum as backbone for EDR

To be able to systematically structure the four studies that will contribute the design principles, I chose the model of van den Akker et al. (2013) as the organizational backbone for the EDR. van den Akker (2003) presents three perspectives on curriculum design: the intended, implemented, and attained curriculum, which I visualized in Figure 1.3.

The **intended** perspective deals with the aims and ideals of teachers and other people involved before the start of the course. In sub-question 1, the research aims to determine with what intentions a course is being designed. To gain a broader understanding of what those intentions might be for transdisciplinary courses, this study not only looks at the Living Lab course but also at seven other courses with a transdisciplinary character taught at Delft University of Technology. This way the starting point of the research is informed by more than the dreams and ideals of several teachers from different contexts before I zoom in on the specific context of the Living Lab course.

The **implemented** curriculum is about the interpretation and operationalization of the curriculum in actual teaching and learning processes. For transdisciplinary courses, the challenge is an important object of learning and the commissioned challenges are the objects investigated in sub-question 2.

The **attained** curriculum deals with what the students learn, whether measured in learning results or through their experiences. Sub-question 3 focuses on the experiences of students with uncertainty in transdisciplinary education.

In the final empirical study, this research develops an intervention with teachers in the Living Lab course that aims to combine insights from the three curriculum perspectives. Sub-question 4 aims to propose a re-design through the development of several interventions based on the knowledge gained in the first stage of the research.

FIG. 1.3 The model of van den Akker (2003) structures the research in this thesis.

1.3.3 Methods per sub-question

Hence, this dissertation includes four empirical studies that each investigate a perspective on uncertainty in transdisciplinary course design, around one of the research questions, with specified methods explained below and shown in Table 1.1.

1 How are learning objectives described in transdisciplinary courses concerning urban sustainability challenges and how does this relate to the aims of the teachers?

Through research question 1 we investigate the intended learning in several transdisciplinary courses at Delft University of Technology and AMS Institute. The study aims to get a better understanding of what students are meant to learn from working on real-world challenges and how extra-academic actors participated in these courses. Additionally, this study allowed us to get an understanding of the uniqueness of the Living Lab course as case study compared to other transdisciplinary courses. We compared the formal intentions of eight courses in their course descriptions with the aims and ideals that teachers described in interviews. In the document analysis of the course descriptions (8) and interviews with the teachers (7), we used the revised taxonomy of Bloom (Krathwohl, 2002) and an adaptation of the ladder of participation (Arnstein, 2019) to research the intended curriculum perspective on transdisciplinary courses.

2 What are the characteristics of uncertainty in urban sustainability challenges implemented in the Living Lab course?

From research question 2 onwards this dissertation zooms in on uncertainty in the specific case study of the Living Lab course. This study analyzes uncertainty in the challenge descriptions of commissioners in the course. We investigate

TOC

the nature of uncertainty in 48 sustainability challenges used in the Living Lab course between 2018-2022. Through document analysis, we review to what extent uncertainty was part of those challenge descriptions and which approaches students are expected to use to deal with those uncertainties. To this end, we develop a framework for uncertainty as in the work of Brugnach et al. (2008) with three dimensions: unpredictability (uncertainty because of societal processes or technological surprises that are sometimes impossible to predict), knowledge incompleteness (uncertainty because of a lack of information, theoretical understanding, or the data is unreliable), and knowledge frame multiplicity (uncertainty because the people involved might have different ways of perceiving the problem). Additionally, we analyze the difficulty level of the uncertainty and distinguish between uncertainty of clear, complicated, or complex difficulty (Alexander et al., 2018).

3 What uncertainty do students encounter when working on urban sustainability challenges (metacognitive awareness) in the Living Lab course and how do they deal with it (metacognitive regulation)?

Research question 3 investigates what metacognitive awareness and regulation students attained while dealing with uncertainty in the Living Lab course. We aim to further specify the kind of metacognitive learning (Veenman et al., 2006) that is necessary to deal with uncertainty. To this end, we interviewed 9 students at three different moments in the Living Lab course (27 interviews in total). To analyze the awareness of uncertainty, we use the analytical framework developed for research question 2. To describe the regulation of uncertainty, we use open coding, as not many other studies have investigated the regulation of uncertainty in education before.

4 What scaffolding strategies do teachers use over time in the Living Lab course to guide students toward problem-solving in uncertainty?

Research question 4 is a design intervention study, where we return to the perspective of teachers in transdisciplinary courses and investigate how they adapt their teaching to offer guidance for students when they face uncertainty. In study, we monitor how 10 teachers in the Living Lab course develop scaffolding based on a workshop they received before the course began. Through 3 qualitative surveys and 3 focus groups conducted every four weeks in the course, teachers reflect on their teaching practices and coaching strategies. We used scaffolding theory (Wood et al., 1976) to collaboratively explore with teachers how they adapted their teaching to the uncertainties students encountered in the course.

TOC

TABLE 1.1 Overview of the aims, questions, methods, and the case study where data was collected for each of the empirical studies

Research aim	Research question	Theory	Methods	Case study
To understand the intended aims and ideals of teachers in transdisciplinary courses	How are learning objectives described in transdisciplinary courses concerning urban sustainability challenges and how does this relate to the aims of the teachers? (Chapter 2)	Ladder of participation, the revised Taxonomy of Bloom	– Document analysis – Semi-structured interviews with 7 teachers	8 transdisciplinary courses at TU Delft and AMS Institute (2015-2020)
To understand in what ways uncertainty has been implemented through sustainability challenges in transdisciplinary courses	What are the characteristics of uncertainty in urban sustainability challenges implemented in the Living Lab course? (Chapter 3)	Complexity, uncertainty	– Review of uncertainty literature – Document analysis of 48 challenge descriptions	Living Lab MSc MADE (2018-2022)
To understand which metacognitive strategies students attain when they respond to uncertainty in transdisciplinary courses	What uncertainty do students encounter when working on urban sustainability challenges (metacognitive awareness) in the Living Lab course and how do they deal with it (metacognitive regulation)? (Chapter 4)	Metacognition	– Longitudinal, semi-structured interviews with 9 students	Living Lab MSc MADE (2022)
To design with teachers scaffolding means to guide students through uncertainty in transdisciplinary courses	What scaffolding strategies do teachers use over time in the Living Lab course to guide students toward problem-solving in uncertainty? (Chapter 5)	Scaffolding	– Design study with 10 teachers monitored in 3 qualitative questionnaire and 3 focus groups to coherently scaffold this.	Living Lab MSc MADE (2023)

1.4 Central case study: the Living Lab course in MSc MADE

1.4.1 The Living Lab course

The Living Lab course[8] within the MSc MADE (Metropolitan Analysis, Design, and Engineering) curriculum is the central case study in three of the four empirical studies in this dissertation. MSc MADE is a joint degree, two-year master's program founded by Delft University of Technology (TU Delft) and Wageningen University and Research (WUR). Amsterdam Institute for Advanced Metropolitan Solutions (AMS Institute) in Amsterdam hosts the program in Amsterdam. Founded in 2014 by TU Delft, WUR, and the Massachusetts Institute of Technology (MIT) and co-funded by the city of Amsterdam, this public-private institute aims to take on the challenges posed by a rapidly urbanizing world by developing research and education in the metropolitan region of Amsterdam. Both AMS Institute and MSc MADE make use of living labs as a method to advance scientific research in practice and to engage with the valuable context of the challenges in urbanized metropolitan areas.

Specifically in the 24 ECTS[9] Living Lab course in the second year of the MSc program, students work on an urban challenge within a living lab project. In the course, living labs are defined as: 'A physical arena as well as a collaborative approach in which different actors have space to experiment, co-create and test innovation in real-world environments defined by their institutional and geographical boundaries.' (Schliwa & McCormick, 2016, p. 174) To be considered a living lab project students start their investigation from an real-world urban challenge formulated by a commissioner (Steen & Van Bueren, 2017) and during the project they collaborate across the quadrupole helix of academia, government, industry, and users (Maas et al., 2017).

8 The learning objectives of the course can be found in Table 4.1.

9 ECTS is the abbreviation for 'European Credit Transfer and Accumulation System,' which is used across higher education institutes in the European Union as a common measure for learning based on specific learning outcomes and their associated workload (European Commission Directorate-General for Education Youth Sport Culture, 2015). 60 ECTS credits are the equivalent of 1 full-time academic year of studies.

The use of the terminology 'laboratory' in living labs is paradoxical. Not only are the conditions of the space where the experiments are done completely different from the isolated rooms that laboratories are associated with, also the co-creative nature of the living lab approach makes for a different way of developing knowledge and innovation (Maas et al., 2017). The real-world experimentation in living labs is often facilitated by digital technologies, such as robotization or big data, and, at the same time, makes use of research methods from the social sciences. Therefore, living labs bridge disciplines within the real-world societal challenges in that part of the city they are focused on.

The deep investigation of the Living Lab course is a form of extreme case sampling of transdisciplinary courses in the Netherlands, because the design of this course offered this research an opening to study teaching and learning in an environment that may not arise so often (Bryman, 2016). This research aims to thoroughly understand how uncertainty affects transdisciplinary education in this unique community of students, teachers, and commissioners. Additionally, this research is motivated by the idea that monitoring and evaluation of educational innovations, such as the Living Lab within MSc MADE, from the perspective of education and learning sciences can advance higher education in general, as well as the local experiment itself.

1.4.2 My position in the Living Lab course

During the research, I have been a course developer, coordinator, and researcher in the Living Lab course. Since 2017, I have been involved in preparing the course setup and coordination. Between 2019 and 2021, I continued as a course coordinator whilst studying the Living Lab as an embedded researcher. During this period, I took several measures to deal responsibly with this embedded position. I made sure that (1) in the MSc MADE program, including the Living Lab course, I was not grading students, (2) in the Living Lab course, I communicated to students, commissioners, and teachers about my role as a researcher and the contents of the research and (3) through regular reflection moments with the supervisors of this dissertation and the teachers involved in MSc MADE, I developed a reflexive practice where findings of the research could lead to informed changes in the program.

1.5 Outline of the dissertation

This dissertation presents four empirical studies that each investigate a different aspect of the design of transdisciplinary courses: learning objectives, sustainability challenges, student experiences, and scaffolding strategies (Figure 1.4).

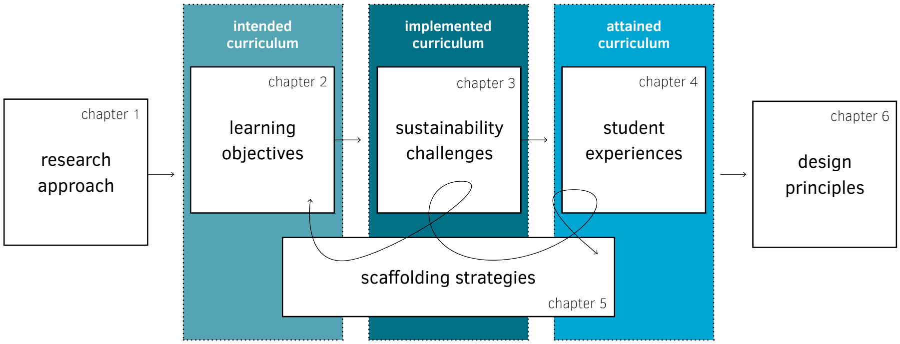

FIG. 1.4 Organization of the chapters in this dissertation

Chapter 2 investigates the intended learning objectives of the transdisciplinary courses that collaborate with cities at Delft University of Technology and AMS Institute. This chapter looks into how far-reaching the collaboration with urban actors in these courses is and what students are meant to learn from the transdisciplinary pedagogies. This way the research takes a broader, more contextualized starting point, before zooming in on the case of the Living Lab course in MSc MADE.

Chapter 3 presents an analysis of the sustainability challenges that students worked on in the Living Lab course between 2018 and 2022. One of the characteristics of transdisciplinary education is that it starts from a complex challenge and here I investigate how that is implemented. More specifically, this study looks into how complex these challenges are and what uncertainties students might encounter when they start working on them.

Chapter 4 investigates how students perceive uncertainty during the Living Lab course. Through 27 in-depth interviews with 9 students at different moments in the course, this study tries to understand what awareness and regulation of uncertainty students develop during the Living Lab course.

In Chapter 5, the research collaborates with the teachers in the Living Lab course to develop adaptive guidance for uncertainty. How teachers guide students through the course combines their understanding of the intended, implemented, and attained curriculum. Based on that understanding, they act in the classroom. Those actions are called ‘scaffolding strategies,’ which can inform and inspire other teachers’ practices in transdisciplinary courses.

In the final chapter, the outcomes of the combined chapters lead to six design principles that teachers, students, and other people involved in transdisciplinary education can use to (re)design courses and curricula to effectively deal with uncertainty in sustainability challenges.

2 Education in collaboration with cities

The intentions of transdisciplinary courses

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ABSTRACT

In collaboration with their home cities, universities increasingly develop courses in which students investigate urban sustainability challenges. This paper aims to understand how far-reaching the collaboration with urban stakeholders in these courses is and what students are meant to learn from the transdisciplinary pedagogies. This research is designed as a qualitative multiple-case study into the intentions of transdisciplinary courses in which universities collaborate with their home cities: TU Delft in Delft and AMS Institute in Amsterdam. The study compares the written intentions of eight courses in course descriptions with the ideal intentions that teachers describe in interviews.

First, seven of the eight investigated courses were designed for urban stakeholders to participate at a distance or as a client, but rarely was a course intended to lead to a collaborative partnership between the city and students. Second, the metacognitive learning objectives, such as learning to deal with biases and values of others or getting to know one's strengths and weaknesses in collaboration, were often absent in the course descriptions. Learning objectives relating to metacognition are at the heart of transdisciplinary work, yet when they remain implicit in the learning objectives, they are difficult to teach.

This paper presents insight into the levels of participation intended in transdisciplinary courses. Furthermore, it shows the (mis)alignment between intended learning objectives in course descriptions and teachers' ideals. Understanding both the current state of transdisciplinarity in sustainability courses and what teachers envision is vital for the next steps in the development of transdisciplinary education.

KEYWORDS Transdisciplinary learning and teaching, university-city collaboration, urban sustainability, higher education

2.1 Introduction

Higher education increasingly consists of transdisciplinary courses (Gibbs, 2017). In their most basic definition, transdisciplinary courses involve a specific context, where students learn by working on real-world challenges with real-world stakeholders (Jaeger, 1998). Increasingly, challenge-based learning is used as a teaching and learning approach in transdisciplinary courses but also pedagogies, such as project-based, experiential, or inquiry learning, can be part of transdisciplinary education (Gallagher and Savage, 2020). When teaching methods become transdisciplinary, the intended learning in those courses changes as well (Van den Akker, 2003).

In the 1970s, transdisciplinary education arose from the need to engage students with the complexity of societal challenges (Piaget, 1972). More recently, there are two additional reasons for universities to make education more transdisciplinary. First, transdisciplinary education speaks to students who want to become agents of change for societal transitions (Newman, 2006). Currently, many young people in Europe consider creating a sustainable society the most prominent societal transition of this time (Horton et al., 2013). The sense of urgency in sustainability challenges motivates students, and transdisciplinary education allows them to be part of the action (Bohm et al., 2020).

The second driver for universities to develop transdisciplinary education is that it enables them to respond to the critical concerns of society (Thomas, 2020). In the past decade, policymakers have been encouraging universities to support their local economies by making the expertise of researchers and the human capital of students accessible to local stakeholders (Kempton, 2019). Generally, universities feel a responsibility to have a societal impact by contributing to sustainable transitions

(Leal Filho et al., 2022). Continuing urbanization, for instance, challenges cities to accommodate a growing population and use of resources, while improving the quality of life (Van Bueren et al., 2012). Through transdisciplinary education, universities are involved in those urban sustainability challenges in their home cities and connect them to societal needs.

Consequently, universities have been seeking ‘university-city collaborations’ to develop transdisciplinary research and education (Goddard and Vallance, 2013). University-city collaborations are collaborations between universities, municipalities, and other urban stakeholders that focus on local challenges (Kempton et al., 2021). These collaborations offer both the proximity of the location as well as the network of actors that is crucial for developing transdisciplinary answers to local problems (Harris and Holley, 2016).

Even though universities are committed to university-city collaborations on an institutional level, little is known about how teachers deal with transdisciplinarity on the level of the course. In the past, not all educational changes on the school level have made it to the classroom (Van den Akker, 2003). Especially in universities, where academic freedom is fundamental, teachers have a deciding role on changes in the curriculum and course design. When it comes to transdisciplinary education, there are two important issues teachers are confronted with.

First, the learning objectives in transdisciplinary education are opaque. Transdisciplinary education is concerned with more than cognitive learning (Thomas, 2010). Therefore, principles of transdisciplinary learning consist of a variety of skills, ranging from teamwork, and co-creative problem-solving, to bridging the gap between academic theory and practice, and abilities to deal with conflicting world views (Biberhofer and Rammel, 2017). Furthermore, several authors find that adding new learning objectives to the existing mix in a course is not enough if students need to become agents of change in sustainable transitions (Biberhofer and Rammel, 2017, Thomas, 2010, Gibbs, 2017). To them, transdisciplinary education should contribute to transformative learning, allowing students to reframe problematic assumptions and expectations (Mezirow, 2000). How teachers currently deal with the unclarity of transdisciplinary learning objectives in practice is unknown.

Second, stakeholders can participate in transdisciplinary courses in various ways. For example, the level of participation of urban stakeholders is different in a course that informs students about the challenges in energy transitions in a presentation by the municipality and a course where students collaboratively make a design for an urban park with a citizens’ group (Gaete Cruz et al., 2022). Hence, teachers need to decide on the level of participation in the course design.

To the knowledge of the authors, research into transdisciplinary education is still limited and fails to offer concrete implementation guidance to teachers (Daneshpour and Kwegyir-Afful, 2021). Little is known about the learning objectives used in transdisciplinary courses or the role urban stakeholders are envisioned to play in these courses. This study compares the transdisciplinary education goals in course descriptions to the transdisciplinary aims of the teachers. The research will answer the main research question: **How are learning objectives described in transdisciplinary higher education courses concerning urban sustainability challenges and how does this relate to the aims of the teachers?**

Eight transdisciplinary courses in two university-city collaborations in the Netherlands are investigated: Delft University of Technology in Delft and Amsterdam Institute for Advanced Metropolitan Solutions in Amsterdam. In Section 2.2 the paper starts with constructing a framework to analyze transdisciplinary learning objectives in courses. In Section 2.3 the authors explain how they used document analysis and semi-structured interviews with the teachers to get to the results presented in Section 2.4. The paper ends with a discussion and conclusion, where the authors discuss the main results, limitations, and implications.

2.2 Background and analytical framework

This section describes the theoretical background of this study and constructs an analytical framework to study learning objectives in transdisciplinary courses. A course can be studied through the lens of its learning objectives by investigating the ‘intended curriculum’ (Van den Akker, 2003). A curriculum, whether on the level of a course or an entire educational program, is not always what it looks like (Martin, 1982). Educational research often distinguishes three curriculum representations: the ‘intended’ curriculum (i.e. the vision as described by its designers), the ‘implemented’ curriculum (i.e. the curriculum-in-action as operationalized by teachers), and the ‘attained’ curriculum (i.e. what is learned and experienced by students). According to Van den Akker et al. (2013), the intended curriculum can be approached from two perspectives: a ‘formal/written’ representation in curriculum materials, and an ‘ideal’ representation that is the vision, rationale, or basic philosophy of a curriculum (see Table 2.1). Ultimately, all representations of the curriculum revolve around a specific rationale. The push toward transdisciplinary teaching and learning suggests that the rationale behind the curriculum is changing.

TABLE 2.1 The two representations of the intended curriculum (authors' work adapted from Van den Akker et al., 2013, p. 56)

Intended curriculum	Ideal	Vision, rationale, or basic philosophy underlying a course
	Formal / Written	Intentions as specified in course documents and/or materials

The shift toward education that prepares students for real-world sustainability challenges has become increasingly visible since Kates et al. (2001) positioned sustainability science as an academic field. Since then, several scholars have investigated which key competencies should be part of that curriculum (Wiek et al., 2011). Rieckmann (2012) found in a Delphi study that systemic thinking, anticipatory thinking, and critical thinking are the most relevant key competencies in educating for the Sustainable Development Goals (SDGs). These thinking skills are not limited to the field of sustainability science alone, Wiek et al. (2011) pointed out that further research should investigate the relationship between learning outcomes in sustainability education and regular academic competencies, such as critical thinking.

At the course level, the taxonomy of Bloom has proven to be a helpful tool in formulating intended learning objectives for regular academic competencies (Biggs and Tang, 2011). Now widely used in course design all over Europe, the 'taxonomy of educational objectives' was once developed to enable the exchange of test items and a common language for educational objectives between universities (Krathwohl, 2002, Bloom et al., 1956). Instead of using a transdisciplinary or sustainability-specific vocabulary, this study made use of Bloom's revised taxonomy to take advantage of this common language to structure the research using the language of university teachers. This will enable us to evaluate if the taxonomy is useful for transdisciplinary purposes as it is for other academic courses.

Bloom's revised taxonomy distinguishes two dimensions within a learning objective (Table 2.2). A learning objective has a 'cognitive process dimension'. This dimension can be recognized by the verb used within the objective. As the level of complexity of the task increases, there are six categories within this dimension: remember, understand, apply, analyze, evaluate, and create. The key sustainability competencies as they are defined by UNESCO (2017, p. 10) include complex cognitive processes, such as "analyze complex systems", "evaluate multiple futures", or "create viable, inclusive, and equitable solution options that promote sustainable development".

In addition to the process dimension (the verb), a learning objective contains a 'knowledge dimension', which is the object of what is being learned. This has been aggregated in the framework on four levels: factual, conceptual, procedural, and metacognitive knowledge. Reflecting on positions, perceptions, and views is especially important to the aims of transdisciplinarity (Leal Filho et al., 2018) and sustainability (Rieckmann, 2012). The metacognitive knowledge dimension is thus expected to be represented in the learning objectives of transdisciplinary courses in particular. In addition to Bloom's taxonomy, previous research also shows the variability of affective learning objectives in higher education (Mintz and Tal, 2014). Furthermore, Taylor et al. (2021) emphasize the importance of collaborative competencies in the context of urban sustainability. However, civic engagement remains difficult to integrate in sustainability courses (Mintz and Tal, 2014).

TABLE 2.2 Description of the different categories in Bloom's Revised Taxonomy (authors' work adapted from Krathwohl, 2002).

Dimensions	Categories	Description
Cognitive process dimension (verb)	**Remember**	Retrieving relevant knowledge from long-term memory.
	Understand	Determining the meaning of instructional messages, including oral, written, and graphic communication.
	Apply	Carrying out or using a procedure in a given situation.
	Analyse	Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose.
	Evaluate	Making judgments based on criteria and standards.
	Create	Putting elements together to form a novel, coherent whole or make an original product.
Knowledge dimension (object)	**Factual**	The basic elements that students must know to be acquainted with a discipline or solve problems in it.
	Conceptual	The interrelationships among the basic elements within a larger structure that enable them to function together.
	Procedural	How to do something; methods of inquiry, and criteria for using skills, algorithms, techniques, and methods.
	Metacognitive	Knowledge of cognition in general as well as awareness and knowledge of one's own cognition.

Investigating the learning objectives in transdisciplinary education offers insights into *what* learning teachers intend to achieve, but it does not explain *how* teachers expect students to attain these objectives in the course. Although the development of sustainability education calls for changing teaching methods, teachers find it difficult to adopt new pedagogies, such as challenge-based learning and prefer traditional lectures, tutorials, and discussions (Christie et al., 2013). This study looks at the levels of participation of urban stakeholders to understand to what extent teachers succeed in adopting transdisciplinary pedagogies in the course.

Participation can be perceived on a continuum of increasing levels. The well-known ladder of participation by Arnstein (1969) has eight rungs, ranging from manipulation of citizens to full control by citizens. Originally, the ladder was meant to

TOC

criticize the often not genuine involvement of citizens in decision-making processes (Arnstein, 2019). Arnstein differentiated between 'empty rituals' of going through the movements of participation without any real decision power for the people participating, and a process in which power is redistributed to parts of society that would otherwise not be heard. Over the years, the ladder of participation has been translated for many different processes, not just aimed at citizen involvement, but also in the context of education (Hart, 1992). This study makes use of a simplified version of the ladder to distinguish the level at which urban stakeholders are expected to participate.

Arnstein grouped the eight levels of participation into three categories (Table 2.3). 'Non-participation' for the bottom rungs of the ladder, where there is no genuine participation objective. In this study, this is translated into a *distant* level of participation in higher education. Stakeholders are only involved in the preparation of the course, but students do not meet or speak with them as part of the course. The second group of rungs on Arnstein's ladder is called 'tokenism'. Applied to the higher education context, participation can be defined as tokenism when there is an exchange of knowledge between students and stakeholders during the course but no collaboration. The stakeholders are involved in the course to inform or consult the students in their work, often in the role of *client*. In some cases, student work is presented as advice to the stakeholders, however, the stakeholders themselves retain the right to decide to use it. Finally, the upper rungs of the ladder form a third group, which Arnstein categorizes as 'citizen power'. On this level, participants have power in the decision-making process. Translated to higher education courses, stakeholders are involved as *partners* of the students and they collaboratively work on solving a problem.

TABLE 2.3 Levels of participation adapted for transdisciplinary learning environments (authors' work adapted from Arnstein, 1969).

Arnstein's levels	Level of participation in higher education	Description
Non-participation (Passive)	**Distant**	The collaboration stops with the collaborative formulation of a problem that originates from the city.
Tokenism (Responsive)	**Client**	There is a client that presents the challenge at the start of the course and that collects the results at the end.
Citizen power (Active)	**Partner**	The students are depending on the involvement of others or are expected to involve others in order to solve the problem.

This study investigates the intended curriculum of transdisciplinary courses in university-city collaborations. In the analysis, the taxonomy of Bloom is used and the levels of participation as the authors have derived them from Arnstein's ladder. The study is structured into three sub-questions:

1. What do course descriptions say about (a) cognitive processes, (b) knowledge dimensions, and (c) levels of participation? (written curriculum)
2. What do teachers say about desired (a) cognitive processes, (b) knowledge dimensions, and (c) levels of participation? (ideal curriculum)
3. What are the similarities and differences between the written (1) and ideal curriculum (2)?

2.3 Materials and methods

2.3.1 Two university-city collaborations as case study context

This study was designed as an explorative and qualitative multiple-case study (Yin, 2009) into the intended curriculum of transdisciplinary courses in two university-city collaborations. The first investigated university-city collaboration is the collaboration between the city of Delft and Delft University of Technology (TU Delft). The TU Delft can be categorized as an 'old' (founded in 1842) and 'big' (over 27.000 students) higher education institute and is therefore expected to focus more on its national or international role than on its local role in the city (Kempton et al., 2021). In the past years, however, national policies have been encouraging the development of a closer relationship with Delft (Netwerk Kennissteden Nederland et al., 2017).

The second university-city collaboration included in this study is Amsterdam Institute for Advanced Metropolitan Solutions (AMS Institute). Founded in 2013 by the TU Delft and Wageningen University, in response to a subsidized call for such an institute by the city of Amsterdam, this smaller research institute facilitates a master program called 'MADE' (Metropolitan Analysis, Design, and Engineering) (<200 students). Research and education at MADE focus on metropolitan challenges of the Amsterdam Metropolitan Region. The relationship with the city is thus already institutionalized in the institute's mission. From these two collaborations, eight transdisciplinary courses were selected as cases that could be investigated in more detail.

TOC

2.3.2 Case selection and data collection

First, the authors selected courses that used an urban challenge in Delft or Amsterdam in the past five academic years (between 2015-2021) in their teaching curriculum. The courses were collected through program coordinators at the two institutions and coordinators of the municipalities in Delft and Amsterdam. Although eleven courses fitted the selection criterion, the coordinating teachers of eight courses (six at TU Delft and two at AMS Institute) were available for interviews. These courses form the case selection in this research.

Some of the transdisciplinary courses in the selection were part of a core curriculum and others were offered as electives. Only one of the cases was a bachelor's course. All other courses in the study were at the master's level. From the eight courses, two types of data were collected: course descriptions and interviews with the coordinating teachers.

First, the course descriptions were collected from course guides in which the general background, objectives, planning and structure of the course were described. In one instance the course guide was not available and the teacher provided us with other documentation: slides from the introduction lecture and the course webpage. All courses were conducted multiple times between 2015 and 2021. Therefore, the authors chose to analyze the course guides from the most recent edition of the course.

Second, the first author conducted semi-structured interviews with seven teachers who coordinated the eight courses. An interview protocol was developed with questions on four themes (Bryman, 2016): the origin of the course, the aims of the course, how the course collaborated with partners in the city, and reflections on the success of the course (Appendix A). The interviews were conducted jointly by two researchers, the first author asked guiding questions based on the interview guide. The second researcher made notes during the interviews and asked verifying questions based on the notes. While the course descriptions provided insights into the written intentions of the course, the interviews allowed us to ask more in-depth questions about the reasoning, visions, and ideals of the teachers in those courses. Written consent for the involvement in the research was obtained from the teachers before the interviews.

2.3.3 Data analysis

The course descriptions and interviews were analyzed through concept coding (Saldana, 2016) using a codebook based on the theoretical framework presented in Section 2.2 (Appendix B). The codebook consisted of three code groups with the main concepts of Table 2.2 and Table 2.3 providing a priori codes. Table 2.4 shows a coding example from each of the code groups for the course descriptions and interviews. The codebook was collectively tested by all authors to resolve unclarities before the first cycle of coding.

TABLE 2.4 Coding examples for each code group in the analytical framework (authors' work).

Code group	Code	Example quote from course guide	Example quote from interviews
Cognitive process (a)	**Apply**	'[The student is able to] compose an analytical survey or interview.'	'Within the group they need to make agreements on how to distribute the work. So that is immediately connected to applying group dynamics.'
Knowledge object (b)	**Conceptual**	'[The student is able to] explain critical issues of AI with respect to fairness, accountability, and trust.'	'So, you're looking for a theme that is complex enough to pull apart, but at the same time, integrated enough to write a synthesis on.'
Level of participation (c)	**Client**	'Apply their academic knowledge, general academic skills and attitude to a project dealing with a complex problem commissioned by a client outside the university.'	'That [the introduction by the municipality] is the first handover of information to the students. At the same time, it is combined with an actor perspective: this is how the municipality looks at it.'

The coding (Saldana, 2016) was done by two researchers in two cycles using *Atlas. TI* as coding software. During the first cycle of coding two researchers coded all documents separately. After calibrating the results, a second coding cycle was done to ensure completeness. The results were based on 109 quotations from the course descriptions and 264 quotations from the interviews. When counting which courses mentioned which learning objectives or which levels of participation, the researchers did not consider how often those codes were mentioned. Furthermore, a thematic analysis (Saldana, 2016) of the interviews was done to include the motives of teachers for transdisciplinary education. The results from the thematic analysis are presented in Section 2.4.2.

TOC

Conflicts that arose were discussed and resolved after the coding was done to come to a consensus on the findings. Conflicts could be codes assigned to a document by one researcher but not by the other researcher or different levels of participation being assigned to the same document. To assign a single level of participation for the entire course, the researchers chose the highest level of participation found in the course descriptions and interviews as the lower levels are contained within the higher levels of Arnstein's ladder.

2.4 Results

2.4.1 Course descriptions (written curriculum)

2.4.1.1 Cognitive processes: a wide variety of objectives

The transdisciplinary courses in the analysis aimed to develop a wide variety of cognitive processes. Table 2.5 shows how many courses include a cognitive process. The eight courses contained verbs ranging from the level of 'understanding' to 'creating'. Only the category of 'remembering' was not mentioned, which indicates that teachers do not use these transdisciplinary courses to train that cognitive process. 'Apply', 'evaluate', and 'create' were most often mentioned in courses.
As many courses were connected to the Faculty of Architecture and the Built Environment, their focus was often on design skills. For example, a learning objective related to design in the category 'evaluate' was:

'[The student is able to] identify and explain the qualities of the proposed design.' (Urban Health 2)

TABLE 2.5 This overview of the analyzed course descriptions shows which cognitive process dimensions (verbs) and knowledge dimensions (objects) were found in the learning objectives, and the course's participation level (authors' work). The courses were connected to Delft excepts the two courses indicated with an asteriks (*) that were hosted in Amsterdam.

Course subject	Cognitive process dimensions						Knowledge dimensions				Levels of participation		
	Remember	Understand	Apply	Analyse	Evaluate	Create	Factual	Conceptual	Procedural	Metacognitive	Distant	Client	Partner
Urban design		•	•	•	•	•		•	•		•		
Social inequality					•	•		•	•			•	
Urban development			•		•	•		•	•	•		•	
Sustainable renovation		•	•	•	•			•	•	•	•		
Urban health 1			•	•		•		•	•			•	
Urban health 2		•	•	•	•	•	•		•			•	
Urban sustainability 1*			•	•	•	•		•	•	•		•	
Urban sustainability 2*			•		•	•		•	•				•

2.4.1.2 Knowledge objects: conceptual understanding and problem-solving at the core

The analysis of the knowledge dimensions showed a more distinct picture, with fewer mentions of factual and metacognitive knowledge. By contrast, the conceptual knowledge dimension was coded 33 times and occurred in 7 of 8 courses. The procedural knowledge dimension was coded 27 times and occurred in all courses. This suggests that these courses emphasize conceptual topics in a specific discipline and the skills or procedures students need to practice within these topics, such as:

'The student is able to divide the tasks in the project within the student group.' (Procedural knowledge in Urban Development)

TOC

2.4.1.3 Level of participation: contextualizing complex challenges

Five of the courses described the participation in the course in the client category. The remaining two are categorized as distant. The highest level of participation, the partner category, was only reached by one course. An example quote from this course guide reads:

'Students are asked to collaboratively shape their projects while also working with the case owners, coaches, and other stakeholders in the case.' (Urban Sustainability 2)

2.4.2 Interviews (ideal curriculum)

2.4.2.1 Cognitive processes: varied objectives but more analyzing and less applying

Create: problem-solving, knowledge application, or stakeholder integration

'Creating' was often mentioned in the learning objectives and was similarly stressed as important by teachers. Whether the result of the course was a product, a participatory process, or a personal learning process, creating was described as the main component.

Teachers talked about three kinds of creating. First, their transdisciplinary courses are meant to train problem-solving abilities and should result in a 'product'. Several teachers mentioned that the product is not the aim, but the tool with which they can guide the learning process of design or problem-solving abilities. In the interviews a teacher described the tensions between different stakeholders:

'The case owners are concerned by the solution, the product. To the students, the product is actually […] not the most important thing. The most important thing is their learning process.' (Teacher Urban Sustainability 2)

Second, teachers mentioned that their course is meant to offer students situations to apply academic knowledge in practice. In the course, students need to recognize where their academic knowledge from previous courses can be of added value when solving problems in the real world, as summarized by this teacher:

‘Students should learn how to apply academic knowledge and skills in the process of solving an issue in practice.’ (Teacher Urban Sustainability 1)

Third, some courses specifically required students to create a process that integrates the perspective of stakeholders. Stakeholders could be citizens living in the area, or other actors that were involved there, such as the municipality or a housing corporation. Teachers mentioned that students were asked to integrate the insights from stakeholders in their design or interact with them in the process of analyzing the problem. These were some questions that could arise during the course:

‘How do you create a process? What sorts of products, or new concepts, are necessary to accommodate the needs of citizens?’ (Teacher Sustainable Renovation)

Evaluate: the student’s position, collaboration, and reflection

In the interviews, teachers described how students should use an evaluation to position themselves within the world and develop the ability to critically reflect on that position. Several teachers mentioned that evaluating the collaboration within the student group is an element of the course. Teachers also mentioned reflection. In one case, a teacher refers to metacognitive, procedural, and conceptual knowledge objects:

‘We asked them to reflect on three things: their learning objectives, the collaboration within the student team, and the content of the course.’ (Teacher Sustainable Renovation)

Analyze: existing or new analytical skills

The learning objectives about creating build upon analytical cognitive processes. Teachers approached this roughly from two directions. Some teachers made use of existing analytical skills from the diverse disciplinary backgrounds of students in their courses. In other courses teachers spent time letting students develop new analytical skills, such as observation and interview techniques. These skills were specifically aimed at gaining insights from local people. Although all courses made use of analysis in the learning process, many teachers stressed that it is not the main learning objective:

'They do some analysis and fieldwork, but that is all quite limited.'
(Teacher Social Inequality)

Apply: skills and collaboration

Teachers expected students to apply a variety of skills in their courses. Some skills that were mentioned were writing a synthesis report, negotiating, phasing a long-term project, and project management. One teacher talked about these cognitive processes as 'basic skills' that are content-independent.

Most teachers specifically mentioned collaboration and group dynamics. One teacher even said this was the most important objective of the course (see the quote below); however, most teachers mentioned that they spend little time on collaboration as a topic. In most courses the dominant philosophy is that collaboration is a process that students learn by doing.

'[The most important objective is] that they learn to collaborate. Although I only have one workshop specifically about collaboration in the course.'
(Teacher Urban Development)

Understand: the complexity of participation

On the level of understanding, teachers were not addressing specific conceptual areas, but aimed for an understanding of the complexities of collaboration or the dynamics of participatory processes. Teachers said that students need to understand the wishes and reasoning of citizens or other stakeholders in the area. This is a different kind of understanding to what is usually meant by this category in Bloom's taxonomy. Understanding or relating to other people refers to the ability to empathize and can be better defined from the perspective of metacognition in learning objectives in the next section. An example of the kind of empathetic understanding teachers aimed for is:

'[Before the course] they have little knowledge about citizens or citizen participation. And they know little about the complexities of these kind of sustainability projects.' (Teacher Sustainable Renovation)

2.4.2.2 Knowledge dimensions: more factual and metacognitive knowledge

Factual knowledge: sharing knowledge

Teachers barely talked about factual knowledge in the interviews. Three interviewees mentioned 'knowledge sharing' as part of their course. They then referred to experts from practice or teachers sharing knowledge on specific (factual) topics that were relevant to the course. One teacher mentioned that students shared knowledge with the commissioners as part of the course:

'It might be the people from the municipality that focuses on knowledge transfer. They think: 'We have twenty students here, what if they gather all knowledge that is available and hand it over to us." (Teacher Urban Sustainability 1)

Conceptual knowledge: complexity and multi-actor perspective of urban challenges

Most courses had specific conceptual themes related to urban challenges, such as socio-spatial segregation, loneliness, climate adaptation, or urban governance. Teachers aimed for students to understand the depth or complexities of these themes, and they aimed for students to understand these themes from a multi-actor point of view. One teacher described this as follows:

'I find it to be important for the teaching staff to point out to the students that the question is often formulated by just one person, or based on the vision of one expert. As an urban designer, you should consider this. You should be sure to integrate public interests and not just the interests of the municipality or the interests of just one expert.' (Teacher Urban Design)

Procedural knowledge: design process, interview techniques, collaboration, and uncertainty

Teachers mentioned four kinds of procedural knowledge. First, procedural knowledge of how to design was mentioned in the objectives. Knowing how to integrate conceptual knowledge into a specific product was core in most courses. Furthermore, the design of a process in which citizens are involved was part of most course objectives. Second, students were meant to gain procedural knowledge on collaboration within a multi- or interdisciplinary student team. Third, the courses that dealt with interview and observation techniques also paid attention to the specific procedural knowledge that comes with applying those analytical skills, as this teacher described:

'They need to learn 'Okay, how do I get this conversation going before those questions I really want to ask'. But in a respectful manner, giving the other person the feeling that it is a pleasant interaction.' (Teacher Social Inequality)

Finally, only one of the interviewees mentioned dealing with uncertainty. This teacher specifically explained how students are expected to deal with uncertainties in the assignment in the course:

'That is a standalone thing: the uncertainties and ambiguities of the assignment that students need to deal with, to be able to, or to dare to, make assumptions, and not knowing what the result will be.' (Teacher Urban Development)

Metacognitive knowledge: personal development, collaboration, and empathy

Teachers talked about the personal development of students in the course. Some courses intended to make room for students' learning objectives, for example. Students develop metacognitive knowledge also in collaboration with others. Within a team students do not only learn procedurally or conceptually about collaboration but also about which qualities or knowledge they can bring to the team.

Almost all teachers described how students were confronted with reality in their courses. Some teachers also added that this was to gain an empathetic understanding of the experiences of citizens or a specific target group that they needed to design for:

'I hope that we deliver students that are somewhat more streetwise. That they understand that outside of these university walls, there is an entire world, where all kinds of things happen that have nothing to do with technology.' (Teacher Sustainable Renovation)

2.4.2.3 Levels of participation: from the real world to city and co-creation

Distant: participating with the real-world complexity instead of the city itself

Teachers in courses in this category aimed for real-world complexity to enter the course material. This resulted in courses that present a challenge from the city to students to work on and, in some cases, also the people involved with that challenge to explain more about it. The realness then adds a level of urgency that motivates students. It was also a way to understand the complexity of the conceptual contents of the course. Some teachers explicitly described that making an impact is not the aim of their course:

'Of course, it is not our primary aim to make an impact. The aim is for students to learn what they need to learn.' (Teacher Urban Design)

Other teachers did want the city to participate more in the course but were not able to organize this. They mentioned two reasons: the limited resources on the side of the partner and the rigidity of the institution's learning objectives. The latter stands in the way of adjusting the course to the needs of the outside world, as this teacher mentioned:

'I'm fine with integrating the interests of a citizen organization into the course, but sometimes, as a coordinating teacher, that is complicated due to the predetermined learning objectives of an existing course.' (Teacher Sustainable Renovation)

Client: starting with an authentic challenge

The starting point for these courses was a challenge defined by a practitioner. Just like courses in the distant category, the teachers that were involved in client courses said that the realness of the problem is crucial to them. However, in this category, teachers actively search for clients that could take the role of the client in the course. One teacher described that ideally, a client seeks help from the university first:

'One of the potential pieces of evidence [for the authenticity of the problem] could be an email saying: 'Hey hello, could you help me with this problem?'.' (Teacher Urban Sustainability 1)

Next to the challenge of finding authentic clients, teachers mentioned three other elements that are important to them in deciding on a challenge. First, the challenge needs to connect to the core themes within the course. Second, the client presenting the challenge needs to be able to invest resources (time and people) in the course. Third, the client's challenge needs to connect to students' interests.

Partner: creating co-creation

In the analysis, one course could be defined as a partner course and one course had aspects of both the client and partner categories. The course that was solely categorized as a partner course gathered as many thematically different cases as there would be student groups each year, and then let students choose which case they wanted to work on. Although all the cases related to urban sustainability, the challenges were diverse within that overarching theme. All cases were brought in by partners from the university-city collaboration. They were vetted by the teachers in the course against the criteria of being an open challenge, having space for a co-creative process, and being able to provide a location for the students to work. The course is unique in that it allows students to co-create a further definition of the challenge together with their partners, as the teacher mentioned in the interview:

'Also, the challenge should be co-created. This way the challenge is more specific and easier to tackle than the original case described [by the partner].' (Teacher Urban Sustainability 2)

In the other course, the teacher described that they were working with the city so that students could learn how to do participatory or human-centered design. In that case, the transdisciplinarity of the courses was not only aimed at bringing the assignment closer to reality, but also at seeking participants that students can learn to interview, observe, or design for. With that knowledge of the experiences of citizens, students worked on new ideas or designs for the neighborhood. Although the course also had a client, students depended on the input of other stakeholders to do the necessary work in the course.

2.4.3 Comparing course descriptions and interviews

2.4.3.1 Cognitive processes: less analyzing and more applying in the course descriptions

In the interviews, teachers emphasize 'analyzing' more often as a learning objective than in the course descriptions (Figure 2.1). Almost all teachers describe analyzing as a critical part of the learning process. They referred to specific research methods, such as interviewing or observations, that students are expected to use, but might not have been familiar with. The importance of analyzing is not clear in the course descriptions.

Conversely, 'applying' certain skills was described more often in the course descriptions than in the interviews. The interviews showed that applying referred to basic academic skills, such as writing and presenting. These were deemed less important in the interviews. They might have appeared more often in the course descriptions to bring learning activities in line with the learning objectives.

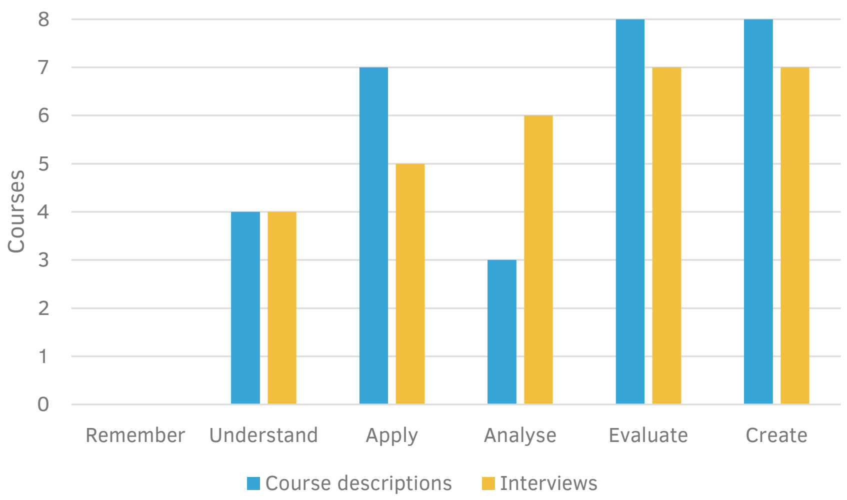

FIG. 2.1 Comparison of the cognitive process dimensions (verbs) in the written and ideal curriculum (authors' work).

2.4.3.2 Knowledge dimension: less factual and metacognitive knowledge in course descriptions

All teachers mention conceptual, procedural, and metacognitive knowledge dimensions as part of the course aims. However, the course descriptions do not represent the metacognitive knowledge dimension (Figure 2.2). As self-knowledge and meta-understanding are important parts of transdisciplinary education (Mokiy, 2019), it could be expected that the metacognitive knowledge dimension would be part of the aims of transdisciplinary courses.

In the interviews, teachers mentioned two metacognitive aspects that were not mentioned as learning objectives in the course descriptions. First, teachers emphasize how students will learn to position themselves within the complexities of sustainability challenges. They refer to the conceptual understanding of these challenges, as well as the personal motivations of students. Second, students learn to collaborate in an interdisciplinary team, while gaining a better understanding of their qualities or the added value of their discipline.

Factual knowledge was mentioned in the interviews but did not appear in the written learning objectives. As teachers expected students to be able to use analytical skills without mentioning them in the learning objectives, also factual knowledge might have played a role in the course implicitly.

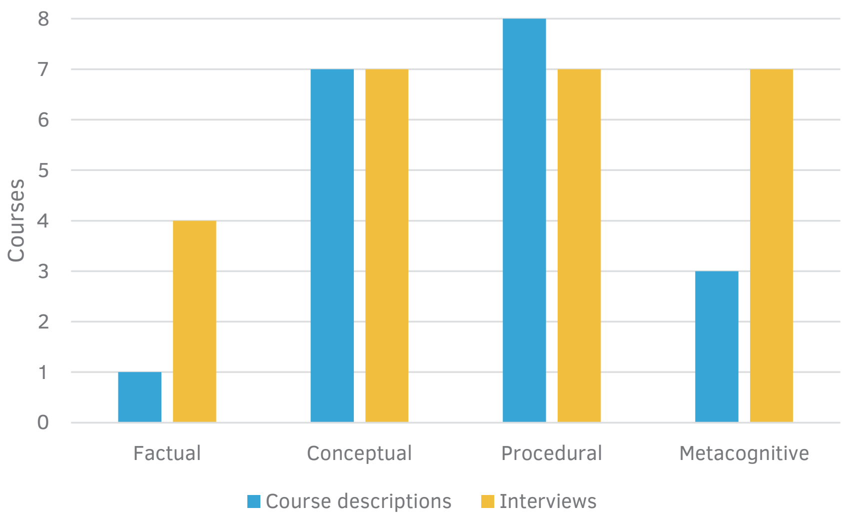

FIG. 2.2 Comparison of the knowledge dimensions (objects) in the written and ideal curriculum (authors' work).

TOC

2.4.3.3 Levels of participation: no differences between course descriptions and interviews

The level of participation was aligned between course descriptions (written curriculum) and interviews (ideal curriculum) (Figure 2.3). Although the written and ideal courses are in line with the transdisciplinary pedagogy they use, only one course aims for the partner level of participation. In the interviews teachers mentioned the barriers to changing the intended curriculum within their courses to make them go beyond a distant or client level of participation. Most teachers feel confined by the rigidity of learning objectives when they want to adapt the course to include the interests of urban stakeholders. Christie et al. (2013) already found that it is hard for teachers to step away from traditional teaching methods. This study suggests teachers experience difficulties in adapting traditional learning objectives to the transdisciplinary pedagogies they envision.

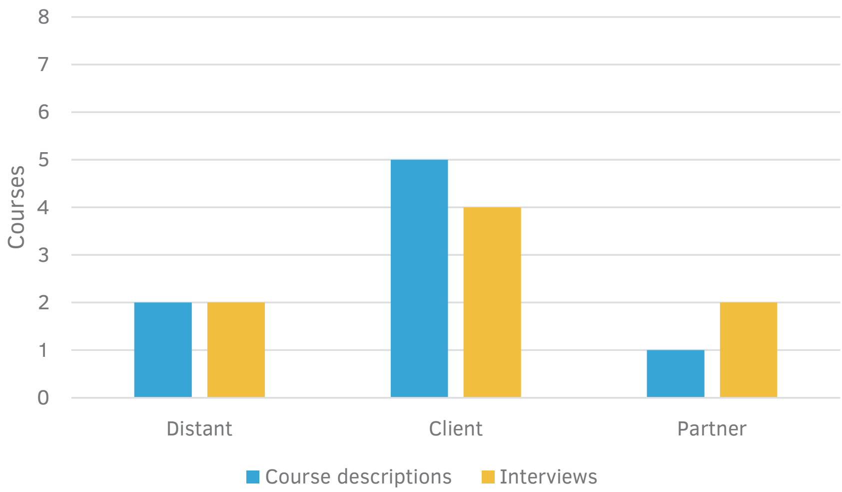

FIG. 2.3 Comparison of the levels of participation in the written and ideal curriculum (authors' work).

2.5 Discussion and conclusion

This research investigated the question 'What is the intended curriculum of transdisciplinary higher education?'. This study aimed to get an understanding of how far-reaching the participation of the city in these courses is and what students are meant to learn from the transdisciplinary pedagogies used. In this final section, the authors discuss the main results, limitations, suggestions for further research, and the implications for transdisciplinary education in practice.

The results of this study show that teachers ideally use transdisciplinary courses to teach problem-solving of conceptual themes and issues in an integrative manner. Additionally, they want the teaching to be centered on authentic issues that are topical and relevant to students' lives. These overarching aims are written down in the course descriptions and are described by teachers in interviews. This study found a misalignment between the written course descriptions and the ideal visions of teachers in three instances.

First, the cognitive processes in the learning objectives focus less on analyzing than teachers explain in the interviews.

Second, students are meant to get to know their strengths and weaknesses in collaborative teamwork in these courses and learn how to undertake participatory research. Through participating in local communities, teachers aim for students to learn to move outside their world of experiences and gain a deep understanding of the biases and values of others that they might be designing for in the future. Empathy and dealing with uncertainty were mentioned as specific skills in working on sustainability challenges. Those skills also occur in the UNESCO (2017) framework of sustainability learning goals yet do not occur in the written curriculum in the analyzed courses. In the interviews, the metacognitive dimension was mentioned, and the courses aimed for students to understand who they are and what they (can) know. The written learning objectives seldom included metacognitive knowledge as an object. This suggests they are more difficult to teach or assess in the implemented or attained curriculum.

Finally, although there are transdisciplinary intentions in all courses, not all courses position stakeholder participation in the same way. The results show that most investigated courses remained at a level of client participation. In those courses, students are expected to develop a professional attitude and in some courses act as consultants to advise the client. However, some scholars argue this is not enough to contribute to sustainable change. Instead, transdisciplinary education should aim for more responsive or active forms of participation from the students with the stakeholders (Gibbs, 2017).

This study is limited to the intended curriculum. Other curriculum representations, namely the implemented and attained curriculum, require different research objects, such as interviews with students and course materials. By focusing on the intended curriculum, this study aimed to provide a better understanding of what teachers aim to achieve on the ground. In future research, the authors will investigate the experiences of students and the assessment of learning in these transdisciplinary courses.

Furthermore, this study was built on the perspective of teachers, who focus on urban sustainability challenges. The authors recognize that in education in general the perspective of students, and in transdisciplinary education specifically the perspective of stakeholders from outside the university, co-shape the curriculum. The focus on teachers emphasizes the academic perspective on transdisciplinary learning in this paper, but it is not an exclusive perspective.

A final limitation of this study is that it zoomed in on two university-city collaborations. In future research a larger selection of university-city collaborations would be preferable, especially beyond the Dutch border. In this study, the courses in Amsterdam profited from the small-scale institutional context. The teachers mentioned that this allowed them to experiment more easily with transdisciplinary pedagogies. However, this study is too small to draw strong conclusions on the impact that the university-city collaboration has on the intended curriculum in the courses.

This study adds a research approach to transdisciplinary education focused on the intended curriculum. By introducing three levels of participation, it can now be analyzed to what extent different transdisciplinary courses intend to involve others. Different levels of participation have different learning effects. Teachers play a crucial role by deciding on the participation level when writing down the intended curriculum. Historically, teachers have had this form of academic freedom to decide how they want to teach their subjects to students. Today, they remain the custodians of transdisciplinary courses, which gives them the power to decide which stakeholders enter the learning arena.

Although academic freedom is essential to higher education, teachers do not necessarily have the means to establish the courses they envision by themselves. Apart from overcoming practical barriers, such as time and resource constraints, teachers need a vocabulary of learning objectives that fits their transdisciplinary intentions. This paper contributes to the development of a common vocabulary and language. That vocabulary of learning objectives should specifically include metacognitive knowledge as vital to transdisciplinary education and consider a more specific way to describe analyzing as a cognitive process. By making implicit intentions in the curriculum explicit, teachers can better prepare students to become agents of change for sustainable transitions in the city.

3 Knowing about the unknown

A case study of uncertainty in sustainability education

An adapted version of this chapter has been submitted for peer review.

ABSTRACT Students learn to deal with uncertainty in transdisciplinary education, where they are confronted with complex sustainability challenges in real-life. However, approaches to teaching and learning about uncertainty are not well-established. This study conceptualizes uncertainty in sustainability challenges and investigates the approaches students are expected to use.

We performed a case study of the course 'Living Laboratory Amsterdam' where we analyzed 48 challenge descriptions from the partners. The analysis is based on three dimensions of uncertainty: incomplete knowledge, multiple knowledge frames, and unpredictability.

The results suggest that the Living Lab course engages with all three dimensions of uncertainty. At the same time, several tensions arise because the partners expect students to simultaneously use conventional approaches, such as studying literature, and transformative approaches, such as co-creating, to solve problems.

Only if teachers and students understand which uncertainty they face in complex sustainability challenges, can they choose the right approaches to respond to the unknown.

KEYWORDS Uncertainty, complex systems, transdisciplinary education, living labs, sustainable cities and communities

3.1 Introduction

Dealing with uncertainty is one of the major challenges for people working on sustainability transitions (Ingold et al., 2018). In the transition to circular building, for example, the lack of practical knowledge makes professionals lose traditional roles and adopt a much more flexible attitude in their work (Kooter et al., 2021). Moreover, dealing with uncertainty is one of the key learning objectives described by UNESCO (2017) to prepare students to work on the Sustainable Development Goals.

Uncertainty is a multifaceted concept. Traditionally, the uncertainty engineering education focuses on how to cope with a lack of technical knowledge (Hayes et al., 2021). This *knowing too little*, as Brugnach et al. (2008) describe it, is perceived as a gap that can be filled with more knowledge. With enough time and means available, this kind of uncertainty can almost always be managed by doing more research. In engineering education, students are taught the methods and tools to obtain more knowledge and reduce uncertainty.

Yet, previous studies show two other dimensions of uncertainty that education is less used to prepare for (Walker et al., 2003; Wehrmann & Van den Bogaard, 2019), but might be instrumental in sustainable transitions. First, *knowing too differently* Brugnach et al. (2008) refer to the kind of uncertainty that arises when different experts have different, sometimes conflicting, views. Especially in sustainability transitions, policymakers can be torn between different strategies to solve the same issue (van Bueren et al., 2003). Second, *accepting not to know* refers to the unpredictability of the world, such as the effect of war on the energy transition. By adopting flexible attitudes as the professionals in the circular building sector are forced to do, people try to account for this kind of uncertainty (Berkes, 2007). These latter two dimensions of uncertainty require students to attain non-technical skills that engineering education is not used to teach (Hayes et al., 2021).

Consequently, engineering education is looking for ways to integrate the uncertainty of sustainability challenges in new pedagogical approaches. Although sustainability science and its implementation in engineering education are relatively young, different pedagogies to deal with sustainability transitions are already being used in universities (e.g. Bohm et al., 2020; Davidson et al., 2020; Sprain & Timpson, 2012). Transdisciplinary courses, for example, involve real-world challenges and the multi-layered conflicts with multiple stakeholders that come with those challenges (Scholz & Steiner, 2015). Therefore, transdisciplinary courses provide an ideal environment for learning to deal with uncertainty (Baumber et al., 2019).

However, little research has been done with the specific lens of uncertainty in transdisciplinary courses. Jacobson et al. (2017) argue that students need to learn explicitly about complex concepts such as uncertainty to be able to apply the right solution strategies. Often uncertainty is mentioned synonymously with other terms, such as ambiguity, complexity, and wicked problems (Fenten et al., 2021). Consequently, it is difficult to distinguish uncertainty as a separate subject and teach students the competencies they need to deal with it.

This study conceptualizes uncertainty in a transdisciplinary course, estimates the difficulty level of uncertainty, and analyzes the approaches students are expected to use to deal with it. As a case study, we analyzed a course called the *Living Laboratory Amsterdam* as part of the Master Metropolitan Analysis, Design, and Engineering. This engineering program is a joint degree of the Delft University of Technology and Wageningen University, located in Amsterdam. The Living Lab course is considered *transdisciplinary education* as it involves real-world challenges provided by the course's partners.

In this paper, we first discuss the theoretical background of uncertainty in complex challenges and develop an analytical framework. We then continue by explaining document analysis as our main method of testing the framework. In the results section, the Living Lab challenges are divided between unpredictability (accepting not to know), knowledge incompleteness (knowing too little), and knowledge frame multiplicity (knowing too differently). Finally, we discuss the tensions arising from the challenges' differences in difficulty level and the mix of approaches students are expected to use. Through a better understanding of the dimensions of uncertainty in sustainability challenges, this paper provides teachers and students with a vocabulary to talk about uncertainty in the classroom.

3.2 Theoretical background and analytical framework

Uncertainty and complexity are closely related concepts. To understand why complex sustainability challenges create uncertainty, this section first investigates the unique characteristics of a 'complex problem' and how it can be distinguished from other less complex problems. The second section in the theoretical background elaborates on the three dimensions of uncertainty that form the foundation of the analysis in this study.

3.2.1 The difference between clear, complicated, and complex sustainability challenges

Complexity is the structure of ill-structured problems (Simon, 1973). City planning, for example, can be understood as a complex problem (Stolk, 2015). Although designers, planners, and engineers have made many attempts to 'create' cities, they are confronted with their limited capacity to control their development. The development of a city happens inexplicably on its own over time, without clear coordination or external direction (Holland, 1995). This 'hidden order' of a complex system makes problems that are part of that system unpredictable. Therefore, uncertainty increases when a problem becomes more complex (Alexander et al., 2018).

Not every problem is complex. Consequently, uncertainty might present itself in different ways depending on the complexity of the problem (Hasan & Kazlauskas, 2013). Scholars across several fields, from technology to sociology, have used the 'Cynefin framework' to distinguish complex problems from other kinds of problems to decide which solution strategies to use (Alexander et al., 2018). The Cynefin framework assigns problems to four difficulty levels: clear, complicated, complex, and chaotic.

The first domain features **clear** problems that have distinguishable cause-and-effect relations (van Beurden et al., 2011). Procedures can be developed to deal with clear problems. On the **complicated** level, cause-and-effect can be recognized but not fully understood. Research is necessary to clarify the links, which will take time and resources. Infrastructure projects are often examples of complicated problems, such as building a metro line underneath a historic city center. In between the complicated and the chaotic lies the domain for **complex** problems, such as the transition

TOC

that is necessary to make the housing stock more sustainable for an entire city. Finally, problems arising from **chaos** are without any structure. A regional climate catastrophe is an example of the chaotic problem domain. There are no cause-and-effect relationships that can inform practice in this case. As it would be unethical to expose students to real-world catastrophes, this fourth domain is out of scope for the transdisciplinary education we analyze here.

Although the Cynefin framework has been used before as a tool to analyze qualitative data, little is known about its application in educational research (McLeod & Childs, 2013). In this study, we experiment with the framework as a tool to describe uncertainty on the clear, complicated, and complex difficulty level.

3.2.2 Three dimensions of uncertainty

Different scholars defined different kinds of uncertainty (Funtowicz & Ravetz, 1990). Brugnach et al. (2008) developed a relational perspective on uncertainty that takes this idea of increasing uncertainty into account. They distinguish three dimensions of uncertainty: unpredictability (accepting not to know), knowledge incompleteness (knowing too little), and knowledge frame multiplicity (knowing too differently) (Brugnach et al., 2008). Based on the work of Brugnach et al. (2008), we describe in this section how teachers and students can recognize each dimension of uncertainty while working on challenges at the different difficulty levels from the Cynefin framework: clear, complicated, and complex (Table 3.1).

The first uncertainty dimension deals with the **unpredictability** of the future. In theory, a world without any unpredictable situations can be completely knowable (Walker et al., 2003). Clear problems can be approached with that precision and certainty (Puik & Ceglarek, 2015). On the complicated difficulty level, several plausible futures can be predicted. These futures are uncertain yet fall within a range of possible outcomes that are based on trustworthy assumptions. The networked nature of complex problems makes them constantly influence each other (Dorst, 2015). Approaches dealing with those dynamics are often designed to be adaptive (van Beurden et al., 2011).

Second, **knowledge incompleteness** is related to epistemic uncertainty or the imperfection of the available knowledge (Walker et al., 2003). Snowden and Boone (2007) describe how clear problems can be approached evidence-based, which means the knowledge is already available (van Beurden et al., 2011). On the complicated level, decision making is less easy, because knowledge or information is lacking; however, it is clear how this knowledge can be gathered. Most of the time, these 'known unknowns' require experts to gain new insights into the problem. On the complex level, doing more research uncovers more uncertainties (Brugnach et al., 2008). Alexander et al. (2018) suggest using experimental methods, because those methods allow for probing solutions in an unpredictable environment.

Lastly, **knowledge frame multiplicity** arises when there are too many possible interpretations of a situation (Weick, 1995). This uncertainty is caused by the diversity of perspectives and active knowledge systems within the network of actors involved in the challenge. Other scholars call this kind of uncertainty ambiguity (Klinke & Renn, 2002). Brugnach et al. (2008) propose to see ambiguity as the third kind of uncertainty that presents itself on the scale from 'unanimous clarity to total confusion caused by too many people voicing different but still valid interpretations' (p. 4).

If actors can agree on facts and procedures knowledge frame multiplicity remains on a clear difficulty level. The way of working can be coordinated (McLeod & Childs, 2013). When different experts give contradicting or conflicting advice, the difficulty level is complicated. Until the research that will resolve these conflicts is done, researchers and decision makers need to cooperate. On the complex difficulty level, the ambiguity of working in a network of actors with different norms, values, and interests demands collaboration. Several authors describe how top-down approaches will fail in this domain; instead, different actors will have to collaborate (Snowden & Boone, 2007; van Beurden et al., 2011). In stakeholder engagement, collaboration does not necessarily mean finding consensus. Constructive conflict also enables people to articulate and confront the diversity of perspectives within a complex problem (Cuppen, 2011).

Table 3.1 presents the operationalization of uncertainty in this study. In the next section, we will explain how we applied this framework to the challenges of a transdisciplinary course. The aim is to see what uncertainty dimensions are part of the challenges and on what difficulty level. Additionally, we aim to refine the analytical framework with the practical approaches partners expected students to use to deal with uncertainty.

TABLE 3.1 Analytical framework for the uncertainty dimensions in the challenges that students work in transdisciplinary education. The uncertainty dimensions are measured on a scale from clear, complicated, or complex, based on the Cynefin framework.

Uncertainty dimension	Difficulty level		
	Clear	Complicated	Complex
Unpredictability	**Predictable** The knowledge environment is predictable and linear. Clear cause and effect ties can be recognized.	**Consistent** The knowledge environment behaves consistently. By careful examination of the system, it can be understood, and future behavior can be predicted. Although the future is unknown, plausible scenarios could be developed.	**Dynamic** The environment of the problem is dynamic. Due to the randomness of nature, human behavior, societal processes, or technological surprises the problem could change drastically (variability uncertainty). What or who is causing the problem is unclear and might only be revealed in retrospect.
Knowledge incompleteness	**Known knowns** The problem is understandable as a sum of parts.	**Known unknowns** Although the knowledge, information, or data itself might not be present, it is clear how it can be gathered. Different fields of expertise are necessary to deal with the problem.	**Unknown unknowns** A lack of information or data, the unreliability of the data that is available, a lack of theoretical understanding or ignorance. Doing more research might uncover more uncertainties.
Knowledge frame multiplicity	**Coordination** Decisions can be made based on agreed upon facts and procedures. Coordination strategies suffice in this case.	**Cooperation** Conflicting advice and conflicting interests are at play. A panel of experts could be used to come to a solution. There is more than one solution to the problem.	**Collaboration** The network of involved public or private actors have different norms, values, and interests. The boundaries of the system or what and whom to put as the focus of attention is unclear. Information about the system is interpreted differently.

3.3 Methods

We analyzed uncertainty in the sustainability challenges used in a case study (Yin, 2009). The case study was a course called the *Living Laboratory Amsterdam* (Living Lab), which was run for the first time in 2018. Because the course was so new, the case study could include all the challenges from the start of the course. The course is part of the Master Metropolitan Analysis, Design, and Engineering (MSc MADE). MSc MADE is a joint degree engineering program of the Delft University of Technology and Wageningen University, located in Amsterdam.

The starting point of the Living Lab course is real-world challenges from local partners, such as the municipality, the local water authority, a design firm, or consultant. These partners applied for the course by submitting a one-page challenge description (Appendix C). The course coordinator then selected which challenge descriptions would be presented based on pre-defined criteria; The challenge should be open and authentic, aimed at the development of an innovative product or process, involve several stakeholders, and focus on a concrete location. In the first week, students chose the challenge they would work on and got to know the local partner. From that moment on, students worked in teams together with their partner to analyze, design, and engineer the challenge and possible solutions.

The Living Lab course used a total of 48 unique challenge descriptions between 2018-2023, in which period the course ran five times. We coded all challenge descriptions based on the analytical framework for uncertainty developed in Section 3.2 (see Appendix D for the codebook). The coding process is summarized in Figure 3.1.

Two researchers coded the documents separately from each other. They decided which part of the text to code based on the ID questions (Almeida et al., 2022) in Table 3.2. These excerpts were then coded by one or several of the nine categories. The researchers calibrated their results after the first 8 challenge descriptions to add details to the code descriptions. After coding all 48 descriptions, the inter-coder reliability (Cohen's kappa $\kappa = 0{,}61$) was substantial (Cohen, 1960; Gisev et al., 2013), which means that the coders had enough agreement to consider the analytical framework as an appropriate tool to recognize uncertainty.

For the thematic analysis, the coders discussed and resolved the conflicts to establish the coded excerpts. The documents that the coders were not able to get a clear agreement on were not included in that part of the analysis. After the coding process, the first author made a thematic analysis of the excerpts to further describe the nine categories.

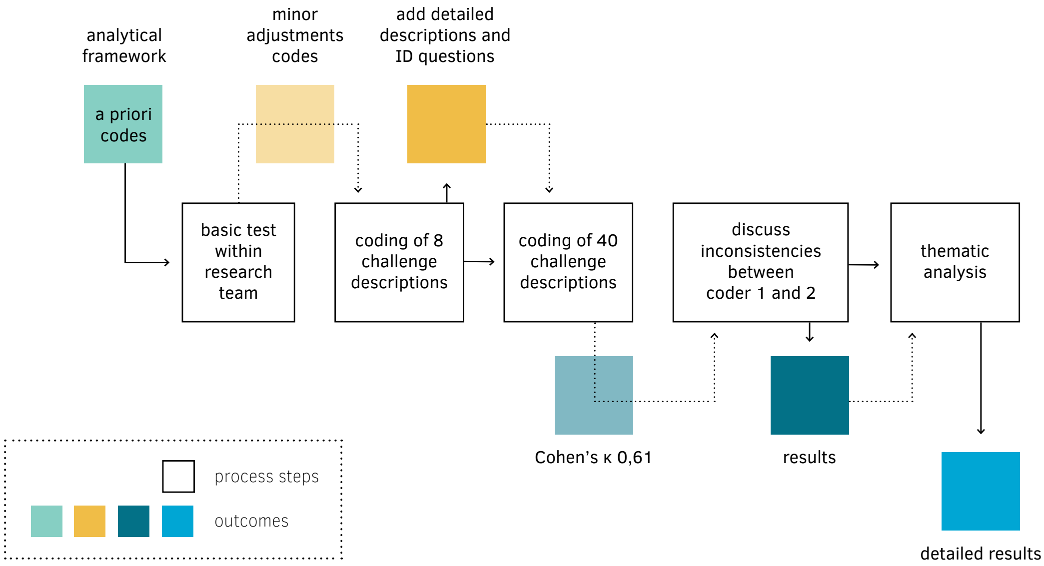

FIG. 3.1 This image depicts the coding approach of this study as a step-by-step process that led to three different results: the codes with detailed descriptions, the coded results, and the results of the thematic analysis.

TABLE 3.2 Codes including the ID question that were used to identify which excerpts should be coded on their level of uncertainty.

ID question	Code group	Code
Where does the partner describe a problem, situation, or environment that students will work on or in?	**Unpredictability**	Predictable
		Consistent
		Dynamic
Where does the partner describe an approach, method, or solution direction?	**Knowledge incompleteness**	Known knowns
		Known unknowns
		Unknown unknowns
Where does the partner describe who needs to be involved?	**Knowledge frame multiplicity**	Coordination
		Cooperation
		Collaboration

3.4 Results

Section 3.4.1 describes an overview of the three uncertainty dimensions: unpredictability, knowledge incompleteness, and multiple knowledge frames. The three sections that follow (3.4.2, 3.4.3, and 3.4.3) each describe one of those uncertainties in more detail. In those sections, we present the results of the thematic analysis.

3.4.1 Overview of uncertainty dimensions in sustainability challenges

Most of the challenge descriptions (42) contained all three dimensions of uncertainty: unpredictability, knowledge incompleteness, and knowledge frame multiplicity. Five challenge descriptions were missing one of the three dimensions. This was mostly because the descriptions were too short to identify all dimensions. In three challenge descriptions, the partner did not mention the involvement or collaboration with other people even though there was space for it.

Although almost all challenges included all three uncertainty dimensions, they did not all describe them on the same difficulty level. Figure 3.2 shows each dimension as a line on the difficulty scale: clear, complicated, or complex. The figure shows that the challenges only occasionally deal with uncertainty dimensions on the lowest difficulty level (clear) and primarily deal with uncertainty on a complicated or complex difficulty level. The complicated and complex difficulty levels are mentioned a similar number of times throughout all the challenge descriptions. Overall, the difficulty level of challenges was most often a mix between complicated and complex.

Figure 3.3 shows that the dimension of knowledge frame multiplicity has a different trend than the other two uncertainty dimensions. Furthermore, knowledge incompleteness is most often mentioned on a complicated level, which we coded as 'known unknown'. In the case of a known unknown, a local partner described an approach to find the knowledge that is lacking. In most challenge descriptions, the partners already wrote down an explicit idea about which (scientific) methods students should use. The next three paragraphs each describe one of the uncertainty dimensions in more detail.

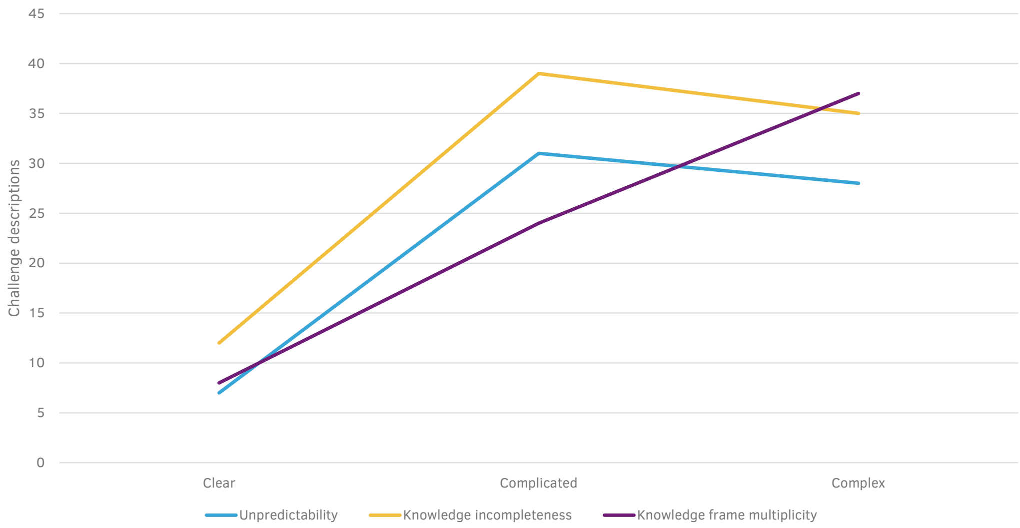

FIG. 3.2 This line graph shows each dimension of uncertainty and how many times it was found on the three levels: clear, complicated, and complex.

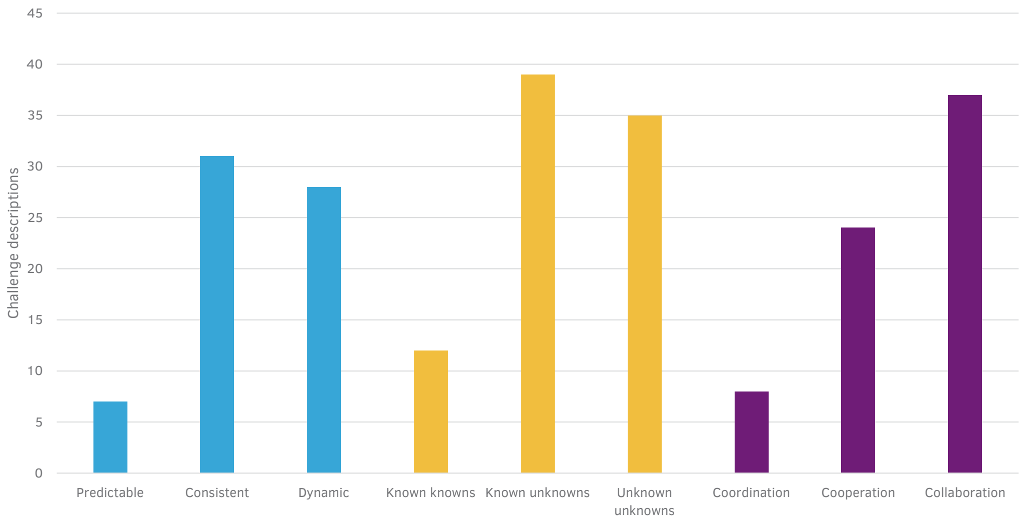

FIG. 3.3 This bar graph shows which categories we used to distinguish between the clear, complicated, and complex difficulty level within each dimension of uncertainty. These categories are further described in the results of the thematic analysis.

3.4.2 The unpredictability of urban problems

The uncertainty dimension 'unpredictability' describes to what extent partners knew what was going to happen in advance. To find unpredictability in the descriptions the ID question was 'Where does the partner describe a problem, situation, or environment that students will work on?'. In seven challenge descriptions, we found 'predictable' problems were described with clear cause-and-effect relationships. "*Students will determine the best use in the city of a new composite material made from urban waste streams.*" (34:2) This excerpt shows a linear expectation that the project will lead to a specific outcome. Additionally, this outcome will also be the 'best' solution.

Most partners that described a predictable problem already had a concrete expectation of what the best solution could be, for instance: "*[students will] explore the best strategies to co-create integral solutions with many stakeholders (both by surveying the literature and by interviewing experienced case-managers)*" (9:6). In this challenge description, the partner presented a problem that could benefit from co-creation (which is a type of complex collaboration that we investigate further in paragraph 3.4.4) and they expected the students to be able to define 'best strategies' to do that co-creation. Such clear expectations of the solution were an exception because most challenge descriptions had a higher degree of unpredictability.

Partners described consistent problems as part of a system that could be better understood and influenced. 'Consistent' problems form the complicated level in this dimension of uncertainty. We coded consistent problems in 31 challenge descriptions. We found two themes amongst the consistent problems; they described a specific area, or they dealt with circularity.

First, part of the challenges focused on one specific area, such as a festival, a zoo, a canal, or a neighborhood. The partner at the zoo described this as follows: "*The zoo offers the freedom to do so in a controlled environment (being that the zoo had control over all processes in the park).*"

In some challenges, partners connected to one of the major ambitions of the city of Amsterdam before zooming into one location, for instance, "*becoming climate-adaptive by 2050*" (24:1) or "*becoming an energy-neutral region by 2040*" (25:1). Then, partners described a specific tool or solution they wanted to further investigate through the course to contribute to that ambition. In challenge 24, the partner developed smart roofs: "*The blue-green roof of a building plays a major role in [dealing with heat, drought, and extreme rainfall]. By activating the roofs,*

TOC

we can keep the city livable.” In challenge 25, the partner wanted to investigate thermal energy recovery from water: “*Among various technologies to achieve energy neutrality, thermal energy recovery from water has been receiving considerable attention owing to its high potential related to both sustainable heating of neighborhoods and industrial cooling*”.

Partners mentioned the need to transfer the solutions from one location to another location. “*The barrier at the Westerdok in Amsterdam is a pilot for the city to test the amount of plastic catch as well as the replicability of the system to other canals.*” (31:5) This suggests there is consistency between systems to make such replication of the solutions or tools for the challenge useful.

A second focus area in the problem descriptions was circularity. Several partners referred to flows of materials or closing loops within an existing system, such as the building construction sector: “*By closing material loops, students will tackle the challenges of (1) the incineration and landfill of valuable urban waste, and (2) the depletion of valuable primary resources that are currently used for construction products.*” (1:4) Because the partner is working toward a circular system, they provide a clear delineation of the challenge.

Under the code ‘dynamic’, we coded 28 challenge descriptions that focused on how intertwined the causes of the problem and how that led to vulnerability in the city. For example, this partner wrote: “*That makes the city vulnerable and affects us all: residents, businesses, and governments. That is why governments, entrepreneurs, and knowledge institutions are looking for new practical solutions to make the city more resilient and thus reduce nuisance and damage caused by water and improve the quality of living.*” (2:2) The focus in this group of excerpts often lies on the unpredictable human influences on the environment. As in the excerpt 2:2, unpredictable human influences are often mentioned as a result of different people working together to solve the problem.

In the excerpts, not only the effect of a specific solution was difficult to predict, but the problem itself seemed to move around. Partners used specific words to describe solutions that could deal with those dynamics. For example, solutions should be resilient, adaptive, modular, flexible, or open. This partner elaborates on the need for adaptive solutions: “*New forms of modular/circular design, generate greater resilience in urban areas. If urban areas are “modular” and “adaptive” by design, they can be “re-functioned” according to the changing needs of the population. If the natural environment changes (rapidly), the artificial (urban) environment responds (rapidly) with a change in function, in accordance with the new demand of its residents.*” (35:3)

Table 3.3 shows the co-occurrence of codes in the same document. The dynamic category occurs most in combination with approaches for 'known unknowns' or 'unknown unknowns'. In the next paragraph, we describe what partners expected students to do to find the adaptive solutions they were looking for.

TABLE 3.3 This table shows the co-occurrence of codes with other codes in the same document.

	Predictable	Consistent	Dynamic	Known knowns	Known unknowns	Unknown unknowns	Coordination	Cooperation	Collaboration
Predictable									
Consistent	1								
Dynamic	4	15							
Known knowns	1	9	6						
Known unknowns	6	25	21	11					
Unknown unknowns	6	22	24	9	27				
Coordination	4	4	4	2	7	6			
Cooperation	4	17	15	9	21	18	5		
Collaboration	5	24	19	10	30	26	5	17	

3.4.3 Anticipated approaches to knowledge incompleteness

The uncertainty dimension 'knowledge incompleteness' described the methods that the partners expected the students to use. The ID question was 'where does the partner describe an approach, method, or solution direction?' We found twelve challenge descriptions that described a well-known method with a clear outcome. These were approaches to challenges with 'known knowns'.

In those challenges, students became part of a well-established plan of the partner. One of the partners described their approach in a sequence of steps: '*our method of tree harvesting in nature, visit or set-up a new tree exchange hub, work together with ecologists make use of our database to analyze the type and locations of the planted trees, set-up events with our volunteers and stakeholders.*' (19:3) In this case, the partner had already decided so much of the method that for the students it cannot be considered an open challenge anymore.

The clear approaches co-occurred ten times with complicated and nine times with complex approaches (Table 3.3). This means that partners in most cases described an additional approach with a higher difficulty level.

The partners of 39 challenge descriptions wrote about approaches to known unknowns. This uncertainty category was the most often found category in the challenges. The approaches described in known unknowns were scientific. The aim of using the approaches was to gain new insights about the challenge.

We found three common elements in the excerpts of this category. First, some challenge descriptions featured concrete research questions for the students to investigate during the course. For example, the partner of a challenge on the strategic use of solar panels wrote: '*Research questions to tackle include: Which policy instruments can be deployed to improve the circularity of solar panels and couple reuse of solar panels to fighting energy poverty and creating sustainable jobs at neighborhood level? …*' (44:7)

Furthermore, the challenge descriptions then described scientific research methods. Sometimes, partners described the methods as a sequence of steps, such as this partner: '*First goal is to collect environmental data, by fabricating and designing a mobile environmental sensor. Second goal is to analyze the data and identify problematic areas. Third goal is to design interventions in problematic areas together with citizens and other stakeholders.*' (38:4) Compared to the steps of excerpt 19:3 in the known known category, the steps in this plan depend more on what the students find and if they will succeed is still uncertain.

Finally, mapping was a common method among the challenge descriptions. In the challenge descriptions, mapping could be applied to physical aspects of the city, such as infrastructure or possible pilot locations for a project: '*However, a thorough analysis and interactive mapping of the actual thermal energy demand and supply possibilities has yet to be done.*' (28:3) Additionally, mapping could also relate to the social aspects of the project, such as stakeholder mapping: '*A thorough (data) analysis forms the basis for this. Students will come up with a methodology or design a tool to easily map representative population of a neighborhood or project area.*' (31:2) The attention for stakeholder mapping might be an explanation for the strong correlation with collaboration in Table 3.3. The analysis of the collaboration category is further explored in Section 3.4.4.

The 35 challenge descriptions with unknown unknowns described experimental methods, such as field-testing, trial-and-error approaches, and living labs. In these challenge descriptions, the method and the outcome were uncertain. This partner described why they preferred experimental methods: '*Due to this complexity* *[of managing a zoo], field-testing and trial-and-error are preferred to theoretical analyses as these would never be able to account for all the interactions between the various needs.*' (3:3) Another partner described specifically why the living lab approach attracted them: '*A living lab setting enables our organization to test and verify theory into practice, taking into account all stakeholder influences that apply to a specific type of location.*' (24:4)

Like the known unknown category, the challenge descriptions in this category often posed questions for the students. However, these were not research questions connected to research methods but open, exploratory questions: '*Although we have our goal set clear, we are creating a regenerative place centered around food and connection we may have missed out on something. Are the guests in the restaurant missing out on the story, have we accidentally targeted the wrong people, or do they just not care enough?*' (37:6)

3.4.4 Collaboration with attention to knowledge frame multiplicity

'Knowledge frame multiplicity' described uncertainty that came from the involvement of stakeholders in the project. We coded this uncertainty dimension based on the ID question 'where does the partner describe who needs to be involved?' This was the only uncertainty dimension where most of the challenge descriptions had a complex difficulty level.

In eight challenge descriptions, partners mentioned their role was to coordinate the students. These excerpts are two examples of coordinating strategies from the partners: '*We [the partner] will shape this project further with one of our clients in the province of North Holland*' (15:4) and '*The desired result can be decided in the interaction between the student team and the case owner*' (9:8). In those cases, the students are depending on the partner to decide on the direction of investigation of the challenge.

'Cooperation' was coded in 24 challenge descriptions. This category included strategies for the students to cooperate with different stakeholders during the project. For instance, through interviewing or gathering feedback on a solution.

The cooperation was often aimed at consensus. For example, this partner writes about how they wanted to include all people working on the festival in the project's aims: '*In order to realize a fully circular festival, all on board must agree on the goal and their required contributions.*' (5:3) The language used in the excerpts suggested that agreement between the stakeholders about a solution was possible.

For instance, when students '*take into consideration the wishes and realities of a very diverse set of stakeholders*' or would be '*keeping all stakeholders' interests in mind*' when designing a solution.

Furthermore, students had to look for an integral solution that combined different expertise fields. In these two excerpts partners describe how students should make use of experts when designing solutions: '*you [the students] will discuss the product with experts with different skill sets – strategy and consulting, technology and interaction*' (14:4) and '*the students will inventory, implement, and liaise with experts around smart mobility to co-create and implement solutions and tools…*' (30:2).

37 challenge descriptions included codes in the category 'collaboration' on the complex difficulty level of this uncertainty dimension. In these cases, conflicting perspectives were described by the partners. The partners did not aim to reach agreement between those perspectives. They thought that the living lab approach in the course could deal with conflicting views of stakeholders: '*Large-scale implementation of thermal energy recovery […] is a complex process as it includes numerous stakeholders, amongst whom some may have different and non-aligned interests. This asks for the multifaceted approach which the Living Lab methodology offers.*' (25:7)

Co-creation between the students and residents of a building or neighbourhood was often part of the excerpts. Table 3.3 shows that the approaches used in those challenges were most often searching for 'known unknowns'. Stakeholder mapping was one of the methods often mentioned in this category and this could be a reason that it correlates with the co-creative collaboration partners were describing in this category.

Furthermore, co-creation and experimentation were often mentioned together. Partners described that students could experiment with solutions they developed in co-creation with others. This also corresponds with Table 3.3 that shows the codes 'collaboration' and 'unknown unknowns' (methods for field testing and real-world experimentation) often appear together in a challenge. Co-creative collaboration is more complex than taking stakeholders into account in the design of a solution as the cooperation strategies do.

In some cases, the partners described that co-ownership or distribution of power to the residents was part of the challenge. For instance, this partner was looking for a structural solution that promoted the involvement of stakeholders in a circularity project: '*an organizational structure that offers a more level playing field* *in which trust, decision making power and ownership of the process are more fairly distributed over a variety of (new) stakeholders.*' (36:5) We found this to be one of the most complex questions posed to the students.

3.5 Discussion

Uncertainty as a concept is hard to grasp in sustainability education. Therefore, this study aimed to conceptualize uncertainty in sustainability challenges, analyze their difficulty level, and describe what strategies students were expected to use to deal with that uncertainty. In this discussion, we relate the results to the three aims of the study and reflect on the limitations of the study.

For this study, the relational dimensions for uncertainty of Brugnach et al. (2008) proofed a useful way to conceptualize uncertainty in the context of sustainability challenges. The results showed that almost all analyzed challenges featured all three dimensions of uncertainty. This suggests that the Living Lab course creates sufficient opportunity for students to engage with uncertainty.

However, engaging with uncertainty and learning to deal with uncertainty are not necessarily the same thing. To learn from those uncertainties, Shao et al. (2022) suggest that teachers need to be able to point out which problems will offer students the right opportunities for learning. The framework we presented in Table 3.1 assigns problems into uncertainty related categories. Such a common terminology can help students to decide what solution strategies they can use and advance their reflexivity.

Furthermore, we analyzed how difficult the uncertainty dimensions were in the challenges. The results indicated that the challenges were a mix of complicated and complex difficulty. What this means to students at the start of a transdisciplinary course is best understood as three tensions.

The first tension arises from the idea that students are always confronted with complex sustainability problems in this course. Although transdisciplinary education is about dealing with ill-structured problems (Simon, 1973), this study showed a more nuanced perception of the challenge, where parts of the partners' challenges were complex but others were complicated. Students require a form

TOC

of epistemic fluency to navigate between the complicated problems that benefit from disciplinary understanding and complex problems that require a merge of different types of knowledge (Markauskaite & Goodyear, 2017). Scholz and Steiner (2015) describe this tension as the difference between the real and ideal type of transdisciplinary processes.

Most challenges dealt with knowledge incompleteness on a complicated level and made use of conventional research methods. In those cases, the partners suggested research questions and proposed specific research methods to be used by the students. Although the course is about teaching experimental methods to do research, such as the living lab approach, this study demonstrates that well-established research methods, such as literature study and interviews, remained an important part of dealing with incomplete knowledge.

On a complex difficulty level, students in the course would most frequently encounter multiple knowledge frames. This uncertainty is about collaboration when there are conflicting norms, values, and interests by the stakeholders. The challenges described a tension between consensus-oriented and approaches to constructive conflict (Cuppen, 2011). This is in line with the conclusion of Popa et al. (2015) that transdisciplinary research needs a combination of consensus-oriented and open-ended or transformative approaches. Whether students succeed in this course to combine those approaches is outside the scope of this study, but students encounter the right ingredients in the challenges to create that combination.

Finally, the thematic analysis showed five concrete approaches to uncertainty that could be useful for other students and teachers working on uncertainty in sustainability challenges: systems thinking, designing adaptive solutions, experimenting, mapping, and co-creating. Most of these approaches are described in existing frameworks for sustainability competencies. For example, the UNESCO (2017, p. 10) SDG learning objectives also describe a systems thinking competency: '*the abilities to recognize and understand relationships; to analyze complex systems; to think of how systems are embedded within different domains and different scales; and to deal with uncertainty.*' Overall, the five approaches in the results of this study could be further supported in the curriculum of transdisciplinary courses.

This study has two important limitations. First, this study focused on the written challenges formulated by partners of the transdisciplinary course. By writing a challenge the partners apply for taking part in the course and they will shape their problem to fit within the course's criteria for a suitable challenge. Therefore, there is some distortion between the authenticity of the partners' challenges and what is ultimately formulated as a challenge in the course. This is specifically relevant to the thematic analysis of this study. For example, in the analysis 'co-creation' was often mentioned by the partners, but they might have stressed co-creation more to accommodate the aims of the course that also mention co-creation.

Second, the generalizability of the results is limited by the single case study design of the research. The challenges used in the analysis all come from the same course. Therefore, they were comparable and offered an ideal case study for testing and validating the analytical framework. However, the generalizability of the results to other contexts is limited. An interesting avenue for future research would be to apply the analytical framework for uncertainty to other transdisciplinary and sustainability courses. This would contribute to a further understanding of uncertainty in higher education.

3.6 Conclusion

Transdisciplinary education aims to prepare students for the uncertainty in complex sustainability transitions, yet uncertainty is a difficult concept to grasp and lacks a clear terminology for teachers in practice. In this study, we conceptualized uncertainty in the challenges students work on in the Living Lab course. The results provide teachers with a framework to talk about the unknown and possible approaches students can use when confronted with uncertainty.

We developed an analytical framework to code different dimensions of uncertainty and their difficulty level. Based on Brugnach et al. (2008), we analyzed 48 challenges based on three dimensions: unpredictability (uncertainty because of societal processes or technological surprises that are sometimes impossible to predict), knowledge incompleteness (uncertainty because of a lack of information, theoretical understanding, or the data is unreliable), and knowledge frame multiplicity (uncertainty because the people involved might have different ways of perceiving the problem). The three uncertainty dimensions were coded on a clear, complicated, or complex difficulty level. Additionally, a thematic analysis of uncertainty showed which strategies students were expected to use in the course.

42 of the 48 analyzed challenges contained all three dimensions of uncertainty. The difficulty levels of the challenges were a mix of complicated and complex. This suggests that the Living Lab course creates sufficient opportunity for students to engage with uncertainty. At the same time, students will experience tensions in the course due to the partners mixed expectations of using conventional and transformative approaches to research.

This study recommends teachers engaging with complex sustainability challenges in their courses to incorporate five approaches in their curriculum: systems thinking, designing adaptive solutions, experimenting, mapping, and co-creating. Additionally, students and teachers can benefit from the analytical framework for uncertainty to come to grips with what the unknowns in their process are.

Moving toward sustainable education, such as living labs, means teachers need to be willing to teach uncertainty as part of that curriculum. Only if teachers understand the uncertainties faced by the students, can they guide them through the process of dealing with those by selecting the correct strategy. That is the kind of sustainable education that will prepare engineers for an uncertain future.

4 How do students deal with the uncertainty of sustainability challenges?

Metacognitive learning in a transdisciplinary course

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ABSTRACT

While tackling sustainability challenges, engineering students confront various uncertainties, including the unpredictability of real-world scenarios, unfamiliar aspects of problems, and conflicting viewpoints among stakeholders. Despite previous research indicating the likelihood of encountering such uncertainties in sustainability projects, it is unclear if students are aware of uncertainty and what specific regulatory behaviors they develop to address them.
This study seeks to deepen our understanding of the awareness and regulation of uncertainty by students while they work on real-world sustainability challenges.

To achieve this, we observed nine MSc students enrolled in a transdisciplinary course on urban sustainability at a Dutch university of technology. Through interviews, we explored the uncertainties they faced and how they navigated them.
Our analysis, conducted through open, consensus-based coding by two researchers, revealed that students primarily encountered the uncertainty of multiplicity, characterized by divergent stakeholder perspectives. Additionally, students increasingly recognized the inherent unpredictability of the challenges over the course. To address uncertainty, students developed three kinds of behaviors to deal with uncertainty: seeking social support from commissioners, coaches, and peers; employing small coping mechanisms to overcome obstacles; and developing attitudes such as empathy, flexibility, and relativism.
This study offers detailed insights into how students navigate uncertainty. Moving forward, efforts in uncertainty education should prioritize how teachers can positively influence the development of metacognition in uncertainty.

KEYWORDS Uncertainty, transdisciplinary education, urban sustainability, metacognition, engineering education

4.1 Introduction

In the past two decades, the idea has grown that engineering education needs to change significantly to become sustainable (Leal Filho et al., 2018). Part of this transformation aims for education to engage with people from industry and other parts of society to work on sustainability challenges collaboratively (Knudsen, 2015). In transdisciplinary courses, students are confronted with the uncertainties of real-world challenges and learn to collaborate with stakeholders in and outside of academia (Gallagher & Savage, 2020). Such educational reconfiguration also requires the investigation of new competencies for sustainability that are being taught there (Bianchi et al., 2022).

One of those new sustainability competencies presented in international frameworks by the European Commission (Bianchi et al., 2022) and UNESCO (2017), is the competency to deal with uncertainty. In simple terms, uncertainty refers both to things that are uncertain and people that feel uncertain (“Uncertainty,” n.d.). Sustainability challenges are often characterized as uncertain things, because of their dynamic and networked nature (Ingold et al., 2018). It is this kind of uncertainty that students and other people working in the sustainability domain need to deal with and that the previously mentioned frameworks refer to. A more detailed view of uncertainty in sustainability challenges suggests that uncertainty has several dimensions. The relational perspective of Brugnach et al. (2008) distinguishes between three dimensions of uncertainty: the unpredictability of a real-world challenge, the knowledge gaps in the problem, and the conflicting perspectives among the people involved. Previous research showed that students are likely to encounter all three dimensions of uncertainty in transdisciplinary courses (Bohm, Klaassen, den Brok, et al., 2024).

To be able to recognize the different dimensions of uncertainty, students need to be aware of the limits of their knowledge. Based on that awareness, students can think of approaches to regulate their thinking and learning about the uncertainty of sustainability challenges. Such awareness of one's knowledge and regulation of one's thinking is called 'metacognition' (Stanton et al., 2021). More than learning *about* sustainability, the transition in education should focus more on learning the new ways of thinking that sustainable transitions need to deal with their uncertainties (Karjanto & Acelajado, 2022; Zoller, 2015). However, what metacognitive awareness and regulation students need to deal with the different dimensions of uncertainty is unclear. Although the effectiveness of teaching metacognition is well-established in several meta-analysis studies (Perry et al., 2019), previous research also suggests that teachers find it difficult to formulate metacognitive learning objectives in transdisciplinary courses (Bohm et al., 2023). Therefore, a better understanding of how students currently deal with uncertainty is necessary to make the teaching of this sustainability competency more explicit.

In this qualitative study, we investigate the question: **What uncertainty do students encounter when working on sustainability challenges (metacognitive awareness) and how do they deal with it (metacognitive regulation)?** We interview nine MSc students at three different moments of a 16-week, transdisciplinary course at a Dutch university of technology. The semi-structured interviews provide us with first insights into the development of metacognitive regulation of uncertainty throughout the course.

Section 4.2 presents the theory of metacognition and the sensitizing concepts that formed the starting point of the semi-structured interviews. In Section 4.3, we explain the course we used as a case study, the interview method, and how we used open coding to analyze the interviews. The results in Section 4.4 first show the awareness of uncertainty students talked about in the interviews, then the three groups of regulatory behavior we found they used to deal with them, and lastly, the connections between awareness and regulation. Finally, we discuss how uncertainty attitudes might be taught and further researched in sustainability education in the future.

4.2 Theoretical background

Metacognition is a well-established phenomenon in educational research. In this theoretical background, we first focus on foundational studies of metacognition that present a clear delineation of the field. We then zoom in on uncertainty in more recent, explorative studies of metacognition, and how they point toward a further investigation of metacognition in the classroom.

4.2.1 Metacognition: awareness and regulation

Metacognition research commonly distinguishes two components of metacognition: metacognitive awareness and regulation (Veenman et al., 2006). In education, metacognitive knowledge generally refers to a student's (correct or incorrect) self-awareness or understanding of their knowledge or learning process. Metacognitive regulation allows a student to regulate their learning processes by, for instance, planning, monitoring, and evaluating them. Mevarech and Kramarski (2014, p. 36) describe that when metacognitive awareness and regulation are combined it enables students to self-regulate their learning:

'It [metacognition] enables learners to plan and allocate learning resources, monitor their current knowledge and skill levels, and evaluate their learning level at various points during problem-solving, knowledge acquisition or while achieving personal goals.'

Although metacognition is a cognitive process (*thinking*), metacognition can be aimed at affect as well (*thinking* about *feeling*) (Tobias & Everson, 1997). Thus, metacognition enables students to manage other aspects of learning beyond the cognitive, such as motivation and emotion (Ben-Eliyahu & Linnenbrink-Garcia, 2012). Equally, how well students can regulate negative and positive emotions while learning does influence their academic achievement (Zheng et al., 2023). Ben-Eliyahu (2021) suggests that specifically sustainable learning should allow for the development of metacognition in relation to emotion.

Overall, metacognition is strongly related to academic achievement, as several overview studies show (Dignath et al., 2008; Hattie, 2009; Perry et al., 2019). An understanding of what you know or how you learn is important to be able to progress in school. Metacognition is important for all school and age groups, from primary school to university (Perry et al., 2019).

Therefore, teaching metacognition is one of the most effective ways to improve learning in education (Quigley et al., 2016). Despite the evidence that underscores the importance of teaching metacognition, this study by Zohar and Barzilai (2013) showed that metacognitive instruction in practice is challenging to teachers. Additionally, teachers in transdisciplinary courses seldom write metacognitive learning objectives explicitly down in their course descriptions (Bohm et al., 2023).

Veenman et al. (2006) suggest three criteria for effective metacognitive instruction. First, teaching metacognition should be an integrated part of the curriculum and not a separate and disconnected subject from the content. Second, it should be an explicit part of the curriculum and it should be clear to students why it is useful to them to learn (about) metacognition. Third, metacognition should be taught over a longer period. The case study in this research matches these three criteria, which we will further elaborate on in Section 4.3.1, and it offers a favorable environment to further investigate uncertainty as a specific metacognitive competency.

4.2.2 Awareness and regulation of uncertainty in sustainability challenges

Complex, societal problems, such as the sustainability challenges this study looks at, create different kinds of uncertainty. In this study, we focus on the uncertainty that arises from the nature of complex problems (Koppenjan & Klijn, 2004). The complexity of sustainability challenges is that they are networked, unstructured, and dynamic (Leijten & de Bruijn, 2005). Therefore, problem-solving and decision-making about sustainability must be done in interaction with many stakeholders and with careful consideration of the uncertainties involved (van Bueren et al., 2003).

Brugnach et al. (2008) defined three perspectives on uncertainty and Raadgever et al. (2011) used these perspectives to analyze uncertainty in sustainability challenges in environmental policy. First, *accepting not to know* relates to the unpredictability of a real-world challenge. Second, *knowing too little* describes the knowledge gaps in the problem. Third, *knowing too differently* arises from conflicting views amongst the people involved. These three perspectives on uncertainty will be used to analyze the awareness of uncertainty among the students in this study.

To analyze the regulation of uncertainty, no previous research has described what students do to regulate uncertainty in sustainability challenges. Generally, regulatory behavior by students can be, for instance, planning, monitoring, and evaluating their learning behavior (Stanton et al., 2021) or, more specifically, setting goals based on what motivates them and seeking help from peers (Zimmerman, 2023). However, specifically for uncertainty, what this regulatory behavior might be is unclear and only a few studies on uncertainty in education take metacognition into account. Smith (2002) investigates uncertainty in a stress management course, but the conclusions do not go into detail on student behavior. More recently, some studies on design education relate to uncertainty and metacognition (Cash et al., 2023). For instance, Christensen and Ball (2017) show that when designers encounter epistemic uncertainty it triggers what they call a 'metacognitive switch': a decision moment to continue with certain information or to immediately resolve uncertain aspects of the design. Furthermore, in the conclusion of their review study, the same authors suggest researching uncertainty in design education from the perspective of metacognition (Ball & Christensen, 2019). In general, Perry et al. (2019) point out that much educational metacognition research has been done in laboratory settings and that there is a need for more research in the classroom.

4.3 Materials and methods

4.3.1 Case study of a transdisciplinary course in urban sustainability

We researched student awareness of uncertainty and regulation of uncertainty in a transdisciplinary course on urban sustainability at a university of technology in the Netherlands. This course, comprising 24 ECTS[10] credits and forming an integral part of a two-year MSc program, provided students with real-world challenges in urban sustainability. Working in small groups of four or five, students tackled these challenges under the guidance of academic coaches (teachers from the university) and challenge commissioners (practitioners from the field). This integrative approach, coupling academic expertise with practical experiences from outside academia, ensured the course had a transdisciplinary character (Gallagher & Savage, 2020).

10 ECTS is the abbreviation for 'European Credit Transfer and Accumulation System,' which is used across higher education institutes in the European Union as a common measure for learning based on specific learning outcomes and their associated workload (European Commission Directorate-General for Education Youth Sport Culture, 2015). 60 ECTS credits are the equivalent of 1 full-time academic year of studies.

TOC

In addition to providing a transdisciplinary learning environment, the course fostered transdisciplinary learning through teaching a 'living lab approach' that focuses on problem solving in the complex conditions of real-world challenges (Steen & Van Bueren, 2017).

The course incorporated metacognitive learning and teaching abiding by the three criteria for effective metacognitive instructions proposed by Veenman et al. (2006): (1) teaching metacognition integrated into the curriculum (and not as a separate course), (2) teaching it explicitly, and (3) teaching it over a longer period. Complying with the first criteria, the course taught metacognition integrated into the 'living lab approach', where students learned to build experiments and design solutions for urban sustainability challenges. Second, metacognition was part of three of the five learning objectives of the course. For example, learning objective three requires students to be able to examine and reflect on their learning experiences and set personal learning goals in the course. Such awareness of their own strengths and weaknesses, and regulation through goal setting can be recognized as metacognitive learning. For an overview of the course's learning objectives with an indication of those involving metacognition refer to Table 4.1. Lastly, the course ran for 16 weeks. Considering that most courses at this university take a maximum of ten weeks, this is a longer period. We assume that during this period, the teachers (academic coaches) in the course would have had time to monitor and adjust students' metacognition.

TABLE 4.1 The learning objectives in the case study course and which of them have metacognitive elements in them. Objectives marked with an asterisk (*) are considered related to metacognition, because they require awareness and regulation of learning, whether this is individual or in collaboration with others.

LO	Students who have completed this course will be able to:
1*	iteratively improve and adjust the living lab process by continuous evaluation and incorporation of feedback;
2	connect real-life challenges to academic theory and the living lab process;
3	present in a way that enables exchange of knowledge, experience, and ideas with other MADE staff, students, and stakeholders;
4*	collaborate with societal actors involved in the challenge; and
5*	examine and reflect upon personal motivations, values, and growth within the context of a learning experience.

4.3.2 Data collection through semi-structured interviews

We conducted in-depth, semi-structured interviews with nine students, each from a different team, at three moments in the course (27 interviews in total). The students were selected by an open call amongst all student teams in the course to participate in the research voluntarily. The participating students (4 male and 5 female students) all had a bachelor's degree from either a university or a university of applied sciences. Those degrees were related to sustainability and innovation (4 students), architecture and design (3 students), or natural resource management (2 students). Two students had previous work experience, but neither more than 7 years before starting this master's program.

We interviewed the students after the plan development stage (after four weeks), in between the midterm and delivery of the final product (ten weeks), and when they finished the course (sixteen weeks). By interviewing at different moments, we gained insights into how students developed their awareness and regulation of uncertainty throughout the course. The first author made interpretative sketches after all the interviews had taken place as a tool to comprehend what we learned about the process of each of the students (see Appendix G for the sketches).

The interview protocol was developed based on sensitizing concepts (Bowen, 2006) in the analytical framework that also formed the starting point for the coding process (Appendix E). We chose a qualitative research method because the competency of dealing with uncertainty has not been described in detail before. Therefore, the interviews aimed to provide us with first insights into the awareness and regulation of uncertainty that can be further developed and validated in future research (Brown et al., 2002).

In a previous study (Bohm, Klaassen, den Brok, et al., 2024), we assessed which dimensions of uncertainty were present in the sustainability challenges at the start of the course. Additionally, that earlier analysis categorized the dimensions of uncertainty on three levels (clear (1), complicated (2), and complex (3)). Figure 4.1 shows the results of that assessment for the nine challenges that the interviewees in this study worked on. These were the uncertainties that students could recognize at the start. Additionally, the student interviews inform us which uncertainties might arise during the process that were not part of the initial challenge.

TOC

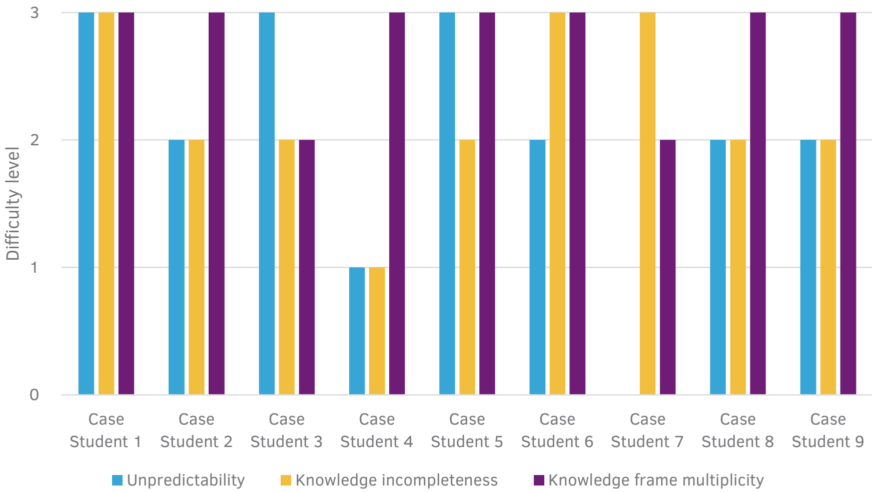


FIG. 4.1 Assessment of the three uncertainty dimensions (unpredictability, knowledge incompleteness, and knowledge frame multiplicity) in the sustainability challenges of the nine interviewed students (Bohm, Klaassen, den Brok, et al., 2024).

4.3.3 Analytical framework

To analyze uncertainty in a transdisciplinary course, we used the two-component model for metacognition (awareness and regulation), as it was first described by Brown (1987), but is still used in more recent metacognition research (Mevarech & Kramarski, 2014; Stanton et al., 2021). Based on that model, we integrated the three dimensions of uncertainty (Brugnach et al., 2008) to develop the analytical framework in Figure 4.2 that supported the data collection and analysis. The two components informed the interview questions with the students. First, we asked for the uncertainties that students recognized: the unpredictability of a real-world challenge, the knowledge gaps in the problem, and the conflicting perspectives amongst the people involved. Second, we asked how students deal with uncertainty to find how they regulated uncertainty once they became aware of it. Through an open coding approach, we looked for the regulatory behavior, such as mapping information or asking for help from peers (Zimmerman, 2023), that will enable them to deal with that uncertainty.

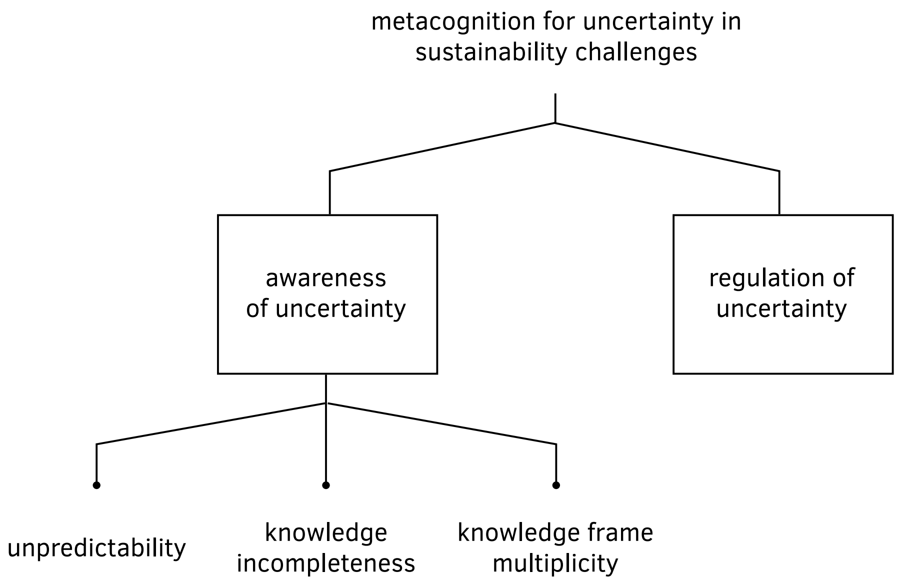


FIG. 4.2 The analytical framework of this study is based on the two-component model of metacognition: awareness and regulation of uncertainty.

4.3.4 Data analysis through open coding

Two researchers coded the interviews in a consensus-based coding process. In the 27 interviews, 1213 metacognitive quotations were coded, 589 codes in the ‘awareness of uncertainty’ category, and 624 in the ‘regulation of uncertainty’ category. To get to those results, the coding was done in three cycles.

The first coding cycle was aimed at establishing a codebook from the nine interviews at the end of the course. For the code category awareness of uncertainty, the first author used three a priori code groups: unpredictability, knowledge incompleteness, and knowledge frame multiplicity. Within those groups, open subcodes were assigned to the quotations. For the code category regulation of uncertainty, all codes were established through open coding.

TOC

For the second coding cycle, the second researcher used this first version of the codebook and added two codes in the awareness category and six codes in the regulation category. Especially in the latter category, the second coder added regulatory behavior that the first coder had merged under the same category. After the first two cycles, the code book contained 38 codes (16 codes for awareness of uncertainty and 21 codes for regulation of uncertainty).

In the third coding cycle, both researchers coded the next 18 interviews with this codebook. In this cycle, three codes were added to the awareness category, and six codes were added to the regulation category. The added codes described regulatory behavior that might not have been so important in the last part of the course, such as 'searching for information' or 'expectation management.' In this stage, we regrouped the codes into three emergent code categories: seeking social assistance, employing small strategies, and transforming attitudes. The final codebook contained 44 codes, 17 codes for awareness of uncertainty and 27 codes for regulation of uncertainty. Appendix F shows the codebook with short explanations of the codes.

4.4 Results

The results are presented in three parts: awareness of uncertainty (4.4.1), regulation of uncertainty (4.4.2), and connections between awareness and regulation (4.4.3). In the first two parts, we give a short overview of the results, before presenting the detailed results. In 4.4.3, we present the co-occurrence table of awareness and regulation.

4.4.1 Awareness of uncertainty

Students increasingly mentioned different kinds of uncertainty throughout the interviews (Figure 4.3). Figure 4.1 showed that all challenges contained uncertainty at the start of the course. Therefore, the results show that the interviewed students became more aware of uncertainty over time.

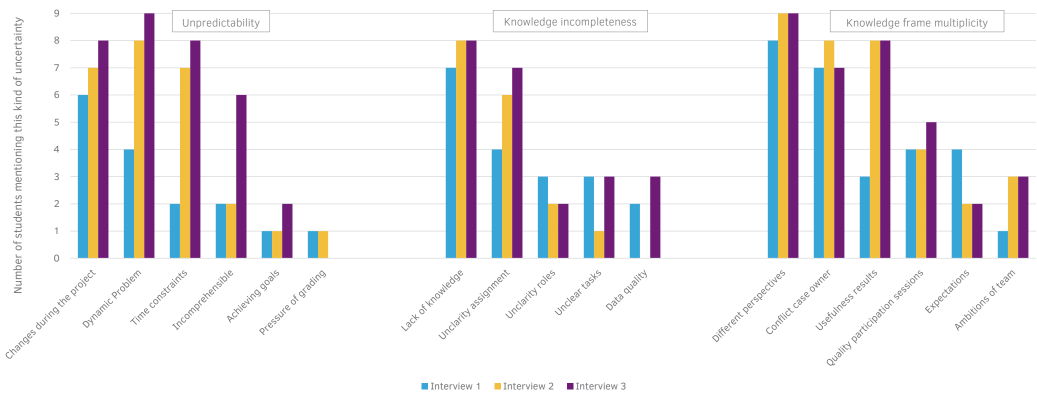


FIG. 4.3 This bar chart shows which uncertainties students mentioned at different moments in the course, organized by the uncertainty dimensions: unpredictability, knowledge incompleteness, and knowledge frame multiplicity.

Specifically, unpredictability awareness grew throughout the course. In retrospect, it was easier for students to recognize which things emerged unexpectedly or surprised them. In the interviews, these things were mentioned as the unpredictable parts of the challenge.

Overall, students recognized uncertainties of the dimension 'multiple knowledge frames' most often. However, only three challenges contained this dimension as the most difficult level in Figure 4.1. Furthermore, even though knowledge incompleteness was the most difficult uncertainty dimension in most challenges according to Figure 4.1 (seven out of nine challenges), students mentioned this dimension least often.

4.4.1.1 Unpredictability

Students most often mentioned 'changes during the project' (in 21 interviews) and 'dynamic problem' (in 21 interviews). As new insights arose while working on the challenges, it caused students to rethink their previous steps. Student 1 said:

'If we had known beforehand that the commercial applicability of wood would not have been worthwhile to research, I think we would have focused much more on the reuse of material within the municipality. Because the entire financial motive [to research this] fell away.' [Student 1]

TOC

In this context, two students said they believed unpredictability was an inherent part of doing research. In the last interview round, six students mentioned uncertainty because the problem was incomprehensible to them. Often students saw the limitations of the research they did. For example, student 8 said:

‘We held on to the outcomes of the interviews, where we found six barriers. But I think, that if you would go back into the literature now you can find many more, or that they will be described differently, or combined, or taken apart. There is an indefinite number of combinations possible.’ [Student 8]

From the start, many students showed awareness of the problem being dynamic. In the final interview round, all students mentioned they encountered this uncertainty. We coded this uncertainty when students experienced constantly moving variables as part of the problem. This code often co-occurred with the code ‘different perspectives’ as part of knowledge frame multiplicity.

4.4.1.2 Knowledge incompleteness

In 23 interviews, students experienced a ‘lack of knowledge’. Students mentioned this at the start, middle, and end of the course. This is an example from a student at the start of the course:

‘Well, what I find difficult is that we are getting started with a challenge where we actually do not have much expertise on.’ [Student 7]

Although the students gain expertise on the challenge during the course, the lack of knowledge does not decrease toward the end. Then, students found (unexpected) outcomes of their research uncovered new uncertainties to them:

‘And, yes, there is now actually a chance that this system has already been in place for a long time, that this canal has existed for a long time, and that we have actually extracted wood from it. That could very well be the case. And that, I would have liked some more insights into that.’ [Student 1]

Additionally, the unclarity of the assignment, roles, and tasks was another source of uncertainty. For example, when students mentioned that the assignment was unclear (17 interviews), they talked about different assignments in the course. Student 7 said to experience stress because of unclarity on the assignments in all stages of the project:

‘At the start, we did not know what we had to do. In between, the uncertainty was about what we were going to make for the commissioner. In the end, we had difficulty deciding what to write down in the report.’ [Student 6]

4.4.1.3 Knowledge frame multiplicity

In 26 of the 27 interviews, students encountered ‘different perspectives’. In that case, the challenge presented different perspectives on the problem, approach, or solution direction that might contradict each other. Additionally, students also described different perspectives within their team. In this quote, student 6 explained how different groups had a different understanding of the problem:

‘So someone who is committed to biodiversity in the city finds that much more important, for example, than someone who is committed to vulnerable groups and heat stress. So that was about the, yes, the weighing of those different, different consequences for those groups.’ [Student 6]

A ‘conflict with the commissioner’ was mentioned in 22 interviews. In that case, specifically, differences in perspective with the commissioner caused uncertainty. Similarly, codes such as ‘unclarity roles’ and ‘expectations’ also refer to uncertainty in collaboration with a partner from outside of the university. Especially at the start of the course, students said they struggled with managing the expectations of the commissioner and giving direction to the research. However, in some cases, these conflicts were not completely resolved at the end of the course.

4.4.2 Regulation of uncertainty

The interviewed students described 27 kinds of behavior to regulate uncertainty. We grouped those into three categories: seeking social assistance, employing small coping mechanisms, and changing attitudes to deal with uncertainty (Figure 4.4).

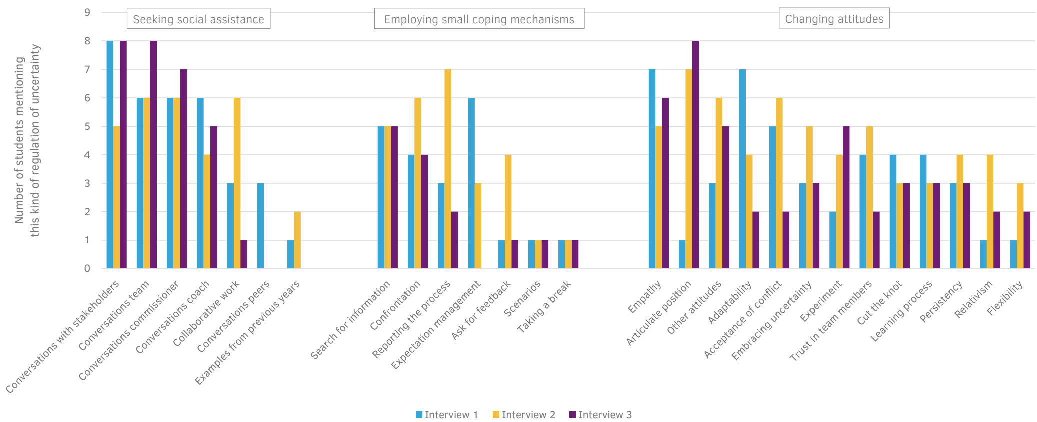


FIG. 4.4 This bar chart shows which behavior students used to regulate uncertainty at different moments in the course, grouped into three categories: seeking social assistance, changing attitudes, and employing small coping mechanisms.

4.4.2.1 Seeking social assistance

The most prominent way to deal with uncertainty for the interviewed students was to talk about it, whether this was in conversations with other stakeholders (in 21 interviews), the commissioner (in 19 interviews), the coach (in 15 interviews), or their team members (in 20 interviews). Different uncertainties were resolved in those discussions. In conversations with the commissioner, students talked about the unclarity of roles in the process or managed expectations about the results. In conversations with the coach, students sought clarity on the assignments and advice on how to deal with their role and the role of the commissioner in the process. The conversations in the team were also about all these relational uncertainties and uncertainties arising from tasks. Student 4, for example, said:

‘Especially from the moment we divided the tasks, if it was unclear to one of us how to proceed, we discussed together.’ [Student 4]

4.4.2.2 Employing small coping mechanisms

Students mentioned several small coping mechanisms to deal with uncertainty and the feeling of being stuck, such as taking a break (6 interviews) or asking for feedback (3 interviews). One student said they made use of examples of the reports from last year in the course to deal with the unclarity of the assignment. Such behavior is often related to uncertainty in specific tasks.

4.4.2.3 Changing attitudes

Students talked about their attitude toward uncertainty in all interviews. In total, we found 13 different attitudes toward uncertainty, including an 'other attitudes' category. In 18 interviews, students said that they gained more understanding of the other perspectives of stakeholders in the challenge.

For some challenges, students started to look for consensus for the solution their project would develop, whereas other students developed an attitude of acceptance of the different perspectives. In 13 interviews students mentioned that they accepted conflict. Accordingly, some students specifically mentioned that failure or conflict were part of the learning process in the course. Student 3 said about accepting uncertainty:

'[…] so part of dealing with it [the uncertainty] was also kind of letting go of the idea that you needed to know stuff before you could move on, or you could decide to just kind of accept it.' [Student 9]

10 interviews mentioned 'persistency' as an attitude toward uncertainty. Those students describe how they tried to persuade others of their story, solution, or interpretation of the problem. More often (in 13 interviews), students adapted their approaches. For example, Student 5 described how acceptance led to an adaptation of the project's approach:

'If you do not know the answer to something, you find a way to accept this and deal with it and find a different way to approach the problem.' [Student 5]

Some attitudes were related to knowledge or epistemology. One of those attitudes was 'relativism' (7 interviews) when a student doubts to what extent the world is knowable. For example, Student 1 said about relativism:

'I'm quick in thinking, I don't know things, then all of it is nonsense.' [Student 1]

4.4.3 Connecting awareness and regulation of uncertainty

The competence to deal with uncertainty is a combination of the awareness of uncertainty and using a strategy to deal with it. However, in the interviews, students did not always mention awareness and regulation in clear relation to each other. Sometimes, a student was able to clearly describe the unpredictability of the challenge, but could not directly answer the question 'How did you deal with that?' They might find an answer to that question later in the interview or were not able to connect the awareness and strategy at all. Therefore, the co-occurrence table that we present in Table 4.2 shows only the instances where a student did connect awareness and strategy to deal with uncertainty in the interview.

Students most frequently changed their attitudes to deal with uncertainty, independent of the dimension of uncertainty they encountered. Specifically, choosing their position toward the challenge and articulating that position was behavior across all three dimensions of uncertainty. Additionally, students went searching for new information (small coping mechanism) or talked to their commissioner, stakeholders, or their team members (social assistance) to regulate uncertainty in general. For knowledge incompleteness, students only use these generic behaviors, but for the other two uncertainty dimensions, we did find specific behavior that co-occurred in addition to the generic behaviors.

To deal with multiple knowledge frames, three kind of behavior related to attitude are mentioned more often: acceptance of conflict, persistence, and empathy. In the interviews, empathy seemed to be the starting point for understanding how different stakeholders perceive challenges. From that understanding, students chose either to accept the conflict or to persist in trying to convince the people involved to see it their way.

To deal with unpredictability, students adopted three attitudes in particular: learning process, flexibility, and relativism. Framing the course as a learning process allowed students to be mild about the unexpected events that made them rethink their choices or the mistakes they made. Students tended to either develop flexibility or relativism as an attitude toward unpredictability. Further research might investigate why students develop this tendency and if specific instruction might influence the development of those attitudes.

TABLE 4.2 This table shows the co-occurrence of codes for the awareness of the three uncertainty dimensions with the codes for the regulation of uncertainty.

	Unpredictability	Knowledge incompleteness	Multiple knowledge frames
Seeking social assistance			
Collaborative work		3	1
Conversations coach	1	2	2
Conversations commissioner	3	5	12
Conversations peers			1
Conversations team	7	6	15
Conversations with stakeholders	4	3	8
Examples from previous years		1	
Employing small coping mechanisms			
Ask for feedback		2	4
Confrontation	4	1	6
Expectation management	3	1	4
Reporting the process			
Scenarios	5	7	4
Search for Information	1		
Taking a break		2	4
Changing attitudes			
Acceptance of conflict	3	1	10
Adaptability		1	1
Cut the knot	3	1	2
Embracing uncertainty	3	2	
Empathy	1	1	9
Experiment	3	2	2
Flexibility	5		
Learning process	4	1	1
Other attitudes	6	3	8
Persistency	1		5
Articulate position	9	7	14
Relativism	10	4	6
Trust in team members		1	1

4.5 Discussion and conclusion

4.5.1 Discussion

The way students deal with uncertainty is highly individual and personal but, at the same time, develops depending on the kind of uncertainty they are confronted with and the assistance they receive. In this discussion, we first discuss the metacognition of uncertainty, how awareness of different kinds of uncertainty might lead to different regulatory behavior. Then, we take a closer look at the role of teachers in the development of uncertainty competency as an important practical implication of this study.

Throughout the course, students' awareness of the unpredictability of sustainability challenges grew. Brugnach et al. (2008) ascribe unpredictability to the complexity of the societal transitions that sometimes show non-linear and chaotic behavior. These authors advise responding by accepting these dynamics as they are and embracing the notion that their unpredictability will not change in the foreseeable future, is the way to deal with this kind of uncertainty. Attitudes accepting conflict and failure that the students in our study adopted correspond with this yet were not the only attitudes toward uncertainty they developed.

Regulating a lack of knowledge, because, for instance, data or people were not accessible, could lead to students responding with the flexibility to seek other approaches to achieve their goals. In some cases, when encountering knowledge frame multiplicity, students developed relativism and lost some of their confidence in what they were doing, or more drastically, their confidence in science.

Students are not the only ones to struggle with scientific expertise in the face of uncertainty. The realization that knowledge is contested and that several experts can give very contradicting advice is unsettling to many people (Koppenjan, 2007). In that context, de Bruijn and ten Heuvelhof (1999) suggest a process of constant interplay between research and decision-making. This process will lead to 'negotiated knowledge:' scientific knowledge that the involved actors can agree on. More recent scientific works investigate the development of reflexive practice, where students choose conscious moments to switch between the research of the problem and the design of a solution (Dorst, 2013; Mierlo et al., 2010; Popa et al., 2015). Overall, the uncertainty of sustainability challenges can not be addressed without also discussing the way that knowledge is constructed. In this, teachers might play an important role in addressing epistemic learning and integrating the different perspectives of students in the same team.

Our findings suggest that teachers can contribute to metacognitive learning on uncertainty in three ways. First, the collaboration with the coach in the course leads to less uncertainty than the collaboration with the commissioner. Students perceive the collaboration with the commissioner as a source of uncertainty related to knowledge frame multiplicity (Brugnach et al., 2008). The coach is only mentioned when seeking ways to deal with uncertainty but not as a source of uncertainty itself. Therefore, when seeking social assistance, students rather turn to the teacher than to the commissioner.

Second, 'seeking social assistance,' from peers, coaches, and commissioners, one of the original self-regulated learning strategies found by Zimmerman (1989), also is a prominent category in the results of this study. By asking for advice, feedback, or other kinds of help, students create their learning environment. The sense of agency that students need to be able to ask for help or feedback or otherwise regulate their learning, is one of the most important qualities in successful students (Zimmerman et al., 2017). Teachers play an important role to foster that sense of agency.

Third, several authors have found that teachers need to teach metacognition explicitly for it to be effective (Muteti et al., 2021; Perry et al., 2019). Additionally, the instruction of teachers becomes more effective when those teachers are aware of the learning strategies of students (Newell et al., 2004), and as this study shows, their attitudes toward uncertainty. Therefore, metacognition in sustainable education seems to be a key area for further investigation for teachers to guide the process of developing positive attitudes toward uncertainty.

4.5.2 Limitations and suggestions for future research

This study is limited by its explorative and qualitative character. The in-depth interviews that form the heart of the methodology are necessary to get to the difficult-to-measure concepts such as uncertainty and attitude. However, the conclusions presented here should be seen in the context of a single case study in a graduate (MSc) program, where students are relatively academically mature. This might have been visible in the diverse attitudes that students described. Where novices in epistemic learning might have more difficulty with reflecting on what is known and unknown to them, the students in this study had more practice experience in this kind of thinking and therefore, they could make their attitudes more easily explicit.

TOC

For a student to be able to seek social assistance is an important condition for self-regulated learning and it has been researched from the perspective of several educational theories (Zimmerman, 2023). However, the other two regulatory groups we found (small coping mechanisms and attitudes), are less well-established and require further investigation. That research is necessary to present the regulatory behavior we found with more clarity. Furthermore, research on how to teach metacognition for uncertainty could offer more support to teachers in their changing role as coaches in transdisciplinary courses. This way teachers will become better equipped to respond to students seeking social assistance from them when they try to deal with uncertainty.

4.6 Conclusion

This study provides the first insights into metacognitive awareness and regulation of uncertainty by students in transdisciplinary education. In 27 in-depth interviews, we asked 9 students at several moments in the course which uncertainties they experienced in the sustainability challenge they worked on and how they dealt with those uncertainties.

The results show that students most often encountered the multiplicity of the challenge when different people had different perspectives on the problem. Furthermore, throughout the course, students became increasingly aware of the unpredictability of the challenge. Although, students conducted research and gained knowledge on the content of the challenge, knowledge incompleteness did not decrease throughout the course. Gaining new insights also uncovered more uncertainties to the students.

Students used three kinds of regulatory behavior to deal with uncertainty. First, conversations with commissioners, coach, and their team members allow students to gain a better understanding of the uncertainty. Second, students use small coping mechanisms, such as taking a break or asking for feedback, to deal with uncertainties related to specific tasks. Third, students develop different attitudes toward not knowing, such as empathy, flexibility, and relativism.

Although more research is necessary to get a deeper understanding of metacognition in relation to uncertainty, this study underscores the importance of conversations between students, teachers, and peers as part of the learning process in transdisciplinary courses. Furthermore, dealing with uncertainty helps to grow self-awareness, and specific attitudes toward regulating knowledge. Ultimately, self-knowledge allows students to critically reflect on what they know, on what they don't know, and, most importantly, on what they can know. It is the task of this generation of students to anticipate what knowledge is needed to make strategic next steps toward a sustainable society.

5 Adaptive guidance for uncertainty

How teachers use scaffolding in transdisciplinary courses

An adapted version of this chapter has been submitted for peer review.

ABSTRACT

Transdisciplinary education poses unique challenges for teachers, particularly in teaching complex competences, such as dealing with uncertainty. Increasingly, sustainability challenges in transdisciplinary courses confront students with different dimensions of uncertainty, such as, unpredictability, lack of knowledge, or ambiguity. However, little is known about how teachers adapt their teaching to scaffold students through such uncertainty.

This design-based study investigates the adaptive guidance, also called 'scaffolding,' employed by teachers to guide students through problem-solving in uncertain situations. Using a sixteen-week challenge-based course called the 'Living Lab' as a case study, we monitored how teachers developed scaffolding based on a workshop they received before the course began. Through qualitative surveys and focus groups conducted every four weeks, teachers reflected on their teaching practices and coaching strategies.

The study identifies teaching problems faced by teachers in transdisciplinary courses, including theoretical grounding, tensions with the commissioner, and assignment clarity. Teachers most frequently used scaffolding to address frustration control, marking critical features, and direction maintenance. Additionally, teachers lacked diagnostic strategies to assess student progress on personal learning objectives.

This research contributes to a deeper understanding of the role of teachers as coaches in transdisciplinary courses and suggests avenues for further exploration of diagnostic strategies and scaffolding for theoretical understanding and personal learning objectives. Practical implications include informing and inspiring teachers to enhance their scaffolding practices in challenge-based courses, thereby fostering effective transdisciplinary approaches in sustainable higher education.

KEYWORDS Transdisciplinary education, challenge-based learning, teacher roles, living lab education, scaffolding, uncertainty

5.1 Introduction

Transdisciplinary education changes the role of the teacher. Traditionally, teachers in higher education are the primary source of knowledge. In transdisciplinary education, knowledge is dispersed, and students need to collect information from all kinds of people, not just their teachers (Fam et al., 2018). In this new role, teachers become coaches who assist in the process of collecting and weighing information and making decisions (van den Beemt et al., 2020). Additionally, the teachers coach team dynamics and advise on the relationship with commissioners from outside the university. Ultimately, they help students deal with the uncertainty of working on complex real-world problems, such as the transition to a sustainable society (Steiner & Posch, 2006).

Previous research has shown that for constructivist learning, such as challenge-based learning or education in living labs, concrete guidance from teachers is crucial (Kirschner et al., 2006). Without it, students will drift off from the learning objectives or get stuck in the complexity of the problems they work on. Additionally, in constructivist learning approaches engagement with the content can vary throughout a course and requires teachers to adapt their guidance over time (Rotgans & Schmidt, 2011). Especially in transdisciplinary education, where knowledge is dispersed amongst stakeholders and where students have different epistemological backgrounds, teachers are urged to look for adaptive approaches to teaching (Kirschner & Hendrick, 2020).

Scaffolding is a teaching model that aims to tune into the level of the student and then provide tailored support to grow to the next level of problem-solving (van de Pol et al., 2010). Scaffolding requires a back-and-forth process between teacher and student, where the teacher holds the idea of where the student wants to go and the student explores how to get there autonomously. Hardy et al. (2022) describe this back-and-forth through the ESRU model of Ruiz-Primo and Furtak (2006, p. 61):

“The teacher Elicits a question; the Student responds; the teacher Recognizes the student’s response; and then Uses the information collected to support student learning.” As scaffolding is an adaptive form of teaching, teachers could use it specifically for teaching the complex competencies that sustainability education deals with (Brundiers et al., 2020).

However, in transdisciplinary or sustainability education scaffolding research is limited (Lönngren et al., 2017) and often focuses on tools rather than the experiences of the teacher (Markauskaite & Goodyear, 2014). Moreover, sustainability challenges are complex, require complex competencies for problem-solving, and therefore, might be scaffolded in a particular way (Acosta-Gonzaga & Ramirez-Arellano, 2022; Birdman et al., 2022). Specifically, dealing with uncertainty is a part of problem-solving in sustainable transitions that is difficult to provide support for (Wijnia et al., 2011). Although in previous research we found that within transdisciplinary courses students encounter uncertainty (Bohm, Klaassen, den Brok, et al., 2024) and find ways to deal with it (Bohm, Klaassen, van Bueren, et al., 2024), we know little about how teachers adapt their teaching to scaffold students through uncertainty.

Therefore, in this educational design research, we investigate what scaffolding strategies teachers use during a transdisciplinary course. We aim to answer the research question: **What scaffolding strategies do teachers use over time to guide students toward problem-solving in uncertainty?**

The design research is done within the ‘Living Lab’ course that is part of a two-year transdisciplinary master program in the Netherlands. This 16-week course teaches students how to deal with a complex sustainability challenge. We introduced the ten teachers involved in the course to scaffolding as a design intervention before the start of the course. Based on the workshop, teachers could decide how and when to use scaffolding in their teaching during the course. We evaluated how teachers adapted scaffolding to their teaching practice and what kind of uncertainty they managed through this. This was done in three design cycles of each four weeks. The evaluation was done every six weeks through a questionnaire and consecutive focus groups.

5.2 Theoretical background

5.2.1 What is scaffolding?

'Scaffolding' is a metaphor to describe how to teach problem-solving. Wood et al. (1976) came up with the term while studying how 3-5 year-olds learn to build a tower of wooden blocks. Problem-solving, such as building a block tower, is a complex skill with a hierarchical structure (Kirschner & Hendrick, 2020). Children need to master lower-order skills before they can move on to more difficult skills (van Merriënboer & Kirschner, 2007). 'Building' a complex skill needs to be guided by an expert, often a teacher or parent. The expert provides temporary support, 'scaffolds', where the child is not yet able to complete a task on their own. The support can take different forms, from a teacher demonstrating a certain task to asking specific questions. Overall, scaffolding happens in interaction. Soon after its introduction, scaffolding was transferred from parent-child interaction to the student-teacher interaction (Cazden, 1979).

The idea of scaffolding in education originates from research with a constructivist perspective on learning (van de Pol et al., 2010). Constructivist theory approaches students as unique individuals with a personal construction of knowledge. Following this perspective, learning means that students add to the construction of knowledge they already have or they adapt the construction to fit new understanding (Illeris, 2018). Therefore, scaffolding is more than helping students complete a task; it means helping them construct a new piece of cognitive, metacognitive, or affective understanding (Lönngren et al., 2017).

5.2.2 The main characteristics of scaffolding

In their review of scaffolding research, van de Pol et al. (2010) found three main characteristics of scaffolding: contingency, fading support, and transfer of responsibility. *Contingency* refers to the tailored support the teacher provides with scaffolding. The difficulty of contingency is finding out what the level of the student is (diagnostic strategies) and connecting to it (scaffolding strategies) (van de Pol, 2012). To find out what the level of the student is, teachers use diagnostic strategies. Contingent teaching takes a constant back and forth between the teacher and a (group of) student(s) to adapt the support to the actual learning process. To do so a teacher holds two mental models at once: their own mental model of the problem and the mental model of the student (Kirschner & Hendrick, 2020).

The two other characteristics of scaffolding are different sides of the same coin. *Fading support* means that the teacher gradually deconstructs the scaffolds they have built. While fading, the student should take control of what they have learned, leading to a *transfer of responsibility* from teacher to student.

Scaffolding strategies consist of intentions (what is scaffolded) and means (how is scaffolding taking place). In their original article, Wood et al. (1976) defined the six intentions of scaffolding that most researchers have been using since (Table 5.1). In addition, Tharp and Gallimore (1988) distinguish six scaffolding means: feeding back, giving hints, instructing, explaining, modeling, and questioning. In this research, we look for the specific means to describe how teachers guide students' problem-solving in complex sustainability challenges based on predefined scaffolding intentions.

TABLE 5.1 Scaffolding intentions according to Wood et al. (1976) and Kirschner & Hendrick (2020).

Intentions of scaffolding	Description
Recruitment	The teacher must somehow elicit the problem solver's interest in the task and the kinds of skills needed to complete it.
Reduction in degrees of freedom	This essentially refers to the teacher simplifying the task to a much smaller number of possibilities so that the tutee is not overwhelmed. For the confused novice, the choice between a right step and an obviously wrong one is much easier than a wide array of different steps which they can't tell apart.
Direction maintenance	Keeping the tutee interested and focused on the task in hand is a vital part of scaffolding, especially when (s)he would experience success on a simpler part of the overall task such as pairing two blocks and want to keep doing that repeatedly as opposed to taking the next step.
Marking critical features	The teacher should mark out or emphasize key milestones in the development of the task. The key thing here is to make visible discrepancies between where the student is at the moment and where they need to go next.
Frustration control	Having empathy concerning the possible frustration of the student is a vital aspect of scaffolding and requires deft skill as there is a danger that if the teacher makes it too easy, then the student can develop too much dependency on the teacher.
Demonstrating	It is not enough to simply model solutions to a task, the effective teacher will perform an "idealization" of the task to be performed. This can be an execution of the problem to be solved by the student, who may have already partially executed the problem. By elaborately performing the task, the teacher allows the student to more easily imitate the steps required to solve the problem.

5.2.3 Scaffolding for sustainability competencies

Scaffolding was already a well-researched field a decade ago and the pedagogical approach remains a widely used concept in educational research (Lönngren et al., 2017; Stone, 1998; van de Pol et al., 2010). In recent years, several scholars in the field of sustainability education started to engage with scaffolding. For example, Lönngren et al. (2017) researched scaffolding in a rubric-based intervention with strong results for cognitive scaffolding. They suggest that future research might focus on further developing scaffolding for metacognitive and affective aspects of sustainability competencies. Furthermore, Peng et al. (2022) researched computer-based scaffolding and found strong results for scaffolding cognitive and metacognitive skills. Specifically, the metacognitive skills (learning about the process of learning) help students to deal with 'not-knowing', the uncertainty in sustainability challenges (Peng et al., 2022).

In previous research (Bohm, Klaassen, den Brok, et al., 2024), we found that different kinds of uncertainty play a role in the complex challenges that students work on in such education: unpredictability, knowledge incompleteness, and knowledge frame multiplicity (Brugnach et al., 2008). Students might feel overwhelmed when confronted with those uncertainties (Lönngren & Svanström, 2015). Although they also develop attitudes, such as empathy and flexibility, to deal with uncertainty in those courses (Bohm, Klaassen, van Bueren, et al., 2024), such learning should be well guided. Therefore, in this research we investigate which scaffolding teachers develop to guide students through different dimensions of uncertainty in sustainability challenges.

5.3 Methods

5.3.1 Educational design research

We approached this research as a series of three design cycles (McKenney & Reeves, 2012). The design cycles took place in a 16-week course called the 'Living Laboratory of Amsterdam', part of the MSc Metropolitan Analysis, Design and Engineering (MSc MADE). The MSc MADE is a joint degree of two universities (the University of Wageningen and the University of Technology Delft) that focuses on urban sustainability. The Living Lab course is a capstone course in the final year of the program, where students work in teams of 4-5 students on a complex sustainability challenge together with a commissioner. Student teams receive guidance from the commissioner they work with, but additionally are coached by an academic teacher. This teacher is responsible for monitoring and assessing the learning process. The aim of this research is to capture the scaffolding teachers use during the coaching sessions.

Each design cycle consisted of three generic design phases. Gravemeijer and Cobb (2013) describe them as: (a) preparing for the experiment, (b) experimenting in the classroom, and (c) conducting retrospective analysis. At the start of the course, the first author gave a workshop on scaffolding strategies to the teachers[11] and set goals with teachers to experiment with the scaffolding strategies in the coaching sessions. After this kick-off, we revisited the teachers three times to collect their use of scaffolding strategies at different moments in the course through a survey and a focus group.

11 At the kick-off workshop, seven of the ten teachers were present. The three teachers that were missing, were sent a recording of the workshop.

5.3.2 Data collection: monitoring design experiments

We monitored the design experiment with two methods (Figure 5.1). First, we used a self-completion questionnaire (Bryman, 2016) with a combination of open-ended and closed questions to collect the perspectives of students and teachers (see Appendix H for the questionnaire questions). This questionnaire was designed to (1) estimate the learning progress of the student team, (2) reflect on how they experimented with scaffolding in their teaching, and (3) set goals for the next coaching session. Parts 1 and 2 of the questionnaire aimed to conduct the retrospective analysis of the design cycle (e.g. Which of the scaffolding strategies did you use during the coaching sessions?) and part 3 aimed to prepare for the next cycle (e.g. Which learning objective is most important to you in the upcoming coach sessions?). The questionnaire was designed in Qualtrics software.

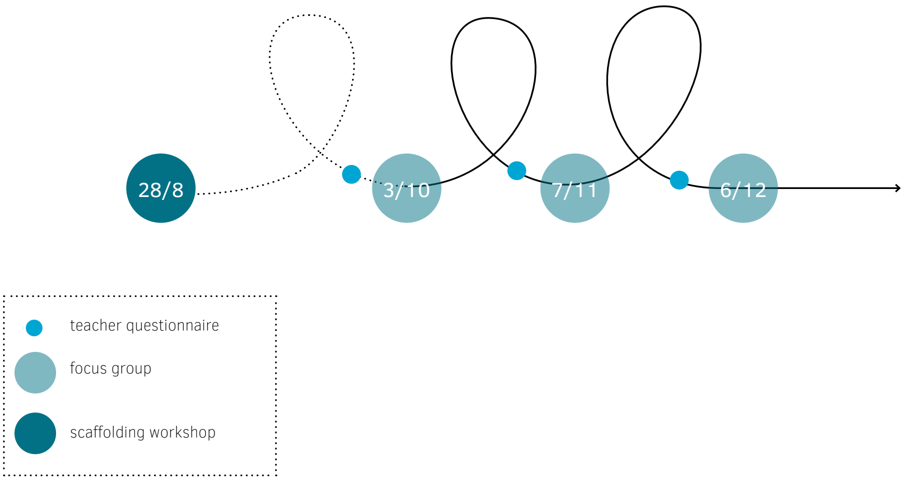


FIG. 5.1 Monitoring process for the three design cycles through questionnaires and focus groups (illustration by author).

The second method we used was observation during the coach check-ins of the course focused on the discussion of the teachers. These check-ins were a regular part of the course, where the ten teachers discussed challenges and prepared the next steps in the course with the course coordinator. In this research, the coach check-ins served as a focus group (Bryman, 2016). The coach check-ins took one hour. The first author observed the teachers during their discussions in the first 45 minutes of the check-in and then moderated a discussion on the use of scaffolding in the next 15 minutes of the course. During the discussion, the first

TOC

author presented the answers of the teachers on the questions Q1.1, Q2.3, Q3.1, and Q3.2 for them to reflect on how they used scaffolding and how they plan to use it in the next cycle.

5.3.3 Data analysis: refining qualitative data in two steps

The results are based on a triangulation of two different data sources: the questionnaires of the teachers and the observations of the researcher during the focus groups. We analyzed the data in two steps based on the analytical framework in Figure 5.2.

First, we coded the qualitative answers on the questionnaires to find the teaching problems and scaffolding in the course. For the teaching problems, we used a codebook based on uncertainty, which was developed and tested in two previous studies (Bohm, Klaassen, van Bueren, et al., 2024; Bohm, Klaassen, den Brok, et al., 2024). This codebook in Appendix J distinguishes uncertainty in three dimensions based on Brugnach et al. (2008): the unpredictability of real-world scenarios (unpredictability), unfamiliar aspects of problems (knowledge incompleteness), and conflicting viewpoints among the people involved (knowledge frame multiplicity). In this study, the teachers reported 25 unique problems throughout the course. 13 of these problems were coded with the a priori codes for uncertainty and 12 were given emergent codes in the category 'other problems.' We used open coding for this category when teachers described a problem that was not specifically related to uncertainty. For the scaffolding strategies, we coded based on the six scaffolding intentions as code groups: recruitment, reduction in degrees of freedom, marking critical features, direction maintenance, frustration control, and demonstration (Appendix K). Within those groups, all codes were emergent. The first author was responsible for the coding and discussed the results with the other authors to calibrate the codes and the code groups.

Second, we observed and discussed the intermediary results we found in the questionnaire answers in the focus groups at different moments in the course. In the results, we present the main themes in their discussion to clarify and contextualize the responses of the survey at that moment in the course. Additionally, monitoring at different moments in time also allowed us to look at how the teachers faded support and transferred responsibility to students.

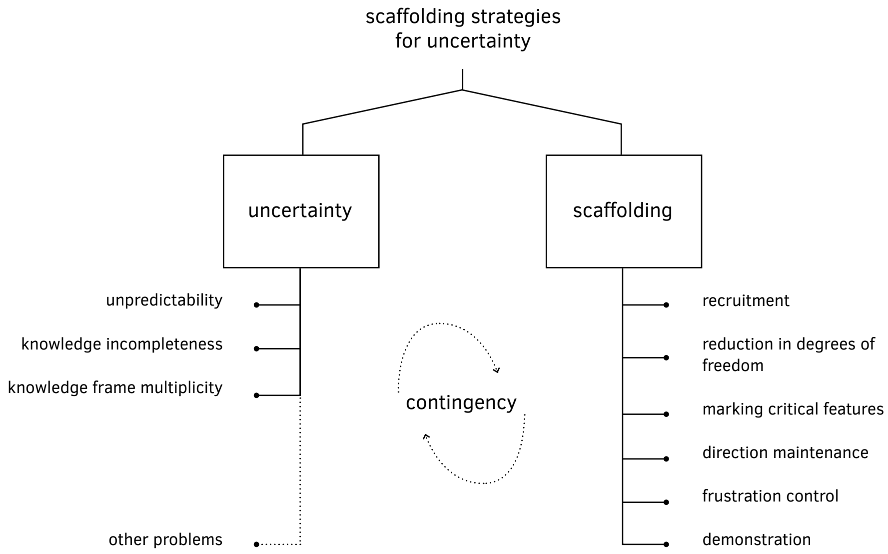


FIG. 5.2 Analytical framework for analyzing scaffolding strategies for uncertainty (illustration by author).

5.4 Results

We present the results in two parts. First, an overview outlines the uncertainties and other problems observed by teachers with their students and the corresponding scaffolding strategies they employed. Second, Section 5.4.2 details the results for three different monitoring moments (after 4, 8, and 12 weeks) in the course.

5.4.1 Overview of the problems and scaffolding throughout the course

The most common uncertainty that teachers encountered was 'knowledge incompleteness' (26). Although an important part of what the teachers were scaffolding was related to uncertainty (57), teachers also had to pay attention to other problems that the students encountered (25).

TOC

The most frequently mentioned problem was ‘theoretical grounding’. Teachers mentioned that students struggled with creating a theoretical framework for several reasons; they found it unnecessary, did not know how to go about it, or felt scared by the academic parts of the project. In the same way, one teacher wrote the living lab format of the course was a challenge, because they, the teachers, did not understand it completely:

‘I am always a bit struggling with the format ‘living lab’ […] I still find it pretty broad, and I don’t feel I ‘master’ this format. So that makes me feel a bit insecure and improvising about how to support them best.’ (1:21)

Additionally, teachers saw that the assignment was unclear to the students (6 times) or that there was unclarity about their role (5 times). In all those cases, students struggled to make decisions on the direction of the research project. On the other hand, teachers also struggled with their own knowledge being incomplete about what the students were doing. In those cases, we coded this as a lack of ‘diagnostic strategies’ (6 times), because teachers sought ways to diagnose what the problems were that students were struggling with.

Furthermore, uncertainty also frequently arose from knowledge frame multiplicity, such as tensions with the commissioner, mentioned 9 times in the questionnaires. Such conflicts arose when the commissioner was absent or unwilling to share necessary information or data with the students. Additionally, one teacher noted that the commissioner’s ideas constrained the students’ freedom within the project:

‘They are working with a well-defined deliverable (instead of a well-defined challenge), which limits their research freedom. I often do not work like this, because I believe students should be able to follow their own interests/passion when exploring a new topic.’ (1:6)

Teachers least often described uncertainty as ‘unpredictability’. In this category, students were uncertain about achieving their goals, the time constraints in the project, or unexpected changes in the project.

TABLE 5.2 Connections between codes for uncertainty that the teachers perceived with the students and codes for the scaffolding they described to deal with this.

		Scaffolding					
		Recruitment	Reduction in degrees of freedom	Direction maintenance	Marking critical features	Frustration control	Demon-strating
Uncertainty	Unpredictability	0	3	2	2	1	2
	Knowledge incompleteness	2	4	3	6	5	3
	Knowledge frame multiplicity	0	3	3	3	5	3
	Other problems	2	1	4	2	2	2

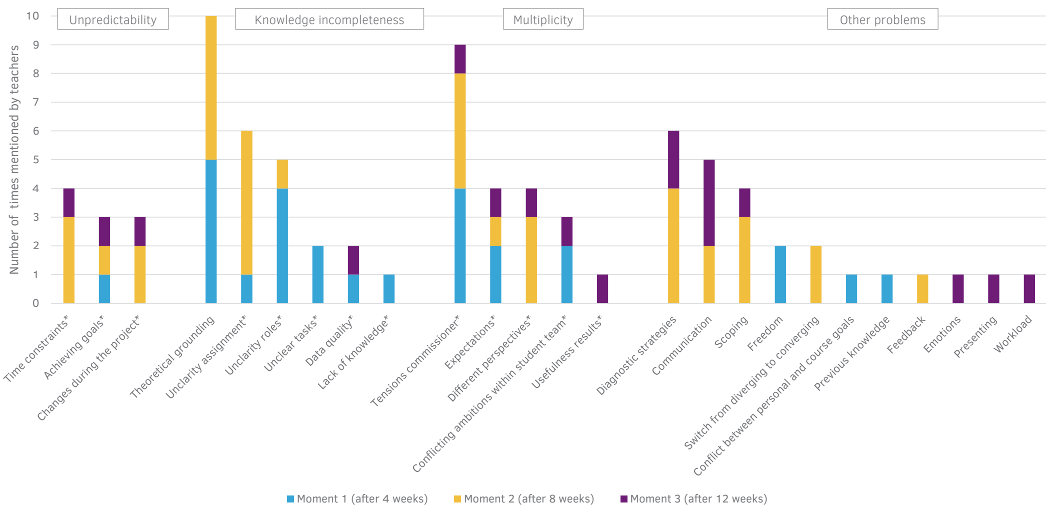


FIG. 5.3 This bar graph shows all the coded problems per category and how often and when they were mentioned by the teachers. All codes with an asteriks (*) were previously mentioned by students in an earlier study in the course.

To respond to these diverse problems, the teachers developed scaffolding to guide students in their problem-solving. Appendix K shows all the scaffolding strategies and their descriptions. Table 5.2 shows how often teachers connected specific problems to specific scaffolding intentions. In other words, how teachers used scaffolding strategies contingently. These were smaller numbers than in Figure 5.3 because teachers also mentioned problems without a specific solution or scaffolding strategy that we could not connect to a specific problem in their answers. We present the most prominent examples for each of the four problem categories.

First, theoretical grounding was mentioned as the most common uncertainty across the student teams. Teachers made use of ‘marking critical features’ scaffolds to guide students, for instance, asking questions about theory and providing feedback. Additionally, they helped students to scope their projects by brainstorming and discussing the consequences of certain research methods, as is illustrated in this quote:

‘The students struggle to find suitable outcomes to present their research. They had several ideas in mind but they didn’t seem to be aligned with what they wanted to achieve. So I provided different examples of outcomes relating them to specific examples while explaining the reasoning/thinking process behind it.’ (2:28)

To scaffold knowledge frame multiplicity and knowledge incompleteness, teachers predominantly used scaffolding for ‘frustration control’. For example, when teachers dealt with tensions that arose from the commissioner (knowledge frame multiplicity), they emphasized to students that it is normal that not everything is clear and that it is a learning process for all of them. Other forms of frustration control would be to offer support, for instance, by joining the students in a meeting with the commissioner.

Lastly, teachers scaffolded unpredictability mainly by ‘reduction in degrees of freedom.’ They helped students by offering an overview of the directions they could choose. One teacher describes that process:

‘Students felt a bit uncertain about to what extent the commissioner’s organization should be incorporated into research questions. I told them that they could go a couple of different directions and that the introduction part should be adjusted in a way that aligns with the direction they would like to go.’ (3:10)

To summarize the results from the questionnaires, the most prominent problems observed by teachers were theoretical grounding, tensions with the commissioner, diagnostic strategies, and unclarity of the assignment. These problems were mainly scaffolded through frustration control, marking critical features, and direction maintenance.

5.4.2 Scaffolding at three different moments in the course

To gain a better understanding of fading support and transfer of responsibility from teachers to students, this section describes which scaffolds were important at different moments in the course. The results in this section triangulate the survey responses with the focus group at the beginning, middle, and toward the end of the course. First, we give a brief overview of what specific scaffolding strategies emerged in both survey and focus groups and then, we present the results for each three design cycles in more detail.

Overall, frustration control was the only scaffolding strategy that faded during the course and that might have led to a transfer of responsibility to students (Figure 5.4). In the early stages of the course (after four weeks), teachers said frustration control was crucial to mediating the tensions with the commissioner and the unclarity of the assignment and their roles. In the middle of the course (after eight weeks), teachers said that the students struggled with the theoretical grounding of the living lab projects. Teachers disagreed on the quality and applicability of common living lab frameworks, but also on how students should make use of living lab and other theoretical backgrounds in their studies. This conflict was not yet resolved in scaffolding strategies. At the end of the course (after twelve weeks), teachers focused on maintaining the students' direction they chose earlier in the project and prepared them for the final assessment. Additionally, teachers were more concerned with measuring the progress on the personal learning objectives of the students at this stage.

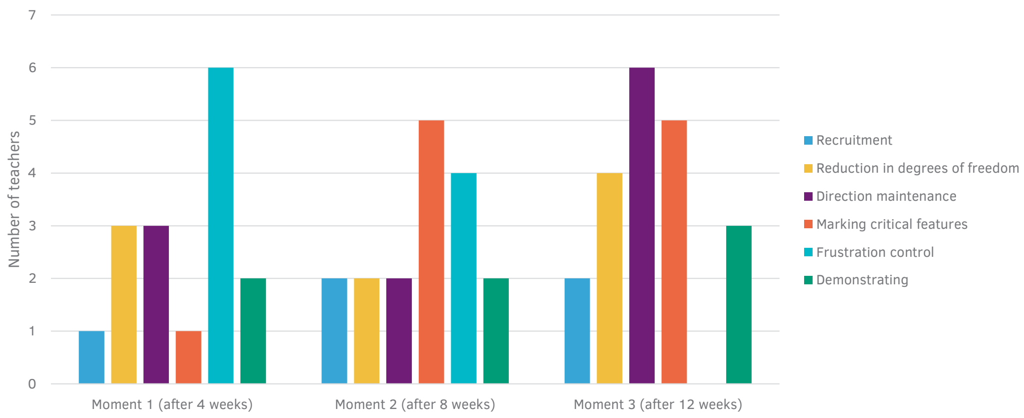


FIG. 5.4 This bar graph shows how the six scaffolding strategies were reported in the survey after each design cycle. Frustration control is the only category that faded out during the course.

TOC

5.4.2.1 Design cycle 1 (after 4 weeks)

During the first focus group, teachers discussed three main topics. First, they discussed co-creation, because this was what students were most concerned with in their meetings with the teachers. However, the teachers would like students to get interested in co-creation later in the course as at this stage their focus should be on plan development. One teacher mentioned this in the questionnaire as a difference in perspectives:

‘There is a small gap between what students feel most excited about (practical activities such as organizing co-creation and co-design sessions) and what I am used to communicating with students (academic stuff such as literature review, data collection, and methodology, etc.)’ (1:14)

Although this quotation shows that at this stage teachers were already sensing tensions between practical and academic activities in the course, they did not talk about this during the focus groups.

Second, teachers planned conversations with the students individually to discuss their personal development goals in the course. These conversations have helped the teachers to gain a better understanding of the passions and interests of individual students in their group. Making sure that students can pursue a direction that they are passionate about, is important to the teachers to avoid frustration. Figure 5.4 shows that frustration control is the most prominent scaffolding strategy in this part of the course. One of them describes this in the questionnaire:

‘In terms of frustration control, I provided multiple suggestions that would allow them to pursue a direction they are passionate about while preventing tensions with the commissioner.’ (1:8)

Third, several teachers encounter challenges in monitoring their students’ activities. While the questionnaire did not reveal any problems with diagnostic strategies, some teachers noted during the focus group discussions that students were not actively seeking their guidance. Within these discussions, the course coordinator contemplated whether an excessive emphasis on fostering student independence at the beginning of the course may have inadvertently contributed to this issue. Consequently, some teachers find themselves uninformed about their students’ progress and consequently unable to offer appropriate guidance.

5.4.2.2 Design cycle 2 (after 8 weeks)

After eight weeks, all teachers in the focus group agreed that relating theory to practice was the most difficult aspect of the living lab for students. The teachers perceived this issue in different ways. Initially, some teachers mentioned that living lab theory is not very helpful to the students when they are developing a tool or a product. The theory does not help them to make decisions. Moreover, some teachers say they do not understand the theory themselves. During the focus group, a teacher says:

'Does the theory really help anybody?' (focus group 2)

In contrast, some teachers argued that it does help to structure the living lab process and the report that students write during the course. One teacher suggested looking at the characteristics of the living lab and discussing with students how these reflect in their projects, because living labs never contain all these characteristics. Another teacher suggested discussing why students need to make use of design thinking, because that explains the purpose of the living lab to them.

Although the teachers' discussion on theoretical grounding is extensive, in the questionnaires they did not describe scaffolding strategies to solve this issue as extensively. In the questionnaire, teachers mentioned 'reduction in degrees or freedom' (simplifying how to write down theory in the report) and 'marking critical features' (by giving feedback on and asking questions about the theory) as main strategies.

Next to the theory discussion, the teachers talked about taking time to reflect with the students and slowing them down in the living lab process. Almost all teams started to do co-creation sessions as part of their living lab at this point in time. Particularly after co-creation sessions, the teachers wanted students to maintain their direction and they helped them to bring the project aims back into focus. One teacher used role-play to do this:

'Sometimes, I have to demonstrate the process and ask them to do role-play in order for them to digest co-creation processes.' (2:16)

5.4.2.3 Design cycle 3 (after 12 weeks)

In the final focus group, the teachers' shared understanding was that the student teams were doing well and that not much scaffolding needed to be done. In contrast, the questionnaire results in Figure 5.4 show that teachers used scaffolding, mainly for direction maintenance.

At the same time, frustration control was brought down to a minimum. Teachers used frustration control before as a scaffold for problems, such as tensions with the commissioner or unclarity of the assignment. Accordingly, Figure 5.3 shows that these problems were resolved at design cycle 3. Instead, teachers focused on keeping the student team on the chosen path. For example, this teacher described direction maintenance as keeping things simple for the students:

'Students want to make a website as a delivery. I saw that there is an idea to make something complex. I suggested that a simple, clickable presentation would be enough, considering the time left and other deliveries to be produced.' (3:19)

Additionally, the personal learning objectives concerned the teachers. During the focus group, most of the discussion was about the assessment, which consisted of many different parts. More specifically, the teachers wondered how to go about the assessment of the personal learning objectives, how to incorporate the peer review of the students, and when to plan the final meeting with the students individually. They also found it difficult to know how to measure the progress on the personal learning objectives. At the same time, many teachers paid attention to the students' ambitions, passions, and personal learning objectives during the course. One teacher also aimed to connect what they have learned to the next step in the curriculum:

'I will connect what they are doing right now to building their professional/personal skills for writing their thesis and the job market as well.' (3:32)

5.5 Discussion

This study used a sixteen-week challenge-based course called the 'Living Lab' to investigate how teachers use scaffolding to guide students toward problem-solving in uncertainty. During the course, we monitored the contingency in how teachers developed scaffolding strategies when they were confronted with a teaching problem related to uncertainty. The teachers reflected on their teaching and coaching of the students groups every four weeks in a qualitative survey and a focus group.

In summary, the most prominent problems observed by teachers were theoretical grounding, tensions with the commissioner, and unclarity of the assignment. These problems were contingently scaffolded through frustration control, marking critical features, and direction maintenance. Additionally, teachers struggled to find out what happened with the student team and they reported a lack of diagnostic strategies to gather that information. The focus groups showed how frustration control was the only scaffolding strategy that faded throughout the course.

This discussion section discusses the challenges of teachers when educating in uncertainty, which scaffolding strategies might be important to consider for CBL, and what scaffolding strategies might still be missing from current teaching practice. Furthermore, we touch upon the limitations and suggestions for future research that arise from this study.

5.5.1 Challenges of uncertainty in challenge-based learning

The results of this study suggest that the issue of theoretical grounding needs further attention. As the teachers in this case did not agree on which way to make use of theory within the transdisciplinary projects of the students, it is difficult to teach students how to do this. Popa et al. (2015) propose that transdisciplinary research needs a combination of conventional and transformative approaches, yet this might confuse students. Similarly, teachers with experience in this area are difficult to find, because the approaches to transdisciplinarity in the university are still quite uncommon (Friman et al., 2021).

Furthermore, the tensions with the commissioner, unclarity of roles and the assignment challenge teachers' adaptivity as they need to decide how much support they would like to offer and to what extent they believe that struggle and failure are a productive part of the learning process (Kapur, 2014). Teachers can provide structure (Wijnia et al., 2011), but this might lead to a loss of the uncertainty that students should learn to structure themselves (Savin-Baden, 2014). Savin-Baden (2014) argues that a lack of agreement on the pedagogical ideas in such learning configurations does not improve the quality of education.

5.5.2 Scaffolding strategies for cognitive, metacognitive, and affective learning objectives

The main scaffolding strategies teachers used to scaffold students in the Living Lab were intended to mark critical features, maintain the direction of learning within the project, and manage frustrations. These three scaffolding strategies each support students in different types of learning activities (van de Pol et al., 2010). First, marking critical features, such as giving compliments or checking if feedback is well understood, supports students' cognitive activities. The rubric-based study of Lönngren et al. (2017) is in line with this finding. At the same time, they conclude that cognitive processes are not sufficient for complex problem-solving that also requires affect and metacognitive activities (Molenaar et al., 2014).

In our study, the second main scaffolding strategy, direction maintenance, should support students' metacognitive activities, where they learn about the process of thinking (van de Pol et al., 2010). In a previous study, we researched how students develop metacognitive abilities to deal with the uncertainty of sustainability challenges and found that social assistance by their teachers is important to the support of their learning (Bohm, Klaassen, van Bueren, et al., 2024). In this study, we found that teachers can support metacognition through direction maintenance, such as discussing the effects of choosing certain methods or visualizing connections between the results. Not only teachers but also computers can provide such scaffolding for metacognition (Peng et al., 2022). However, both Peng et al. (2022) and Lönngren et al. (2017) found that supporting students' affect through scaffolding needs further attention, neither rubrics nor computers are sufficient as support tools for affect.

The third scaffolding strategy, frustration control, supports students' affect. It was the only scaffolding intention that faded out during the course. Students can be overwhelmed with uncertainty at the start of the course (Lönngren et al., 2017), but as they decide upon a specific direction to approach the challenge and their assignment is clarified, also the frustrations decrease and teachers start using other scaffolding strategies that focus more on the cognitive and metacognitive learning activities. How to provide effective scaffolding for affect is scarcely studied through an empirical lens (Zheng et al., 2023) and difficult to research (van de Pol et al., 2010). At the time of writing, several engineering education researchers explore pathways to research emotions in sustainability education (Lönngren et al., 2023).

Our study implies that emotion is an important factor when learning to deal with uncertainty. Especially at the start of the course, when assignments and roles are unclear and different perspectives can be overwhelming, teachers need tools to scaffold frustration control. This scaffolding should aim for students to, in time, be able to address their emotions and support others in their team when faced with climate anxiety and uncertainty in sustainable transitions.

5.5.3 A lack of diagnostic strategies for team dynamics and personal development

Furthermore, teachers encountered difficulties in understanding student team dynamics and the personal development of individual students in the group, which hindered the contingency of their teaching. The teachers lacked diagnostic strategies to assess the situation. Although diagnostic strategies are essential for teachers to be able to provide scaffolding, research in this direction is limited (van de Pol et al., 2010). Hardy et al. (2022) found that even if teachers made use of the appropriate diagnostic strategies, they rarely acted adaptively. This adds to the general idea that scaffolding is an advanced teaching practice and requires the professionalization of teachers (Kirschner et al., 2022). In this educational design research, teachers were able to evaluate their behavior and through reflection professionalize their teaching as part of the research. We recommend other researchers and teachers to collaboratively work on educational research this way and at the same time advance teaching practice. Especially in challenge-based learning, where students are frequently asked to set their own learning goals and teachers need to guide those personal objectives adaptively (van Ravenswaaij et al., 2022), scaffolding offers a concrete approach to start professionalizing such guidance.

TOC

5.5.4 Limitations and suggestions for future research

At the same time, the EDR approach to research does present some limitations. Scaffolding is always difficult to measure but most studies are based on observations during classroom interaction (van de Pol et al., 2010). In this study, we based our findings on the experiences of teachers and their reflections on those experiences. Although this phenomenological approach allows for a deeper understanding of the teacher perspective, direct observations of the interactions by a researcher might provide a deeper understanding of what happens in the learning environment. Future research in the context of transdisciplinary education would benefit from observations, as well as a further examination of teaching for the uncertainty in sustainable transitions. Specifically, the perspective of the student on some of the issues found in this study would be relevant for future research, as these might not necessarily correspond with what teachers experience (den Brok et al., 2006).

5.6 Conclusion

In transdisciplinary education, how to teach complex competencies, such as dealing with uncertainty, challenges teachers. In this design-based study, we investigated the scaffolding teachers used to guide students when problem-solving in uncertainty by answering the question: What scaffolding strategies do teachers use over time to guide students toward problem-solving in uncertainty? Based on the scaffolding strategies the teachers in this study described, other teachers might advance their practice of guiding students through uncertainty and other problems they face in transdisciplinary work.

This study contributes to a further scientific understanding of what teachers do when they become coaches in transdisciplinary courses. Particularly, they do so by scaffolding frustration control, marking critical features, and maintaining students' direction at different moments in time. It suggests scaffolding strategies are time-bound and possibly need to be linked to pivotal moments in the learning process. Further research on scaffolding might explore some of the issues we found more extensively, such as which diagnostic strategies could be used in an early stage, and how to scaffold theoretical understanding and personal learning objectives in a transdisciplinary environment.

In teaching practice, this study might inform and inspire teachers to identify, reflect, and improve their scaffolding in challenge-based courses, such as the living lab, or any other form of constructivist learning environment. For example, teachers might collaboratively use the specific scaffolding means in Appendix K to evaluate their teaching practice. Ultimately, we aspire for this study to contribute to the growth of teachers as adept coaches for transdisciplinary approaches in sustainable higher education.

6 Conclusion and Discussion

In engineering education, transdisciplinary courses integrate sustainability challenges, and their inherent uncertainty, into education. Such uncertainty might be confusing and affect the self-confidence of students yet, at the same time, it might offer an opportunity to learn problem-solving for complex, societal challenges. This dissertation is motivated by a lack of understanding of how uncertainty impacts the design of transdisciplinary courses. It aims to understand how to design education where students learn to deal with uncertainty; ultimately, to better prepare both students and teachers for a future of sustainable transitions.

The four empirical studies in this dissertation each study a different aspect of the design of transdisciplinary courses. Following the model of van den Akker et al. (2013) for educational design research, the first three studies investigate the intended (Chapter 2), implemented (Chapter 3), and attained learning (Chapter 4). The final study is based on a design intervention with teachers (Chapter 5). Several transdisciplinary courses are case studies in this dissertation. Chapter 2 studies the intended learning by taking a broader look at the aims and ideals of teachers in several transdisciplinary courses taught at Delft University of Technology and AMS Institute in Amsterdam. Then, Chapters 2 to 5 zoom in on one specific course: the Living Lab course as part of the master program MSc MADE (Metropolitan Analysis, Design, and Engineering). The uncertainty of the implemented challenges in the Living Lab is studied in Chapter 3. The way students attain the metacognitive competency of 'dealing with uncertainty' is studied in Chapter 4. In Chapter 5, it is studied how the teachers in the Living Lab course develop adaptive guidance, also called 'scaffolding,' for students when they are working in uncertainty.

Overall, the four research questions of the empirical studies in this thesis are:

1. How are learning objectives described in transdisciplinary courses concerning urban sustainability challenges and how does this relate to the aims of the teachers? (Chapter 2)
2. What are the characteristics of uncertainty in urban sustainability challenges implemented in the Living Lab course? (Chapter 3)
3. What uncertainty do students encounter when working on urban sustainability challenges (metacognitive awareness) in the Living Lab course and how do they deal with it (metacognitive regulation)? (Chapter 4)
4. What scaffolding strategies do teachers use over time in the Living Lab course to guide students toward problem-solving in uncertainty? (Chapter 5)

The answers to the research questions in these studies contribute to an interrelated perspective on what uncertainty does to the challenges, students, and teachers and how they respond to it. In this final chapter, I synthesize the findings of these studies to answer the main research question:

How can transdisciplinary education be designed so that students learn to deal with uncertainty in sustainability challenges?

The conclusion chapter is divided into four parts. First, it summarizes the main findings of the four studies included in this dissertation. Based on the main findings, I propose six design principles for uncertainty education. Third, the discussion is structured by the three key insights of this dissertation on how the dimensions of uncertainty change during the course, what most students struggle with, and what this demands of the role of the teacher. Fourth, I discuss the limitations of the research and how they inform future research on uncertainty, transdisciplinarity, and sustainability in education. At the end of this chapter, a few final words conclude the dissertation.

TABLE 6.1 Overview of research aims, questions, and main findings of the four studies

Research aim	Research question	Main findings
To understand the intended aims and ideals of teachers in transdisciplinary courses	How are learning objectives described in transdisciplinary courses concerning urban sustainability challenges and how does this relate to the aims of the teachers? (Chapter 2)	– Teachers ideally use transdisciplinary courses to teach problem-solving in an integrative manner. Additionally, they want the teaching to be centered on authentic issues that are topical and relevant to students' lives. – Although metacognitive and analysis learning objectives were missing in the course descriptions, teachers aim to teach them in transdisciplinary courses. – Transdisciplinary courses position extra-academic actors in different roles. In most investigated courses the role remained at a level of client participation.
To understand in what ways sustainability challenges implement uncertainty in transdisciplinary courses	What are the characteristics of uncertainty in urban sustainability challenges implemented in the Living Lab course? (Chapter 3)	– The Living Lab course engages with three dimensions of uncertainty: unpredictability, knowledge incompleteness, and multiple knowledge frames. – Tension in the course arises when students have to use conventional approaches and transformative approaches simultaneously to deal with those uncertainties. – Possible approaches to uncertainty in complex problems: systems thinking, designing adaptive solutions, experimenting, mapping, and co-creating.
To understand which metacognitive strategies students attain when they respond to uncertainty in transdisciplinary courses	What uncertainty do students encounter when working on urban sustainability challenges (metacognitive awareness) in the Living Lab course and how do they deal with it (metacognitive regulation)? (Chapter 4)	– Students most often encounter the uncertainty dimension of knowledge frame multiplicity. – Students seek social assistance from teachers, team members, and, to a lesser extent, their commissioner. – Students employ coping mechanisms to deal with feeling stuck. – Students develop attitudes toward uncertainty, such as flexibility, empathy, and relativism.
To design with teachers scaffolding strategies to guide students through uncertainty in transdisciplinary courses	What scaffolding strategies do teachers use over time in the Living Lab course to guide students toward problem-solving in uncertainty? (Chapter 5)	– In the early stage of the course, teachers use frustration control to scaffold tensions with the commissioner and unclarity of the assignment. – Later in the course, the approach to theory leads to uncertainty, but teachers lack agreement to be able to coherently scaffold this. – At the end of the course, both diagnostic and scaffolding strategies for personal development become more important.

6.1 The main findings per sub-question

6.1.1 How are learning objectives described in transdisciplinary courses concerning urban sustainability challenges and how does this relate to the aims of the teachers?

Chapter 2 investigated the intended learning in several transdisciplinary courses at Delft University of Technology and AMS Institute. The study in this chapter aimed to get a better understanding of what students are meant to learn from working on real-world challenges and how far-reaching the collaboration with urban actors in these courses was. To study the intentions of teachers with such courses, we compared the formal intentions of 8 courses in their course descriptions with the aims and ideals that 7 teachers described in interviews.

Overall, teachers in the study wanted to use their transdisciplinary courses to teach problem-solving in an integrative manner. Additionally, they aim for their teaching to be centered on authentic issues that are topical and relevant to students' lives. These ambitions for the course were aligned between the course descriptions and the interviews with the teachers. However, the teachers also described intentions that were not written down clearly in the course descriptions and those misalignments were visible in the learning objectives and on the level of participation.

In the learning objectives, the teachers seldom defined the analyzing skills or the metacognitive knowledge that they aimed for the students to develop in their courses. For example, the metacognitive learning objectives, such as learning to deal with biases and values of others or getting to know one's strengths and weaknesses in collaboration, were often absent in the course descriptions, although teachers deemed them important for transdisciplinary work. It shows that teachers are looking for a vocabulary of learning objectives that fits their transdisciplinary intentions.

Furthermore, the study introduced three levels of participation to analyze to what extent different transdisciplinary courses intend to involve extra-academic actors. The study found that seven of the eight investigated courses were designed for extra-academic actors to participate at a distance or as a client. Rarely is a course intended to lead to a collaborative partnership between the city and students. Although some teachers would like to collaborate more actively with extra-academic actors, they are limited by a lack of time and resources.

In conclusion, transdisciplinary courses ideally teach integrative problem-solving through participation of extra-academic actors, whether they participate on a distant, client, or partner level. Further attention needs to go to the learning objectives related to analysis and metacognition in such problem-solving for teachers to clarify the aims of the course.

6.1.2 What are the characteristics of uncertainty in urban sustainability challenges implemented in the Living Lab course?

From Chapter 3 onwards this dissertation zooms in on uncertainty in the specific case study of the Living Lab course. **Chapter 3** analyzes uncertainty in the challenge descriptions of commissioners in the course. We investigated the nature of uncertainty in 48 challenge descriptions used in the Living Lab course between 2018 on 2022. Through document analysis, we reviewed to what extent uncertainty was part of those challenge descriptions and which approaches students were expected to use to deal with those uncertainties. The analysis is based on a framework for uncertainty as in the work of Brugnach et al. (2008) with three dimensions: unpredictability (uncertainty because of societal processes or technological surprises that are sometimes impossible to predict), knowledge incompleteness (uncertainty because of a lack of information, theoretical understanding, or the data is unreliable), and knowledge frame multiplicity (uncertainty because the people involved might have different ways of perceiving the problem). Additionally, we analyzed the difficulty level of the uncertainty and distinguished between uncertainty of clear, complicated, or complex difficulty.

The study showed that in almost all challenges students are likely to encounter some level of unpredictability, knowledge incompleteness, and knowledge frame multiplicity. To deal with unpredictability, commissioners suggested students work on solutions that are resilient, adaptive, modular, flexible, or open. To deal with knowledge incompleteness, conventional scientific approaches were described by the commissioners, such as collecting and mapping data, but commissioners also suggested transformative methods, such as field-testing, trial-and-error approaches, and living labs as experimentation spaces in the city. Lastly, to deal with multiple knowledge frames, students were expected to do stakeholder mapping and co-create solutions with residents of the buildings and neighborhoods that were involved in the challenge.

Although almost all challenges included all three uncertainty dimensions, they did not all describe them on the same difficulty level. Most challenges dealt with knowledge incompleteness on a complicated level and, on a complex difficulty level, students in the course would most frequently encounter multiple knowledge frames. To work on the complicated issues, commissioners suggested conventional research methods, yet for the complex issues they expected students to be able to experiment with transformative approaches to research. Students are likely to experience tensions in the course due to the commissioners' mixed expectations of using such transformative approaches to research in combination with conventional approaches.

This study establishes that the three uncertainty dimensions defined by Brugnach et al. (2008) are also part of transdisciplinary courses when they integrate sustainability challenges. Furthermore, this study implies that more clarity should be given to which (combination of) approaches that are being taught to students by means of those challenges, so commissioners, students, and teachers might align their expectations.

6.1.3 What uncertainty do students encounter when working on urban sustainability challenges (metacognitive awareness) in the Living Lab course and how do they deal with it (metacognitive regulation)?

Chapter 4 investigated what metacognitive strategies students attained while dealing with uncertainty in the Living Lab course. We aimed to further specify the kind of metacognitive learning that is necessary to deal with uncertainty. To this end, we interviewed 9 students at three different moments in the Living Lab course (a total of 27 interviews). To analyze the awareness of uncertainty, we used the analytical framework with the three dimensions of uncertainty from Chapter 3. To describe the regulation of uncertainty, we used open coding, as not many other studies have investigated the regulation of uncertainty in education before.

The results showed that students most often were aware of the uncertainty of multiplicity in the challenge, where different people had different perspectives. Furthermore, throughout the course, students became increasingly aware of the unpredictability of the challenge, such as changes during the project or the dynamics of the problem. For students, the lack of knowledge remained the same during the course, which does not mean that they did not gain new insights but rather that new insights uncovered new knowledge gaps for them.

TOC

We found that students used three types of metacognitive regulation to deal with uncertainty. First, students seek social assistance from the people around them. They looked for emotional support and practical advice from teachers, team members, and, to a lesser extent, their commissioner. As students experienced tensions with the commissioner as a source of uncertainty, they looked for other people to help them resolve that tension. Therefore, peers and teachers have a crucial role in learning to deal with uncertainty.

Second, students intentionally employ small coping mechanisms to deal with the feeling of being stuck. In addition to talking about it with peers, they ask for feedback on a specific task or take a break from their work to do sports and take their mind of uncertainty.

Third, students changed or further strengthened their attitudes as a response to not knowing. Students developed flexibility and acceptance of conflict or failure as positive attitudes toward uncertainty. As a response to multiplicity, students can also develop relativism and lose confidence in what they are doing. In such cases, uncertainty in education can have the unwanted effect of discrediting the role of scientific research in general and create a sense of hopelessness.

This study showed how students are capable of self-regulating uncertainty and, at the same time, how they seek help from commissioners, peers, and coaches to deal with uncertainty. Dealing with uncertainty, especially dealing with multiple knowledge frames, is not an individual activity. Additionally, learning to deal with uncertainty forces students to reflect on their attitudes toward uncertainty.

6.1.4 What scaffolding strategies do teachers use over time in the Living Lab course to guide students toward problem-solving in uncertainty?

Chapter 5 returned to the perspective of teachers in transdisciplinary courses and investigated how they can adapt their teaching to offer the social assistance that students look for when dealing with uncertainty. In this design-based study, we monitored how 10 teachers developed scaffolding strategies based on a workshop they received before the course began. Through 3 qualitative surveys and 3 focus groups conducted every four weeks, teachers reflected on their teaching practices and coaching strategies. We used scaffolding theory to collaboratively explore with teachers how they adapted their teaching to the uncertainties students encountered in the course.

TOC

The study showed that teachers most often encountered the uncertainty of knowledge incompleteness, because of a lack of theoretical grounding in the way students were working. Teachers noted that students had difficulties in developing a theoretical framework for various reasons: some deemed it unnecessary, lacked guidance on how to approach it, or felt intimidated by the academic aspects of the task. Furthermore, the teachers saw students struggle with the expectations of the commissioner. Teachers least often described uncertainty as unpredictability.

Overall, the main scaffolding strategies teachers used to guide students in the Living Lab were intended to mark critical features (to scaffold knowledge incompleteness), maintain the direction of learning within the project, and manage frustrations (to scaffold knowledge incompleteness and knowledge frame multiplicity) but teachers also adapted their focus during the course. In the early stages of the course, that guidance was aimed at frustration control due to the unclarity of the assignment and tensions with commissioners. As students progressed in the course, they were confronted with the tension between conventional and transformative approaches and teachers noticed their struggle with establishing a theoretical grounding for their projects. At the end of the course, teachers moved their scaffolding to direction maintenance. At the same time, teachers were concerned with the personal learning objectives of students but did not know how to measure their progress on those objectives.

In both Chapter 4 and 5, the uncertainty dimensions change over time in the course and scaffolding, as adaptive guidance, allows teachers to deal with that. Teachers scaffold not only cognitive, but also metacognitive and affective learning objectives, such as how to deal with frustration. Furthermore, this study implies teachers lack the diagnostic strategies they need to guide personal development and group dynamics in transdisciplinary courses.

6.2 Six design principles for educating uncertainty in transdisciplinary courses

At the start of this research, not many studies had investigated uncertainty as a concept in transdisciplinary courses, although such courses are increasingly part of higher education (Gibbs, 2017). To design transdisciplinary education where students learn to deal with uncertainty in sustainability challenges, I propose an explorative model for educating uncertainty in Figure 6.1. It suggests how uncertainty can lead to a productive struggle that challenges uncertainty attitudes, while students learn integrative problem-solving in a complex context. Through social assistance from peers, teachers, and other support mechanisms that struggle can become a well-guided learning journey.

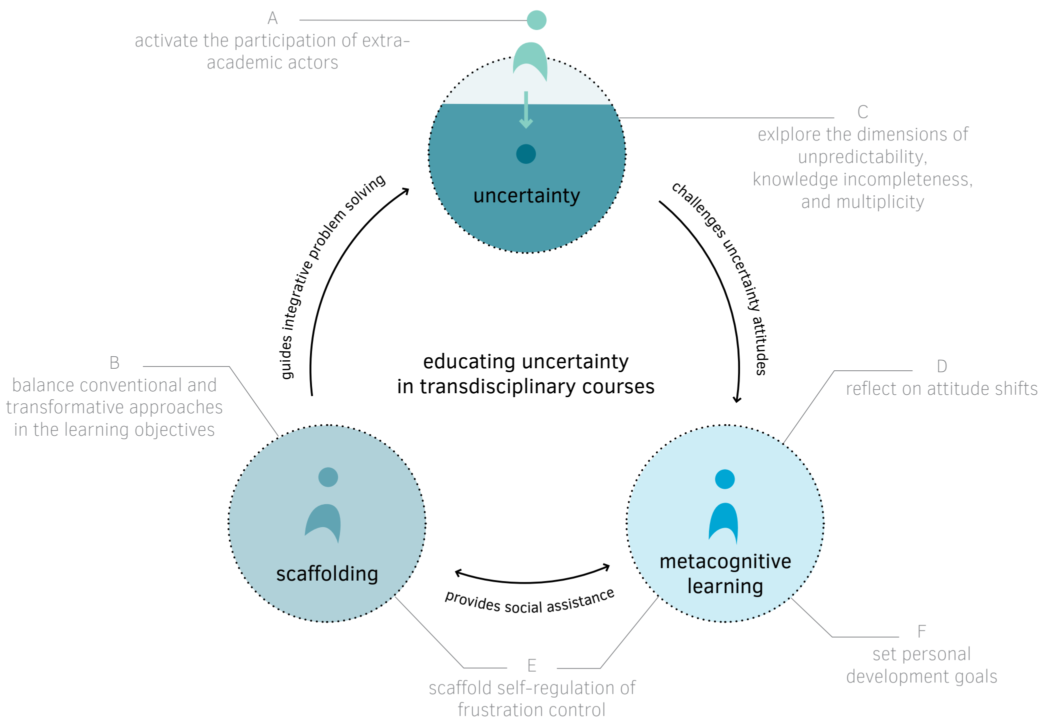


FIG. 6.1 Illustration of the design principles for educating uncertainty in transdisciplinary courses.

Additionally, this research results in six design principles that inform other teachers, students, and commissioners that are already working in this complex field of educational innovation on a daily basis. These design principles are a combination of the main findings of this research and the practical experiences of people involved in the research (Kali et al., 2009). Design principles A and B deal with the initial stages of the course design where it is important to pay attention to the (cognitive, metacognitive, and affective) learning objectives and the way extra-academic actors will be involved in relation to uncertainty (Chapters 2 and 3). Then, design principles C and D are based on the findings that show how uncertainty changes during the course and how the attitudes towards uncertainty can be made more explicit (Chapters 3 and 4). Lastly, design principles E and F suggest how course design might better facilitate learning to deal with uncertainty by paying attention to personal development and emotions (Chapters 2, 4, and 5).

A **Activate the participation of extra-academic actors:** Involvement of extra-academic actors, for instance as commissioners, is crucial in transdisciplinary education. There are different ways participation can be shaped. The framework in Chapter 2 presents three levels of involvement of participants, ranging from low to high involvement: distant, client, and partner. This framework could be used to consider the level of participation from other actors involved in the course, especially in relation to the aims and ideals of the course. If transdisciplinary courses are intended to teach students to deal with different dimensions of uncertainty, active participation from actors as partners will allow them to encounter all these dimensions.

B **Balance conventional and transformative approaches in the learning objectives:** Formulate learning objectives that describe the analytical skills students need to learn from dealing with the uncertainty in the challenge and clarify the expectations of theoretical grounding in the project. Such analysis might be applied to conventional data collection methods, such as interviews and observations, but they can also be part of transformative approaches to research, such as systems thinking, experimenting, mapping, and co-creating. Additionally, formulate learning objectives that describe metacognition as the knowledge object that students attain during the course, for instance, by reflecting on uncertainty with peers or setting personal learning objectives.

C **Explore the dimensions of uncertainty (unpredictability, knowledge incompleteness, and knowledge frame multiplicity):** The framework in Chapter 3 presents the three dimensions of uncertainty on different difficulty levels: clear, complicated, and complex. This framework allows students and teachers to recognize which uncertainties are most prominent in a sustainability challenge at different moments in the course. Additionally, the framework could be used to define the complexity and uncertainty in the challenge with potential commissioners before the start of the course.

D **Reflect on attitude shifts:** Make time for the discussion and development of attitudes toward uncertainty. Students can develop attitudes such as flexibility, empathy, and relativism. These could be strengthened and regulated when they become a more explicit part of the course.

E **Scaffold self-regulation for frustration control:** Develop support mechanisms, such as scaffolding (adaptive guidance) throughout the course for frustration control. Especially at the start of the course, there is a need for such support mechanisms. In general, support mechanisms can be offered by teachers, but also by peers, because students have their small coping mechanisms for uncertainty and they might be willing to share those if the right atmosphere is created for that exchange.

F **Set personal development goals:** Integrate goal setting regarding personal development to increase self-awareness and self-knowledge. Only if you know what you know can you become aware of what you don't know. By clarifying the way that goal setting happens, teachers can become more involved in guiding personal development throughout the course. This way learning and teaching of metacognition will go beyond the common reflection report at the end of the course and can start to support dealing with uncertainty during the course as well.

6.3 Discussion

This section discusses the main findings and their implications for the theory and practice of transdisciplinary education. We discuss three overarching insights based on the findings that we consistently found in several of the studies: how the dimensions of uncertainty change during the course (6.3.1), what most students struggle with when confronted with uncertainty (6.3.2), and how the role of the teacher in such education changes and demands new skills (6.3.3).

6.3.1 The dimensions of uncertainty change during transdisciplinary courses

This dissertation operationalized uncertainty in sustainability challenges from three perspectives based on the work of Brugnach et al. (2008): unpredictability, knowledge incompleteness, and knowledge frame multiplicity. We found in Chapter 3 that these three dimensions of uncertainty are present in almost all sustainability challenges at the start of the course. However, once students started working on the challenge in collaboration with the commissioners and guided by the teachers, some dimensions of uncertainty became more prominently part of the learning process. In other words, some dimensions of uncertainty are dominant in different stages of the course.

At the start of the course, both students and teachers consistently described knowledge frame multiplicity as a challenging dimension of uncertainty for students. Students described how within their challenge different perspectives on the problem, approach, or solution conflicted with each other and how these uncertainties did not decrease over time. Teachers mainly noticed the tensions with the commissioner but also saw that students struggled with the different perspectives in and outside their project team. Integrating different perspectives and reconciling values and preferences is central to transdisciplinary research in sustainability science (Lang et al., 2012) and it should come as no surprise that that is what students and teachers constructively struggle with in this course.

Toward the end of the course, students in Chapter 4 became more aware of unpredictability. For them, it was easier to see the unexpected developments in the project in hindsight. For the teachers in Chapter 5, unpredictability played a negligible role. To them, this was mainly about the time constraints of their availability to the students. Neither teachers nor students refer to the unpredictability as part of a dynamic problem, where behavior is chaotic and impossible to predict (Brugnach et al., 2008). Although this kind of uncertainty might be part of the challenges at the start of the course, it might be difficult to incorporate it in the problem-solving later on in the course.

A more unexpected outcome of this uncertainty research is the emergence of the dimension of knowledge incompleteness during the course. Traditionally, engineering education focuses on how to cope with a lack of technical knowledge and teaches the means available to fill such knowledge gaps (Hayes et al., 2021) yet transdisciplinary courses often aim to teach other approaches as well. Already in Chapter 3, we saw that commissioners expected students to make use of such conventional approaches to science but, at the same time, they were expected to use experimentation, trial-and-error, and build living labs to create solutions for complex challenges. This might explain why from the perspective of the students knowledge incompleteness does not decrease during the course, nor does the assignment become clearer to them.

Especially, the teachers clearly defined the issue of theoretical grounding as part of knowledge incompleteness. They demonstrated a lack of agreement amongst themselves regarding what could be expected from the students on theoretical grounding in such an unusual environment as a transdisciplinary course. Concerning this theoretical challenge of the teachers, many scholars, such as Sterling (2021), Leal Filho et al. (2018), Barnett (2018), and Brown et al. (2015) already described how transdisciplinarity is a fundamental, but necessary, change in the way the university is organized and therefore will also take considerate effort to change. It is important to approach involving students in this challenge with caution. Their focus should be on learning from uncertainty rather than feeling overwhelmed by how to handle it. Uncertainty should contribute constructively, not destructively, to the learning environment, acting as a source of growth rather than a hindrance (Vermunt & Verloop, 1999).

6.3.2 Behind transformative approaches lies an uncomfortable struggle to develop attitudes that embrace uncertainty

If uncertainty leads to constructive friction in the course, it enables students to enlarge their self-awareness and self-regulation of their learning process yet this can be an uncomfortable struggle. Chapter 4 offered first insights into what students might learn from this. In this metacognition-oriented study, we identified three groups of metacognitive behavior: changing attitudes toward uncertainty, employing small coping mechanisms, and seeking social assistance.

The latter two behaviors show that learning to deal with uncertainty is not only a cognitive activity, but also deals with emotion regulation. Students employed small coping mechanisms to deal with a feeling of being stuck in their projects. Becoming aware of uncertainty is often an experience of discomfort. When experiencing such discomfort, students cope by taking a break, doing physical exercise, or spend time with friends. Additionally, students look for their peers for social and emotional support. Such support was also offered by the teachers in Chapter 6 when they scaffolded frustration. Although emotion played a role in the way teachers in Chapter 2 talked about the intentions of their course, in the interviews with students and in the scaffolding of teachers, was perceived as being difficult to teach. This dissertation suggests that integrating elements in the course design that mediate feelings of uncertainty is an important part of transdisciplinary education.

One of the necessary steps to raise attention for the role of affective learning activities is rethinking Bloom's taxonomy. In Chapter 2, we used Bloom's revised taxonomy (Krathwohl, 2002) as it is the most implemented framework in this higher education research context (Biggs & Tang, 2011). However, Bloom's revised taxonomy organizes affect under metacognitive knowledge, considering the regulation of learning part of the same activities as regulation of emotion. Consequently, affective learning activities, such as motivating, judging oneself, and dealing with emotions (Vermunt & Verloop, 1999), might be overlooked by teachers. It might be time to revise the revised taxonomy of Bloom and take a fresh look on how learning objectives are formulated in higher education with the specific aim of making affective learning activities a more explicit part of transdisciplinary courses.

The idea that the attitudes toward uncertainty change through transdisciplinary education might be one of the more intriguing findings of this dissertation because attitudes are considered difficult to teach. Although education might influence the formation of attitudes, especially those toward knowledge and scientific research, it is hard to distinguish this kind of learning from all kinds of other life events or previous experiences that students already have or might gain while they are part of a formal education program. However, in research on interdisciplinary education such attitudes are being described by seminal works of Perry (1970) and Repko and Szostak (2021). Perry (1970) describes a stage of intellectual development that he calls 'multiplicity'. As part of their development, students find that knowledge is subjective and everybody has their own view of the problem. As a result, students might distrust authority, reason, and science, which some of the students in Chapter 4 described they did. From the perspective of Perry (1970), relativism is not an unwanted side-effect of uncertainty but a necessary part of learning to come to grips with multiplicity and a start to integrate different kinds of knowledge. After the stage of relativism, students will be able to develop a more open, empathetic attitude toward different disciplines. Ultimately, they become able to learn approaches that aim to integrate different perspectives in models, methods, or metaphors (Repko & Szostak, 2021). In Chapter 4, some of the students made a conscious decision to act upon the outcomes of co-creation during the course, embracing the uncertainty that their solution might be informed by all those perspectives but not necessarily solve all problems that the stakeholders addressed. This is similar to the balancing act that Perry (1970) described in the commitment stage, where students both show confidence and a tolerance for ambiguity. Additionally, we found that the development of attitudes toward uncertainty is not a straight line from dualism to commitment but students might fall back into relativism when confronted with newly emerging uncertainty.

6.3.3 Teachers support learning in uncertainty by offering social assistance, also, on individual learning objectives

The need for support on metacognitive and affective learning in addition to cognitive learning in uncertainty requires new skills from teachers as well as from the students. The teachers in Chapter 2 and the commissioners in Chapter 3 mentioned transdisciplinary education should aim to teach approaches for integrative problem solving, such as systems thinking, designing adaptive solutions, or co-creating. In Chapter 2, the learning objectives for analyzing were found to often be missing from the learning objectives in transdisciplinary courses, while teachers did find analysis an important part of teaching integrative problem solving. One of the explanations as to why learning objectives for analysis are missing is that the transformative approaches in transdisciplinary courses are relatively new and uncommon in the university and teachers are not yet familiar with the vocabulary of learning objectives to teach them.

Additionally, this dissertation showed that while teaching the skills students need for integrative problem solving, at the same time, they will struggle through the development of different attitudes toward uncertainty. Such a struggle with attitudes could be supported through adaptive guidance or scaffolding, which Chapter 5 showed as a useful perspective on teaching in uncertainty. In Chapter 2, such metacognitive learning was also found to be important for teachers but rarely described in the objectives of the course. The explanation for this might similarly be a lack of vocabulary but might also have to do with how highly individual attitudes are.

The major challenge for teachers, when they are educating in uncertainty, is that awareness of uncertainty and attitudes toward uncertainty are personal. The Living Lab course, as many transdisciplinary courses, is open to students with different disciplinary backgrounds. Therefore, these students will not only bring different kinds of knowledge from their respective disciplines but also have different learning styles that they might have attained during their previous education (Vermunt, 1996). Thus, teachers need to first find out what metacognitive regulation students have at their disposal before they can decide on the right scaffolding.

In scaffolding theory, teachers use diagnostic strategies to determine the current level of students (van de Pol et al., 2010). In Chapter 5, we found that such diagnostic strategies are missing, mainly at the start and the end of the course. In the Living Lab, the philosophy that students should be 'thrown in the deep end' hampered teachers in taking initiative with such diagnostic strategies. At the end of the course, teachers had difficulty to determine the development of students concerning their individual learning objectives. The lack of diagnostic strategies and clear guidance of individually formulated learning objectives of students suggests an opportunity for better integration of goal setting as a skill in transdisciplinary courses. More attention to setting goals for personal development aids the self-regulated learning of students in the course and allows for more explicit scaffolding on such goals by teachers. However, recent research on a similar course by van Ravenswaaij et al. (2022) suggested that teachers need to further broaden their scope of learning to encompass the full diversity of learning on personal development that is part of transdisciplinary education. In addition to the regulation of emotion, transdisciplinary courses create space for learning to self-regulate individual learning paths yet such learning needs to be explicit and requires more diagnostic strategies than teachers currently have available.

6.4 Limitations and recommendations for future research

This dissertation offers a new perspective on transdisciplinary education by studying it through the lens of uncertainty. Although suggestions for the role of uncertainty in sustainability and transdisciplinary education existed before the start of this research, it has not been studied to this extent before. Therefore, this research and the chosen Educational Design Research approach are of an explorative character. I chose qualitative methods to be able to dive deep into the different perspectives and experiences of the people involved in transdisciplinary education. Overall, the methodological choices in this research allowed me to start to understand the networked and fluid world of transdisciplinary education, but also limited the generalizability of the main findings.

Although I accounted for the limitations of the chosen methods by triangulating methods, making use of coders in and outside of the research environment, and developing a reflexive practice with some of the participants (Le Roux, 2017), it is inevitable that certain dominant perspectives in the research environment reflect also on the main findings. For example, the context of engineering education that might lead to dominant learning or teaching styles with the participants. Additionally, challenge-based learning environments, such as the Living Lab, are based on constructivist learning theory and other perspectives on learning (e.g. behavioral or embodied learning) might also have led to a different understanding of how learning happens. As Law (2004) puts it: "[…] methods, their rules, and even more methods' practices, not only describe but also help to produce the reality that they understand" (p. 5) Furthermore, geographically, this research has an urban, Dutch, and Western-European perspective. Further contextualization of the findings might be done by researching uncertainty in transdisciplinary courses in other places in the world. By carefully describing the environments and my position in them, I accounted for this specific limitation of the chosen methods in this research. Future research can contribute to advance the understanding of uncertainty in transdisciplinary education in several ways.

Although this first qualitative exploration of the experiences of teachers, students, and commissioners with uncertainty was necessary to develop a way of researching uncertainty in such an educational context, future research might build on different methods to broaden this first understanding. Such a broader understanding could start from each of the three main perspectives in this research, where I focused on commissioners, students, and teachers.

For commissioners, future research might investigate how uncertainty affects them. This research considered the perspective of commissioners as part of the challenge descriptions they wrote down. Researching how commissioners perceive uncertainty through interviews, focus groups, or observations would be a valuable addition. It would allow to include their attitudes toward uncertainty in future research as well.

For students, future research could engage with a larger group of student participants. This could be done through quantitative or mixed methods research in addition to a qualitative approach as the one developed and used in this dissertation, but it might also be valuable to involve students in participatory or design-based research aimed at one of the main findings in this study. When it comes to the support of group dynamics, the recent work by Van Woerden (2023) already offers new insights into how students work in multidisciplinary teams on complex challenges, which was one of the issues for teachers in this research. Further research might investigate attitude shifts, goal setting in personal development, or the way students self-regulate frustration.

This research accounted for the perspective of teachers in a coordinating role in transdisciplinary courses and teachers involved in the coaching of student teams. Both perspectives need to be considered for future research and they both require a different kind of research. For coordinating teachers, the design principles in this research provide a basis for further development of practice and research. For instance, the misalignment between analyzing in the written and ideal course design can be immediately addressed by teachers in reformulating learning objectives. At the same time, further research could focus on learning activities and assessments that would align with those newly formulated learning objectives. For teachers coaching students in teams, this research investigated teaching through scaffolding theory. Although it took some effort of the teachers to familiarize themselves with the theory to operationalize it in coaching students, this research suggests scaffolding is a useful perspective for both research and design. Also, future research can build on scaffolding theory to ensure that well-established learning theory finds a way to contribute to the unexplored territories of educational innovation.

Overall, this dissertation contributes to a first understanding of uncertainty in education. That first understanding would benefit from further research with different methods and in different contexts as suggested above. At the same time, this dissertation is part of a growing body of scientific work on design studies in education. The careful, systematic investigation of educational innovations helps to better understand what works and what does not work, and makes educational practice translatable across contexts. Additionally, and at least as important, design studies investigate why education is designed in a certain way. Opening educational research to include what intuitive and normative considerations contribute to the course design allows for the critical evaluation innovation needs. Therefore, design interventions and systematic evaluations of these interventions are an essential part of the future of education.

6.5 Final statement

In this dissertation, I made an effort to understand how students and teachers deal with what lies between what they know and what they do not know: uncertainty. A significant part of this research deals with resolving uncertainty or finding ways of constructively struggling with it for the people involved in transdisciplinary education. The students in this dissertation are not the only ones dealing with uncertainty. Uncertain times lie ahead for future generations of students, teachers, and other people concerned with or affected by climate change. Transitioning to a society that can respect planetary boundaries brings about feelings of uncertainty for many of us. But if there is one thing that can be learned from these students, it is the fundamental human ability to ask for help. In the face of uncertainty, one of the most comforting thoughts hidden in this dissertation is that we are not alone. Dealing with uncertainty is not a solitary affair, yet asking for help exposes vulnerability and it takes courage to do so. I hope this dissertation is a building block for the construction of the brave learning spaces that our future education needs.

Appendices

APPENDIX A

Interview protocol [CH2]

Initial Questions (20 minutes)

1 Intended curriculum
- What is your position and your background?
- How did you become involved in this field?
- What is the role of the city in your field?
- How do you collaborate with others in the field?
- What should they learn from it? What are the learning objectives?
- What is essentially the problem that the field revolves around?

2 History of the course
- How did the collaboration with the city come about?
- Can you describe the process in different steps?
- What tools do you use in this process?

During Journey Mapping (20 minutes)

3 Negotiation or alignment between problem and education
- What have been the key moments in the process?
- What happened there?
- Did your view of the problem change during the process?
- How has your understanding of the problem changed since the students started working on it?
- What has surprised you since the students started working on it?

Wrap-up questions (10 minutes)

4 Reflecting on the outcome of the mapping
- What makes this type of education successful?
- What ambitions do you have for the future of your own courses?
- Evaluation of the journey mapping. How was it to not be directly involved in the mapping?

APPENDIX B

Codebook [CH2]

Code group	Code	Description
Cognitive process dimension	**Remember**	Retrieving relevant knowledge from long-term memory.
	Understand	Determining the meaning of instructional messages, including oral, written, and graphic communication.
	Apply	Carrying out or using a procedure in a given situation.
	Analyse	Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose.
	Evaluate	Making judgments based on criteria and standards.
	Create	Putting elements together to form a novel, coherent whole or make an original product.
Knowledge dimension	**Factual**	The basic elements that students must know to be acquainted with a discipline or solve problems in it.
	Conceptual	The interrelationships among the basic elements within a larger structure that enable them to function together.
	Procedural	How to do something; methods of inquiry, and criteria for using skills, algorithms, techniques, and methods.
	Metacognitive	Knowledge of cognition in general as well as awareness and knowledge of one's own cognition.
Level of participation	**Distant**	The collaboration stops with the collaborative formulation of a problem that originates from the city.
	Client	There is a client that presents the challenge at the start of the course and that collects the results at the end.
	Partner	The students are depending on the involvement of others or are expected to involve others in order to solve the problem.

APPENDIX C

Sample template challenge description [CH3]

Title case	<a stimulating title that sparks curiosity>
Case-owner	<name of the organisation that is submitting the case>
Urban challenge	<which of the urban challenges is the case connected to? *Climate resilient cities, metropolitan food systems, circularity in urban regions, urban data & intelligence, smart urban mobility and/or urban energy*>
Description of the case	<brief description of the case: What is the big metropolitan challenge that this case deals with? How will students work on the challenge? What are the goals and what is the impact you expect students to have?>
Urban living lab setting	<description of the context and the way of working: Why is it necessary to work in a living lab setting and what does that mean in your organisation? How could co-creation be done? What are the possibilities for testing, designing and experimenting?>
Collaboration	<who is (or should be) involved in the living lab? Provide a list of all stakeholders involved, i.e. users, private actors, public actors, knowledge institutes>
Required expertise	<MADE students have a vast variety of backgrounds and work in academic, entrepreneurial and policy contexts. What types of expertise do you expect would make a good combination in the living lab team?>
Location	<Name of the organisation, where the student group will be located> <Address of the organisation>
About the case-owner	Contact person: <name, function> T: E:
Academic coach	*No information needed*

APPENDIX D

Codebook uncertainty in challenge descriptions [CH3]

Code group (ID)	Code	Description
Unpredictability (problem / situation / environment)	**Predictable**	The knowledge environment is predictable and linear. Clear cause and effect ties can be recognized.
	Consistent	The knowledge environment behaves consistently. By careful examination of the system, it can be understood, and future behavior can be predicted. Although the future is unknown, plausible scenarios could be developed.
	Incomprehensible / Dynamic	The knowledge environment is dynamic. Due to the randomness of nature, human behavior, societal processes, or technological surprises the problem could change drastically (variability uncertainty). What or who is causing the problem is unclear and might only be revealed in retrospect.
Knowledge incompleteness (approach / method / solution)	**Known knowns**	The problem is understandable as a sum of parts.
	Known unknowns	Although the knowledge, information, or data itself might not be present, it is clear how it can be gathered. Different fields of expertise are necessary to deal with the problem.
	Unknown unknowns	A lack of information or data, the unreliability of the data that is available, a lack of theoretical understanding or ignorance. Doing more research might uncover more uncertainties.
Knowledge frame multiplicity (people)	**Coordination**	Decisions can be made based on agreed upon facts and procedures. Coordination strategies suffice in this case.
	Cooperation	Conflicting advice and conflicting interests are at play. A panel of experts could be used to come to a solution. There is more than one solution to the problem.
	Collaboration	The network of involved public or private actors have different norms, values, and interests. The boundaries of the system or what and whom to put as the focus of attention is unclear. Information about the system is interpreted differently.

APPENDIX E Interview protocol [CH4]

Before the interview (researcher)

- Plan interview
- Send agenda invitation
- Send consent form and research information (for the first interview)
- Reserve a space for the interview at AMS Institute
- Read on the case of the interviewee

Before the start of the interview (5 minutes)

- Discuss consent form (sent in advance), answer possible questions, and sign (for the first interview)
- Start audio recording
- Discuss the purpose of the interview
- Discuss the course of the interview
- “It may happen that I interrupt you occasionally during the interview to ask follow-up questions or to introduce a different topic. This has nothing to do with it being uninteresting, but with the time management of the interview.”
- “Additionally, there may be questions to which you might expect that I already know the answers, because I also work as a teacher in the Living Lab. I would appreciate it if you could still answer those questions, because your own words are often important for my understanding.”

Theme	Sensitizing concept	Question	Possible answers
Warm-up questions (10 minutes)		What is your background? And how did you end up with MADE?	Previous study background and motivation to study MADE
		What is your Living Lab about?	Description project
Challenge (10 minutes)	**Transdiscipli-narity**	Could you describe in your own words what the challenge is that you work on in the project?	The student's perspective on the sustainability challenge.
	Complexity / uncertainty	What is complex about the challenge?	The student's perception of the complexity, possibly mentioning uncertainties as well.
	Unpredictability	What has changed in your perception of the problem since the last time we spoke?	Important events in the project that changed the student's perception.
Collaboration (15 minutes)	**Transdiscipli-narity / multiple knowledge frames**	Who have been important in the project the past weeks? What was their contribution?	Naming the different actors and their contributions.
	Transdiscipli-narity	How are you collaborating with them in the Living Lab?	Description of relations, interdependencies, and conflicts.
	Complexity / uncertainty	What is complex about these collaborations?	The student's perception of the complexity, possibly mentioning uncertainties as well.
Metacognition of uncertainty (15 minutes)	**Uncertainty / knowledge incompleteness**	How do you know you're making the right decisions?	Describing how the student team makes the decisions and the role of the student.
	Uncertainty	What is uncertain about the decisions you're making? How do you deal with that?	Student perspective on uncertainty. Strategies of dealing with uncertainty in decision making.
	Strategies for multiple knowledge frames	How do you deal with others who might have a different perception of the problem of the solution?	Strategies for dealing with multiplicity.
	Strategies for knowledge incompleteness	How do you deal with certain insights or knowledge that is missing?	Strategies for dealing with knowledge gaps.
	Strategies for unpredictability	How do you deal with unpredictability? That you do not know what might happen in the future?	Strategies for dealing with unexpected changes in the project.
	Self-awareness	What have you learned about yourself?	The student's perception of their learning.

Wrap-up (5 minutes)

- Stop recording
- Thank participant for their contribution to the study
- Discuss new appointment

After the interview (researcher)

- Make reflection logbook
- Safely store the interview recording
- Plan new appointment

APPENDIX F

Codebook uncertainty students [CH4]

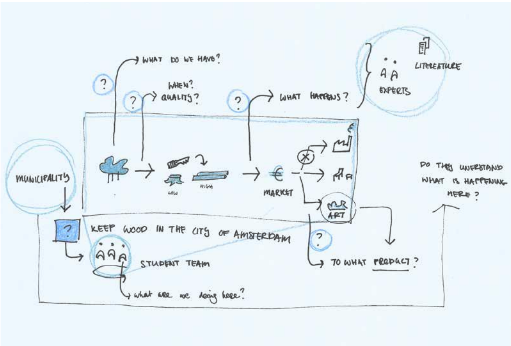
Metacognition	Code group	Code	Description
Awareness of uncertainty	**Unpredictability**	Achieving goals	Uncertainty if it would be possible to contact the people that the student wanted to reach out to.
		Changes during the project	Because of new insights arising during the project, the student would have made other decisions when looking back.
		Dynamic problem	Uncertainty due to the different moving parts in the challenges (variability uncertainty).
		Incomprehensible	Student describes the limitations of being able to know reality (ontological uncertainty).
		Pressure of grading	Uncertainty if the quality of the work would reach a certain grade.
		Time constraints	Uncertainty due to a lack of time to comprehend everything.
	Knowledge incompleteness	Data quality	Uncertainty about the quality of the data that the student gathered.
		Lack of knowledge	Student was unable to find certain answers or information.
		Unclarity assignment	Unclarity about the expectations of assignments.
		Unclarity roles	Searching for the position of the student or student team in collaboration with others.
		Unclear tasks	Not knowing what to do next.
	Multiple knowledge frames	Ambitions of team	Peer pressure arose through ambitions the team set out to achieve together.
		Conflict case owner	Challenges, tensions, or conflicts that arise from working with the case owner.
		Different perspectives	Different perspectives on the problem, approach, or the solution direction that can be in conflict with each other. Students are depending on others to find answers to their questions.
		Expectations	Students are confronted with their own expectations of the course turning out different.
		Usefulness results	Uncertainty about the quality of the outcome and the usefulness for practice.
		Quality participation sessions	Uncertainty about the quality of the outcome of participation in the process.

>>>

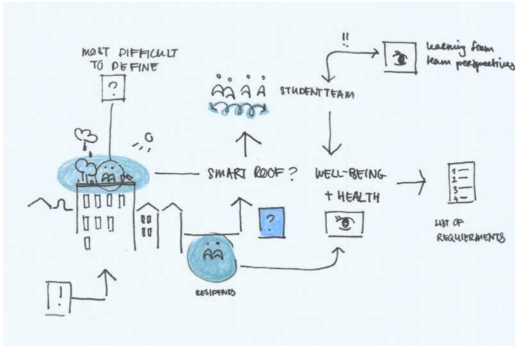
Metacognition	Code group	Code	Description
Regulation of uncertainty	**Seeking social assistance**	Collaborative work	Making use of the expertise of other team members to solve a problem.
		Conversations case owner	Talking to the case owner about uncertainty (for instance in roles or differences in expectations).
		Conversations coach	Talking to the coach about uncertainty (for instance to clarify assignments).
		Conversations peers	Conversations with students outside of the team.
		Conversations team	Discussing challenges with other team members to resolve them or get a better understanding of them.
		Conversations with stakeholders	Talking to different stakeholders or experts.
		Examples from previous years	Looking at student work from previous years of the course.
	Employing small coping mechanisms	Ask for feedback	Ask for feedback from different people.
		Confrontation	Students confront stakeholders with different views or try to facilitate the conversation between stakeholders about those views.
		Expectation management	Managing expectations of case owner or other people in the project.
		Scenarios	Thinking of the challenges that could arise beforehand.
		Reporting the process	Describing the uncertainties in the report.
		Search for Information	Students search for more information or further research the challenge they ran into.
		Taking a break	Going home early or taking a walk.
	Changing attitudes	Adaptability	Accept e.g. lack of knowledge, deal with it and look for another way to find a solution.
		Acceptance of conflict	Accept that conflict can be part of the process.
		Articulate position	Student decides on position or focus.
		Cut the knot	Actively create moments in the team to make decisions.
		Embracing uncertainty	Accept that certain knowledge is not available.
		Empathy	Empathy towards others that might have caused uncertainty.
		Experiment	Students accept that there is not enough information and just experiment with a solution: 'we will see.'
		Flexibility	Student describes a positive attitude towards change.
		Learning process	Framing the uncertainties or challenges as a valuable part of the learning process.
		Other attitudes	Student describes dealing with uncertainty as a specific attitude towards not knowing (embracing uncertainty). This can also be an emotional response to uncertainty.
		Persistency	Stick to the plan and convincing others of this direction.
		Relativism	Letting go of responsibility or acknowledging that they cannot solve the problems.
		Trust in team members	Trust in the competency, expertise, or agreements with team members.

APPENDIX G

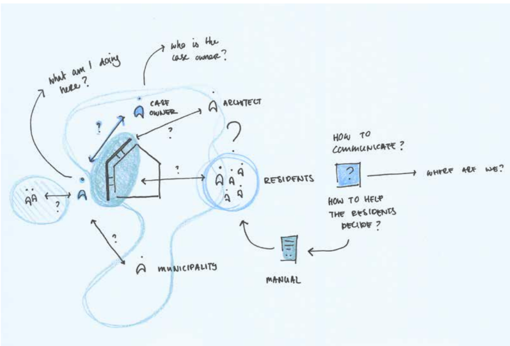
Interpretation sketches interviews [CH4]



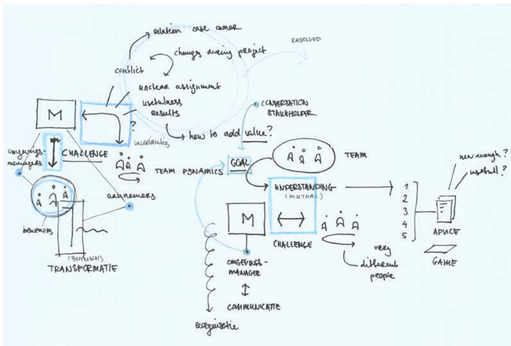
Interpretative sketch of interviews with Student 1



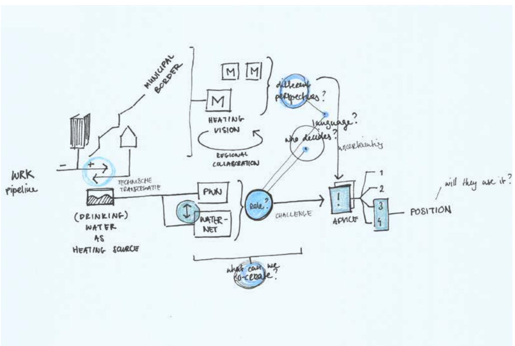
Interpretative sketch of interviews with Student 2



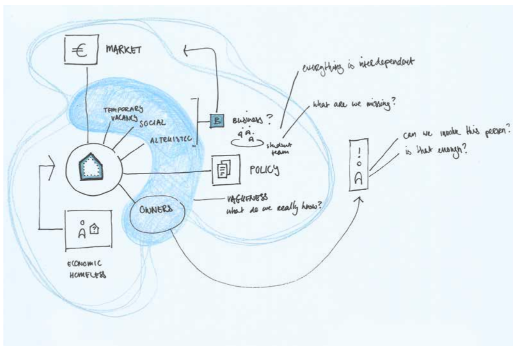
Interpretative sketch of interviews with Student 3



Interpretative sketch of interviews with Student 4

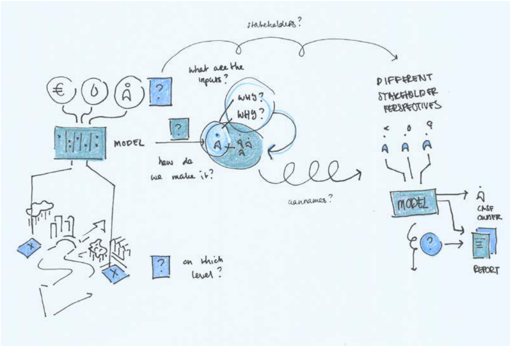


Interpretative sketch of interviews with Student 5

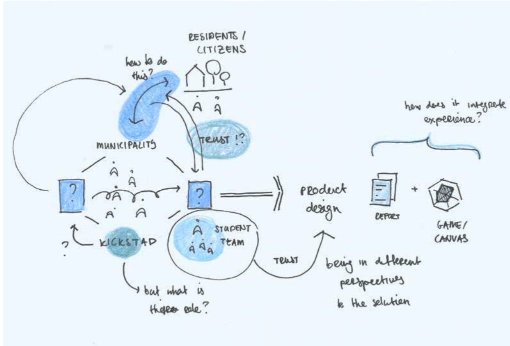


Interpretative sketch of interviews with Student 6

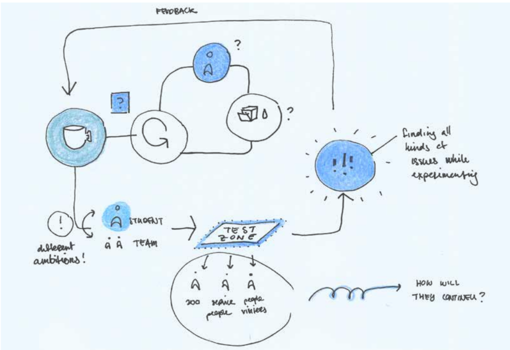
TOC



Interpretative sketch of interviews with Student 7



Interpretative sketch of interviews with Student 8



Interpretative sketch of interviews with Student 9

TOC

APPENDIX H

Teacher Questionnaire [CH5]

Start of Block: Opening statement

Opening statement

Thank you for taking part in this research study titled 'Scaffolding in the age of uncertainty'. The purpose of this research study is to **gain insights into the way you guide students in their learning process**.
The questionnaire consists of three parts and will take you approximately **10-15 minutes** to complete.
Participation in this study is entirely voluntary and you can withdraw anytime. You are free to omit any questions, but you help us most by taking the time to answer all of them.
Don't hesitate to reach out to me if you have any questions,
<researcher and contact details>

End of Block: Opening statement

Start of Block: Reflection on learning

The first part of this questionnaire is about what the students have learned so far.

Page Break

Q0.1 Which student team are you coaching?
[Drop down menu with student teams]

Page Break

Q1.1 How would you currently assess the performance of the student team on the learning objectives?
This is an assessment of the team and not of individual students. Please try to give an overall evaluation to the best of your ability.

	Not well at all	Slightly well	Well	Very well	Extremely well	*I don't know*
The students are able to **iteratively evaluate the living lab process**.						
The students are able to **adjust the living lab process by incorporating feedback**.						
The students are able to **connect real-life challenges to academic theory** within the living lab process.						
The students are able to **present in a way that enables exchange** of knowledge, experience, and ideas with other MADE staff, students, and stakeholders.						
The students are able to **collaborate with societal actors**.						
The students are able to **examine and reflect upon their personal development** (for instance, on motivations, values, and growth).						
The students are able to **relate learning experiences in the living lab to their personal development**.						

Q1.2 What are the students struggling with?

End of Block: Reflection on learning

Start of Block: Reflection on your teaching

In this part of the questionnaire, we ask you to reflect on your own teaching and scaffolding.

Q2.1 What went well in your teaching during the coaching sessions?

Q2.2 What was challenging in your teaching during the coaching sessions?

Q2.3 Which of the scaffolding strategies did you use during the coaching sessions?
[These answers were presented in randomized order]

- ☐ I stimulated students to get interested in a task or topic (recruitment).
- ☐ I simplified a task that students were not yet able to perform (reduction in degrees of freedom).
- ☐ I prevented students from deviating from their goals (direction maintenance).
- ☐ I made visible to the students where they are and where they need to go to reach a learning objective (marking critical features).
- ☐ I prevented students' frustration or motivated them to move past frustration (frustration control).
- ☐ I performed a specific task myself for students to imitate (demonstrating).

Q2.4 Can you give a concrete example of an action during the session based on one of the scaffolding strategies?
You can think of questions you asked, tasks you modelled, or hints, feedback, explanation, or instruction you gave. Please also mention which strategy you used.

End of Block: Reflection on your teaching

Start of Block: Setting goals

This is the last part of the questionnaire, where we would like to know what your goals are in the upcoming coaching session with the students.

Page Break

Q3.1 Which learning objective is most important to you in the upcoming coach sessions?

- ☐ The students are able to iteratively improve and adjust the living lab process by continuous evaluation and incorporation of feedback.
- ☐ The students are able to connect real-life challenges to academic theory and the living lab process.
- ☐ The students are able to present in a way that enables exchange of knowledge, experience, and ideas with other MADE staff, students, and stakeholders.
- ☐ The students are able to collaborate with societal actors from the metropolitan region of Amsterdam.
- ☐ The students are able to examine and reflect upon personal motivations, values, and growth within the context of a learning experience.
- ☐ ____

Q3.2 Which scaffolding strategy would you focus on for this learning objective?

- ☐ Getting students interested in a task or topic (recruitment)
- ☐ Simplifying a task that students are not yet able to perform (reduction in degrees of freedom)
- ☐ Preventing students from deviating from their goals (direction maintenance)
- ☐ Making visible where the students currently are and where they need to go to reach a learning objective (marking critical features)
- ☐ Keeping students motivated by preventing frustration (frustration control)
- ☐ Performing a task yourself for the students to be able to imitate it (demonstrating)

Q3.3 How would you use this scaffolding strategy? Can you give a concrete example of what you plan to do in the next session?
Think of questions you want to ask, modelling of certain tasks, or hints, feedback, explanation, or instruction you want to give.

End of Block: Setting goals

APPENDIX I

Focus group guiding questions [CH5]

[Slide on Q1.1]

Q1.1 How would you currently assess the performance of the student team on the learning objectives?

- What stands out to you on student performance?
- How do you know that students are performing? How do you diagnose where they are?

[Slide with questions]

- What went well in your coaching the past weeks?
- What was challenging?

[Slide on Q2.3]

Q2.3 Which of the scaffolding strategies did you use during the coaching sessions?

- Did you actively try to implement certain scaffolding strategies?
- What went well? Or what was challenging about implementing these strategies?

[Slide on Q3.1]

Q3.1 Which learning objective is most important to you in the upcoming coach sessions?

- What will be your focus in the next coaching session?
- Why are these learning objectives important now?

[Slide on Q3.2]

Q3.2 Which scaffolding strategy would you focus on for this learning objective?

- Could you think of a concrete action you want to take based on the scaffolding strategies?

APPENDIX J

Codebook uncertainty teachers [CH5]

Concept	Code group	Code	Description
Uncertainty	**Unpredictability**	Achieving goals*	Uncertainty if it would be possible to reach the goals or finish the tasks that students set for themselves.
		Changes during the project*	Because of new insights arising during the project, the student would have made other decisions when looking back.
		Time constraints*	Uncertainty due to a lack of time to comprehend everything. Teachers want to slow students down.
	Knowledge incompleteness	Lack of knowledge*	Student was unable to find certain answers or information.
		Theoretical grounding	Students struggle with positioning theory in their project.
		Unclarity assignment*	Unclarity about the expectations of assignments.
		Unclarity roles*	Searching for the position of the student or student team in collaboration with others.
		Unclear tasks*	Not knowing what to do next.
	Knowledge frame multiplicity	Conflicting ambitions within student team*	Peer pressure arose through ambitions the team set out to achieve together.
		Different perspectives*	Different perspectives on the problem, approach, or the solution direction are in conflict with each other. Students are depending on others to find answers to their questions.
		Expectations*	Students are confronted with their own expectations of the course turning out different.
		Tensions commissioner*	Challenges, tensions, or conflicts that arise from working with the case owner.
		Usefulness results*	Uncertainty about the quality of the outcome and the usefulness for practice.
	Other problems (not directly related to uncertainty)	Communication	Issues of communication between students and teacher.
		Conflict between personal and course goals	Personal learning of students do not allign well with the goals of the course or the commissioner.
		Diagnostic strategies	Teachers are not aware of what the student team is doing.
		Diverging - Converging	The students struggle with switching between diverging and converging in the process.
		Emotions	Teachers worry about the emotional and/or mental load of the process for the students.

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Concept	Code group	Code	Description
Uncertainty		Feedback	Teachers wonder if their feedback is clear to the students.
		Freedom	The freedom in the project challenges students.
		Living lab format	Teachers struggle with how to teach the living lab format.
		Presenting	Students struggle with presenting their work in a clear way.
		Previous knowledge	Unclarity about previous knowledge of the students.
		Scoping	Scoping and decision making by the students during the project. This might relate to uncertainties, but teachers do not always describe those uncertainties specifically.
		Workload	Students have a high workload in addition to the course.

* *All codes with an asteriks (*) were mentioned by students in the study in Chapter 4.*

APPENDIX K

Codebook scaffolding strategies [CH5]

Concept	Code group (scaffolding intention)	Code (scaffolding means)	Description
Scaffolding	**Recruitment**	Methodological choice	Motivating students to be explicit about the methods they use, for instance, by creating a semi-structured interview protocol
		Personal interest questions	Asking about the interests and passions of the students
		Recruitment questions	Asking questions to draw attention to a specific topic, solution, or subject
		Sharing passion	Using the teacher's own excitement to raise interest and curiosity
	Reduction in degrees of freedom	Converging methods	Suggesting exercises that help to narrow down their ideas
		Diverging methods	Suggesting different but limited directions that students could explore
		Divide tasks	Advising students to divide tasks
		Limiting tasks	Limiting students to take on new tasks
		Overview of tasks	Providing overview of all the tasks
		Simplifying report	Simplifying the task of report writing
	Direction maintenance	Align product with project aims	Providing feedback to align the product with the aims of the project
		Brainstorm	Brainstorming with the students for new ideas in the project, for instance, through thinking-aloud strategies
		Focus on goal	Asking students to focus their work on specific goal
		Methodological choice	Explaining how different methods will lead to different outcomes
		Quick direction choice	Motivating students to quickly choose a direction
		Simplifying design	Advising students to keep the product design simple without too many details
		Visualize	Drawing connections on a board to visualize the process or the results

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Concept	Code group (scaffolding intention)	Code (scaffolding means)	Description
Scaffolding	**Marking critical features**	Compliments	Giving compliments
		Feedback check	Checking if the feedback was well understood
		Insight questions	Asking questions to provide insight to the students
		Personal development	Motivating students to work on personal development goals
		Process questions	Asking questions to clarify the process
		Provide feedback	Providing feedback, for instance, on a questionnaire
		Specifying	Assisting students to be specific about outcomes of, for instance, a co-creation session
		Theory questions	Asking questions to clarify links to theory
	Frustration control	Case initiator tensions	Managing tensions with the case initiator
		Learning process	Encouraging students to see the project as a learning experience
		Not everything is clear	Reassuring that it is normal that not everything is clear
		Offer support	Supporting students, for instance, by attending meetings with the case initiator
		Overthinking	Preventing students from overthinking all different directions
		Passion	Suggesting ways to pursue their passions in the project
	Demonstrating	Group dynamics	Chairing a meeting to demonstrate how to deal with group dynamics
		Inspiration and examples	Showing examples or suggesting places where students can find inspiration
		Interviews	Showing how to interview stakeholders
		Reasoning	Explaining the reasoning behind decision making for students to copy
		Role play	Letting students use ‘role play’ some of their ideas to understand stakeholder perspectives

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Tot slot, papa, ik mis onze gesprekken nog iedere dag. Wat had ik graag willen weten wat jij hiervan denkt.

Curriculum Vitae

Nina Bohm was born on July 29, 1992, in Amsterdam, The Netherlands. She followed her secondary education at St. Ignatius Gymnasium between 2003 and 2010. She received a BSc degree at Delft University of Technology (TU Delft): Architecture, Urbanism, and Building Sciences. As part of her bachelor program, she gained international experience during an abroad semester at the University of Bath in the UK. Before starting her masters, she was a board member at the study association D.B.S.G. Stylos, where she was student representative for education and student-chair of the educational committee of the Faculty Architecture and the Built Environment. For her masters, she continued her education at the TU Delft, obtaining a double degree in Urbanism and Science Communication.

In 2017, Nina started working as an education coordinator at the Amsterdam Institute for Advanced Metropolitan Solutions (AMS Institute). Here, she could combine her interests in urban sustainability and education. She coordinated the two-year joint degree MSc MADE (Metropolitan Analysis, Design, and Engineering) of TU Delft and Wageningen University, where she co-designed the Living Lab course in the second year of that program with Dr. Arjen Zegwaard and Toine Andernach. The Living Lab course would become the main subject of her PhD research and she would continue to coordinate the course for another four years.

Since 2019, Nina has conducted PhD research at the Faculty of Architecture and the Built Environment of TU Delft, funded by the 4TU Centre for Engineering Education. Her PhD focused on uncertainty in transdisciplinary education. This topic relates to multiple research themes, such as transdisciplinary and interdisciplinary learning, sustainability in higher education, educational philosophy, and challenge-based learning. The research was supervised by Prof.dr. Ellen van Bueren and Prof.dr. Perry den Brok, and Dr. Renate Klaassen.

Given the educational relevance of her PhD research, Nina has actively communicated her research findings to contribute to educational innovation within and beyond her research environment. In the first year of her PhD, she successfully applied for funding through Regieorgaan SIA/NWO to design a roadmap for teachers in higher education in the Netherlands seeking collaboration with urban partners. Additionally, she presented her work at several international conferences, such as SEFI and CDIO. In the final years of her PhD, she contributed to the development of the POW (Personal Development Weeks) in the new bachelor curriculum at the Faculty of Architecture and the Built Environment, in collaboration with a diverse team of committed students, teachers, and staff members.

After finishing her PhD, Nina will continue to energetically work on educational transformation as postdoc researcher at the Copernicus Institute for Sustainable Development at Utrecht University. In this next step in her research, Nina will focus on design thinking as one of the ways to deal with uncertainty in transdisciplinary sustainability education.

List of publications

Peer-reviewed journal articles

Bohm, N. L., Klaassen, R. G., van Bueren, E., & den Brok, P. (2024). How do students deal with the uncertainty of sustainability challenges? Metacognitive learning in a transdisciplinary course. *Frontiers in Education, 9*, Article 1362075. https://doi.org/10.3389/feduc.2024.1362075

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Conference articles

Bohm, N. L., Klaassen, R. G., van Bueren, E. M., & den Brok, P. (2023). Between flexibility and relativism: How students deal with uncertainty in sustainability challenges. In G. Reilly, M. Murphy, B. V. Nagy, & H.-M. Jarvinen (Eds.), *SEFI 2023 - 51st Annual Conference of the European Society for Engineering Education: Engineering Education for Sustainability, Proceedings* (pp. 212-221). TU Dublin, Dublin, Ireland. https://doi.org/10.21427/PCG5-D760

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Podcasts and other media

Ioannou, O. (Developer), et al. (2023). Knowledge Clip Uncertainty in Circular, Architectural and Engineering Education and Challenge-based Learning. *Circularity for Educators*. Web publication/site, Delft University of Technology, Faculteit Bouwkunde. https://circularityforeducators.tudelft.nl/article/uncertainty-in-circular-architectural-and-engineering-education-and-challenge-based-learning/

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24#18

Educating Uncertainty

How students and teachers deal with uncertainty in transdisciplinary courses on urban sustainability

Nina Bohm

Transdisciplinary approaches are increasingly prevalent in higher education curricula. These approaches involve partnering with real-world actors to tackle real-world problems, perhaps most notably the contemporary *sustainability* challenge. How to balance environmental sustainability with social and economic goals is a contested issue, with varying perspectives on the problems and solutions, even among experts. Furthermore, sustainability education is shaped amidst an unpredictable political landscape and yet unknown technological advancements. This diversity of viewpoints, unpredictability, and a lack of knowledge makes uncertainty an inescapable part of transdisciplinary sustainability education.

Until now, little research has informed teachers and students how to deal with uncertainty. The central question in this research is therefore: **How can transdisciplinary education be designed so that students learn to deal with uncertainty in sustainability challenges?**

The purpose of this dissertation is twofold: (1) to further refine the theoretical understanding of uncertainty in transdisciplinary education and learn to deal with it; and (2) to highlight principles for designing education that empowers both students and teachers to navigate uncertainty effectively. The research approach is based on Educational Design Research (EDR), which aims to combine scientific research findings with practical experiences from people involved in education. The research highlights how learning to deal with uncertainty is an uncomfortable struggle for students and teachers. The conclusion suggests six design principles to help transform this struggle into a well-guided learning experience. These design principles focus on defining transdisciplinary learning objectives, making uncertainty attitudes explicit, and emphasizing personal development and emotional awareness in future sustainability education.

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