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Multi- and interdisciplinary design of urban infrastructure development

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Due to the environmental crisis, there is a need for a more conscious and integrating design process within the field of urban infrastructure development. Through cooperation between civil engineering and spatial design resilience of the built environment can be increased. Delft University of Technology investigates interdisciplinary design as a method and incorporates this into its MSc-level education of students in the faculties of civil engineering and architecture. The focus of the research was on the reconstruction projects after disasters like hurricanes and tsunamis. By way of surveys of the participating students, the effectiveness of the interdisciplinary design methods used, and the interpretation of the terms multidisciplinary and interdisciplinary are revealed. From survey results about understanding of multidisciplinary and interdisciplinary it can be concluded that interdisciplinary design should entail a conscious and orchestrated process in which the disciplines present their ideas within a shared value system before systematic integration. The challenges are at personal and cognitive levels, an open attitude is necessary to be able to perceive and react, process and understand, retrieve information. Only then decisions on – and production of – appropriate responses come out of co-creation between engineering within the spatial design process.

Keywords: design methods & aids/infrastructure planning/knowledge management/UN SDG 11: sustainable cities and communities

1. Introduction

The demand for a more conscious and integrated design process within the field of urban infrastructure development is based on the fact that natural disasters can only be endured by increasing the resilience of the built environment (Meerow *et al.*, 2016). According to Cutter *et al.* (2008), multidisciplinary co-operation is required to implement resilience resulting in interdisciplinary design. The term 'multidisciplinary' is the integration of the contributions of several disciplines to a problem and is about assembling interdependent parts of knowledge into harmonious relationships (Stember, 1991). While the term 'interdisciplinary' is, according to Huutoniemi *et al.* (2010), 'best understood not as one thing but as a variety of different ways of bridging and confronting the prevailing disciplinary approaches'. 'Interdisciplinary design' involves, according to Miller (1982), 'juxtapose, apply, combine, synthesize, integrate or transcend parts of two or more disciplines'. To this Heinzlef *et al.* (2018) add that interdisciplinary design is achieved by way of collaboration to integrate interests and needs among the disciplines.

The references to the definition of these terms, multidisciplinary and interdisciplinary, and interdisciplinary design, are representative of the fact that they have been theorised and discussed over six decades (Huutoniemi *et al.*, 2010). It is interesting to observe that during this time period the topic is sometimes 'hotter' than others, so attention towards the topic varies, as does founding and closing of institutions focused on the topic such as the Center for the Study of Interdisciplinarity (2007–2014) at the University of North Texas (USA) (Jacobs and Frickel, 2009).

The other observation is that research about interdisciplinary collaboration or the sharing of expertise between stakeholders in different contexts addresses a wide range of fields and disciplines and therefore also remains quite general. The sharing and combining of expertise are generally reflected on with positive words, especially highlighting the widening of perspectives and the added insights in all participating domains. Also in general terms a number of challenges are emphasised – for example, the communication of experiential knowledge and the utilisation of the added value of collaboration in a meaningful way.

In this paper the two terms 'multidisciplinary' and 'interdisciplinary' are discussed specifically in the context of urban flood risk that involves disciplinary fields within civil engineering (hydraulic engineering, water management, geoengineering, transport engineering) and spatial design (architecture, urban design, landscape architecture, building technology, management of the built environment). The objective is twofold: first to address the gap in literature on what these terms behold for spatial development and second to be able to generate appropriate tools to operationalise interdisciplinary design and to understand when multidisciplinary becomes interdisciplinary design.

In the *Oxford Handbook on Interdisciplinarity* (Frodeman *et al.*, 2017), there is one chapter by Boradkar on 'Taming wickedness by interdisciplinary design' that makes a start on theorising design in general, by relating to the study of Rittel and Webber (1973). The latter's research is important in creating the basic difference between the fields of engineering and spatial design. They argue that engineers typically deal with 'tame' problems, where the problem itself is clear and it is clear when the problem has been solved. In contrast, spatial designers typically deal with 'wicked' problems relating to open societal systems without clearly defined boundary conditions. The Industrial Revolution in the nineteenth century brought about professionalism and the domination of the idea of efficiency through machinery. Optimisation became the guiding concept of civil engineering, aiding also to a dramatic change in urban design, which was considered as a process of designing solutions to problems that might be undertaken and operated in the most cost-effective way.

Rittel and Webber (1973) make the connection to the military systems-approach, since that is one of the foundations of the discipline of urban design:

> The classical systems-approach of the military and the space programs is based on the assumption that a planning project can be organized into distinct phases: 'understand the problem or the mission', 'gather information', 'analyse the information', 'synthesize information and wait for the creative leap', 'work out the solution' or the like. For wicked problems, however, this type of scheme does not work. One cannot understand the problem without knowing about its context […].

Table 1. Solution strategies for different types of problems

Measures	Problems and goals	
	Familiar and with existing agreement	Unfamiliar and there is no agreement
Known	Optimisation	Negotiation
Unknown	Innovation	Design

Source: Van de Ven *et al.* (2009) derived from Thompson and Tuden (1964)

Rittel and Webber (1973) mark the change, the end of the idea of efficiency, at the end of the 1970s when the urban context is reintroduced.

The collaboration between the civil engineering and spatial design disciplines encompasses substantially more complex challenges. Foremost among these challenges are differences in vocabulary beginning with the definition of 'design' itself. In the broadest sense, design is a method to find common ground in cases when both the measures, and problems and goals, are still undefined (Van de Ven *et al.*, 2009). However, engineers are trained in using an optimisation approach to designing the solution to a problem, while spatial planners use a research by design approach. Each field uses different paradigms and rationales in problem solving (Table 1).

The spatial design field is already inter- and transdisciplinary in itself. It is interdisciplinary due to the fact that as a scientific discipline it is supported by different fields: architectural theory, sociology, technology (such as soil mechanics and traffic), geography, demography and policy. For example, almost all theoretical writings originate from sociologists and architects. Marshall (2012) even considers urban design theory a pseudoscience partly because its theory is not robustly based on a fully scientific underpinning. The field is characterised by an epistemic culture, as it builds on diverse scientific fields but needs to translate their methods, instruments and tools of enquiry, into its own way of reasoning and establishing evidence (Knorr Cetina, 1999). However, engineering has been taken out of this range of fields (or this epistemic culture). Designers worked on the hypothesis that technological prosperity could realise any design they created. As a consequence, engineering follows creative design, no longer as an integral part of it (Hooimeijer, 2014). Design, until the global challenges of climate change, mostly relied on social and economic indicators; the way the project was to be engineered, also to be able to engineer it smartly, was no longer at the base of urban design. Today, the biggest challenge is re-integrating engineering within the spatial design process, necessary to build cities of the future.

The spatial design field in practice is transdisciplinary due to the fact that it involves stakeholders as an essential part of the

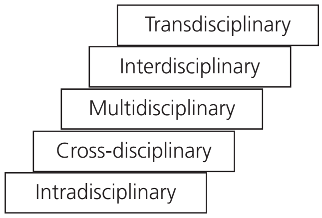

Figure 1. Typology for enterprises within and across disciplines (source: Stember (1991))

development process. However, this is not a next step in the sequence of typologies for exchange between disciplines in the way that Stember (1991) had proposed (Figure 1). Here 'intra-disciplinary' means within one discipline, 'cross-disciplinary' is viewing of one discipline from the perspective of another and involving several disciplines that each provides a different perspective on a problem or issue. 'Multidisciplinary' is the integration of the contributions of several disciplines to a problem and is about assembling interdependent bits of knowledge into a coherent whole. 'Interdisciplinary' is a more synthetic attempt at mutual interaction, and the highest level of integrated research and practice is 'transdisciplinary', concerned with the unity of intellectual frameworks beyond individual disciplinary perspectives.

In the field of spatial development all these typologies by Stember (1991) occur simultaneously and not necessarily in this hierarchy, which makes this way of approaching the differences between the terms variable. The focus of this paper is on the understanding of the two terms 'multidisciplinary' and 'interdisciplinary' in order to operationalise them in urban infrastructure development, whereas 'transdisciplinary' is considered an activity of spatial development and not included in the study.

To be able to connect better the definitions of multidisciplinary and interdisciplinary design to the process of design the main questions posed in this paper are: what should interdisciplinary design entail, what are its challenges, how these challenges can be overcome, to achieve re-integration of engineering within the spatial design process? In this paper, the lessons learned based on 3 consecutive years of interdisciplinary project-based research and education are discussed. The methods and tools of interdisciplinary design developed through research by the Delft University of Technology have been tested by six multidisciplinary groups of students.

This paper is structured as follows. First, the framework of interdisciplinary methods was set-up that were used in the approach to the interdisciplinary design projects. Subsequently, insights on interdisciplinary design that results in a survey among the participating students were discussed. The survey consisted of four components: understanding of multidisciplinary and interdisciplinary, multidisciplinary and interdisciplinary team process, the role of the engineer and useful outcomes of the projects. In the final section, the results are placed in a broader context and conclusions are drawn.

2. Framework of interdisciplinary methods

Over the last decade, a body of literature has emerged about the interdisciplinary field, where different fields of knowledge can interact in order to obtain a better understanding of problems, or to produce better answers to complex problems. Despite handbooks (Frodeman *et al.*, 2017; Hirsh Hadorn *et al.*, 2008; Lyall *et al.*, 2011a, 2011b) listing practical approaches to interdisciplinary working, a methodology for interdisciplinary methods in the field of urban infrastructure development is still lacking. In general, interdisciplinary research in all its forms, ranging from non-committal knowledge sharing to mandatory knowledge integration of parallel research trajectories, is known for its challenges (COST, 2014; De Boer *et al.*, 2006), in particular due to paradigmatic confusion between engineering and spatial planning. De Boer *et al.* (2006) acknowledge five forms of integration on a scale with increasing interdependency: mutual exchange, mutual influence, goal-integration, basic integration and managed integration. In building the interdisciplinary design conditions all these aspects are considered to be necessary throughout the entire process:

(*a*) *Mutual exchange*: a common problem to solve, physical co-location and establishment of a team philosophy to support interdisciplinary research are helpful (National Academies, 2015). Practically this means creating a group in which there is an organised exchange, such as group building through excursions, regular presentations and meetings, workshops and shared mentors from research staff from other disciplines. For example, a fieldtrip is important for creating informal exchange that builds trust. This is a major step in analysis and synthesis, to be able to create a framework that all disciplines can use for evaluation and decision making.

(*b*) *Mutual influence*: key is the extent to which a multi-layered problem-statement affects the interdependencies in the design project. Interdisciplinary design works best when it responds to a problem or process that exceeds the reach of any single discipline or investigator, but fails when a team does not function collaboratively. This failure of a team to gel or function collaboratively may happen for various reasons: individual members may place the importance of their own work ahead of the team vision or devalue the contributions of other team members, or the team may lack leadership. Other contributing causes of lower-than-expected outcomes may be inadequate recognition for contributions to each team, lack of participation or understanding by senior staff members (National Academies, 2015), inadequate time for participants to establish close working relationships, a poor match in personalities within the team (Belbin, 2000) and/or insufficient funding. According to (Lyall *et al*., 2011b), 'Interdisciplinary collaborations fail when there is a lack of understanding of the roles that the contributing disciplines can play. This can lead to unrealistic over-expectations or a trivialized view, for example, of the role of the social sciences within an engineering-led project'.

(*c*) The approach of goal integration probably has the largest degrees of freedom for the researchers involved; and a comparatively smaller chance of resulting in inter-, rather than multi-disciplinary findings.

(*d*) Basic integration can be carried out by making clear the scoping per discipline, which through a charrette method can be exchanged in an organised manner and in which knowledge from different disciplines is integrated. This takes quite an effort, because the process and structuring of using knowledge can differ in distinctive ways (Bradbeer, 1999) and are based on different rationales. Therefore, reflective skills are necessary to understand the challenges, difficulties and limitations of interdisciplinary design. For example, it may be difficult for engineering students to deal with the fact that there is not a single 'best' solution to a wicked problem, and thus designers have to work with variation and selection, and with the knowledge that solutions are always tentative and temporary (Van Gunsteren, 1976).

(*e*) Managed integration is the actual integrated design in which integrated knowledge is synthesised.

The interdisciplinary design process does not differ from the general spatial design process in the sense that it is ambiguous, personal and somewhat intangible. Van Dooren *et al*. (2014) have shown that integration of other disciplines is an essential part of the process of spatial design and that it can be included in a framework. This framework is not a step-by-step guide for a successful design process, but is an overview of five generic elements involved in designing, that make the design process more explicit and structured. The five elements are:

(*a*) *domains*: design is about making space with structures, for functions and within an urban and social, historical and philosophical context.
(*b*) A frame of reference or library of examples of other designs or principles.
(*c*) *Sketching/modelling*: representation or visualisation of ideas.
(*d*) *Guiding theme or qualities*: considering the programme or another idea as a starting point/concept.
(*e*) *Experimenting*: trying out different alternatives, out-of-the-box thinking.

These elements can be organised in the analysis and synthesis phase (Table 1), where the domains of context are investigated and a frame of reference is built on the base of which experimenting and sketching/modelling disciplinary ideas are brought towards interdisciplinary ideas. The process is characterised by moving from 'divergence', or consideration of many possible approaches, to eventual 'convergence', where promising design directions are developed and refined for eventual introduction. The analysis is devoted to co-creative and participatory activities to generate ideas worth exploring, and the synthesis is devoted to developing, evaluating and refining design directions.

In the second phase (design), the group creates several rounds of designs by way of simulation, evaluation and decision, while developing the disciplinary knowledge to support each design. The final phase is the delivery of the final product and conclusions.

Considering this theoretical frame, the interdisciplinary design approach was built on integrating conditions and an integrating process. The conditions include the five forms of De Boer *et al*. (2006): mutual exchange, mutual influence, goal-integration, basic integration and managed integration.

This integrating process includes three project phases: (*i*) analysis and synthesis, (*ii*) design-stage simulation, evaluation and decision and (*iii*) delivery of the project and conclusions based on the spatial design framework of Van Dooren.

3. Method of interdisciplinary design

The first important aspect of setting up an interdisciplinary design project is assigning staff members to intensively guide the student design groups. Then the project follows the three main phases of the interdisciplinary process: analysis and synthesis, design and conclusion as described in the theory framework and built on the interdisciplinary conditions, described above. In the following, each phase is elaborated on (Table 2).

3.1 Analysis and synthesis phase

In the first phase of analysis and synthesis the conditions and context of the project are created. This was achieved by way of a number of workshops and a site visit.

Preparatory workshop 1: multidisciplinary context: The first workshop was aimed at making practical working arrangements including how the information exchange will take place.

Table 2. Sequence of activities in the developed interdisciplinary process

Analysis & synthesis phase →		Design phase →		Conclusion phase
Setting multidisciplinary context Making cross-disciplinary relations Investigation of the context: fieldtrip	I. Form an interdisciplinary preliminary group vision on the problem(s) and potential solutions strategies. II. Form a disciplinary body of knowledge. III. Define a scope of each discipline applying the same criteria for evaluation. IV. Integrate the scopes in several charrette rounds and define the final framework. V. Connect the framework to the preliminary vision.	Iterations of disciplinary refinement and interdisciplinary integration		Final plan and report

The students were also forced to get to know each other on a personal basis by performing a 'speed dating' session. The context was set by lectures focused on an introduction to the local case and on interdisciplinary working methods. This is how the interdisciplinary condition is created.

Preparatory workshop 2: cross-disciplinary relations: In preparation for the second workshop, the students were asked to formulate questions for their own discipline, what they would like to ask the other disciplines and what they can offer the other disciplines. Also, in preparation for the workshop the disciplinary groups made an inventory of available and missing data and information about the case for their discipline as well as necessary general knowledge. The agenda of the second workshop was discussion of the prepared questions, discussion of relation schemes, presentation of disciplinary information and discussion of the research questions. In this process a charrette method is adopted, in which all disciplines meet each other one on one, taking turns. The 'charrette' (Lennertz *et al.*, 2014) is about creating involvement by organising a discussion in successive rounds in which the data are discussed and step-by-step, or round-by-round, integration of information that can be used for synthesis and design becomes group knowledge. The agenda items of the workshop helped students formulate relations between the disciplines and learn the value of the different disciplines and what their scope is towards the project at hand.

Site visit: interdisciplinary vision and framework: The two 'in-house' workshops prepared for the site visit, where the staff and students visited the site and met stakeholders. The workshop that was held during the fieldtrip is a long working session over several days (depending on the amount of disciplines in the group) that has the following agenda:

(I) form an interdisciplinary preliminary group vision on the problem(s) and potential solution strategies,
(II) form a disciplinary body of knowledge,
(III) define a scope of each discipline applying the same criteria for evaluation,
(IV) integrate the scopes in several charrette rounds and define the final framework and
(V) connect the framework to the preliminary vision.

I: Form an interdisciplinary group vision: The base group is the multidisciplinary team that will perform the interdisciplinary synthesis and design. Before starting the buildup of the group's body of knowledge that through scoping will lead to an interdisciplinary framework that will support the strategy and design, the base group formulates its vision for the proposed project. This is important because the direction that is chosen defines the knowledge necessary and sets the scene for goal-integration. It is important to have a shared response to what each team member has learned. The vision is not about problem solving, but problem seeking; about how the future of the case will be best served and which problems will be addressed with what motivation. Setting long-term goals for the site (i.e. 40 years), doing a strength–weakness–opportunities–threats (SWOT) analysis, and finding a motto for the approach helps encourage fundamental agreement on the group vision.

II: Form a disciplinary body of knowledge: Next, the students are put back into the comfort zone of their disciplinary group, and connect their experiences on the fieldtrip to references of other international projects and to potential measures in their discipline, to be able to identify the interfaces with the other disciplines from their own clear perspective. Each disciplinary group answers the following questions:

- What do you know about the site?
- What do you still need to know about the site?
- What kind of solutions do you see possible for the site?
- Do you know reference projects that could be used as a source of inspiration?
- Can you define an overarching concept or theme for the solutions you have in mind?

After defining the site-specific measures, sets of measures within a specific concept or the different overarching concepts are chosen by each disciplinary group.

III: Define a scope of each discipline the same criteria for evaluation: The integration of information and ideas will be carried out using a method of scoping. With the scoping method, the first condition is met by creating a common understanding of the problem and context of the case. Each group, within their created body of knowledge, evaluates their chosen measures or concepts by ranking them with the 4P-tetraether theory by Duijvestein and Van Dorst (2006). The 'triple bottom line' of the tetrahedron consists of the three Ps (UN, 2002): people, planet and prosperity. In spatial planning and design, the very general sustainability aspects of these three Ps are translated into territorial interventions seeking balance and synergy. This crucial strategic activity is captured by a fourth P in the tetrahedron, representing both project and process. 'Project' stands for the physical results of the balance between the three Ps and represents spatial quality, relations through scales, (bio)diversity, robustness and aesthetics. 'Process' regards the interaction between stakeholders, their skills and the institutional context in realising a balanced design.

In adopting this theory, each group ranks their previously chosen concepts and/or (sets of) measures using the following scopes, all as estimates:

- *people*: organisation (private/bottom-up to public/top-down),
- *planet*: engineering impact (green, nature-based solutions to grey, hard structures) or sustainability goals and
- *prosperity*: financial (inexpensive and highly cost effective to expensive, low cost-effective) or non-monetary value impact.

  On the basis of this they balance out their decisions and formulate the last scope:
- *project*: preferable to least preferable measures or concepts.

The making of the scopes (see e.g. Figure 2) provides the disciplines better insight and understanding into the concepts and sets of measures they formulated and also allows them to connect their proposals to the proposals of the other disciplines that used the same scopes. Then the chosen concepts and measures can also be weighed in relation to measures and concepts of the other disciplines; true interaction between the disciplines takes place during these dialogues.

IV: Integrate the scopes in several charrette rounds and define the final framework: Next, the interdisciplinary framework of possibilities is built-up from the disciplinary scopes that are brought together using the charrette method. Each disciplinary group confronts their scope with another discipline to create a common understanding of connections and barriers. They create a new combined set of scopes. After rounds of confronting two disciplines each, a round with three, and possibly four, disciplines are done in which the scopes are more and more integrated, leading to a final combined scope of interdisciplinary possibilities, which is the interdisciplinary framework.

V: Connect the framework to the preliminary vision: The last step in the analysis and synthesis phase is to connect the framework to the preliminary vision. The students return with the framework to their multidisciplinary base group and review their preliminary vision by discussing the sets of choices for each discipline. This leads to the projection of a script or strategy that executes their vision. With this exercise, the framework shows the relation between the choices within the scopes of the disciplines to explain and assess the case from an interdisciplinary viewpoint.

3.2 Design phase

During the former phase the mutual exchange, mutual influence, goal-integration, basic integration and managed integration were extensively established. The transition to the phase of design takes place gradually during the fieldtrip working session and delivers a preliminary interdisciplinary design.

Series of workshops: Iterations of disciplinary refinement and interdisciplinary integration: This preliminary design is further developed after the fieldtrip through simulation, evaluation and decision making. This is done in alternating disciplinary and interdisciplinary workshops, group meetings, subgroup meetings and individual work sessions. Each discipline develops their component of the proposal more in depth, after which the group re-valuates the proposal accordingly to decide on the refinement necessary. Each team member develops their disciplinary component of the plan towards the final design proposal.

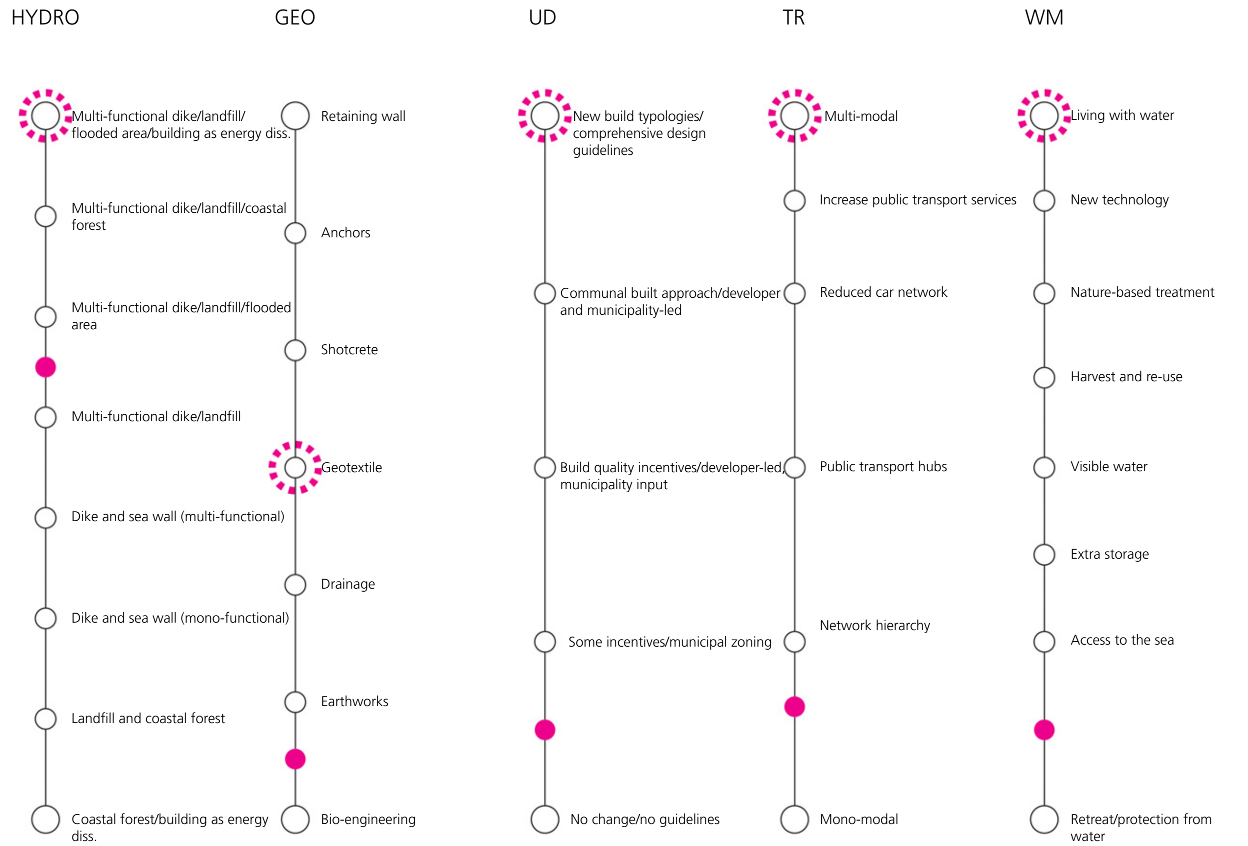

Figure 2. Example of a set of scopes from a student group that made a conceptual design for Yuriage, Natori, Japan (2017/2018). This graph represents the first step of separate scopes that were merged in the charrette rounds. From left to right the scopes of: hydraulic engineering, geo-engineering, urbanism, transport and water management. The shaded dot is the status quo, and the dotted circle is where the students identified the ideal situation for each scope

3.3 Conclusion phase

In the conclusion phase the final products of the project are delivered. The overall proposal and the disciplinary components are presented in a coherent plan that can be evaluated according to the formulated vision and the interdisciplinary framework that is now used to evaluate the final product.

Deliverables: Report/paper and reflection: The results are presented in a report or scientific paper and include a reflection from each team member about the process and the project content. The group work also results in a short video presentation (https://youtu.be/OoANpXJsxT4; https://youtu.be/R1sNUlpeIss).

4. Evaluation of student survey results

To obtain insight about the effectiveness of this interdisciplinary design method, an anonymous survey of students participating in the projects was carried out, and 38 responses were received. Of these, 66% participated by way of a multidisciplinary project group, and 34% participated by way of an individual MSc thesis project (they fully took part in the workshops and site visit activities in the analysis and synthesis phase, but thereafter branched off to work on their thesis research and only 'loosely interacted' with the multidisciplinary project groups that continued with the design and conclusion phases). In total, 71% were still students at the time of the survey, while 29% had graduated and were working. Students from the faculty of civil engineering are from the master tracks hydraulic engineering (ten students), geo-engineering (two), transport infrastructure and logistics (seven), transport and planning (one) and urban water management (three). Students from the faculty of architecture and the built environment are from the master tracks urbanism (eight students), landscape architecture (four), architecture (one), building technology (one) and management in the built environment (one). Among the 38 students, two participated in the 2016–2017 Tokyo case, eight in the 2017–2018 Yuriage case, five in the 2018 Tirana case, 12 in the 2018–2019 Otsuchi case, five in the 2019 Ghana case and six in the 2019 Houston case. Some of the sub-disciplines were not strongly represented, so most of the following analysis is framed in terms of the faculties involved (architecture and engineering) rather than the sub-disciplines. This is legitimated by the fact that urban infrastructure development can be characterised as a 'broad' interdisciplinarity: conceptually diverse fields cross the boundaries of broad intellectual areas, the epistemological heterogeneity is a huge challenge (Huutoniemi *et al.*, 2010). Within each group (architecture or engineering) there is a so-called 'narrow' interdisciplinarity': participating fields are conceptually close to each other, typically representing the same broad domain (Huutoniemi *et al.*, 2010).

The first batch of 14 questions related to student's background and perspective on collaboration among multiple disciplines. The next 22 questions related to their perspective on the methodology and results of the overall project. The answers are subjected to a quantitative (I-7, I-I-9 to I-13, II-1 to II-4, II-11, II-12, II-14, II-18, II-20) and a qualitative (I-6, I-8, I-10 to I-14, and II-5 to II-10, II-13, II-15 to II-17, II-19, II-21, II-22) analysis.

The following evaluation of the survey results is structured into three sections. The first section discusses how notions of 'multidisciplinary' and 'interdisciplinary' were understood. The second section analyses the multidisciplinary team and interdisciplinary process of the projects. The last section analyses the products of the projects.

4.1 Understanding of multidisciplinary and interdisciplinary

There is little consensus on what the characteristics are that define multi- and interdisciplinarity. To understand each student's perspective hereon, they were asked what they consider as the core activities of multidisciplinary working (question I-6) and of interdisciplinary working (question I-8). They could choose multiple options from a list of activities, where for both questions the list was the same. The list included activities that concerned personal/individual aspects, aspects that are needed to work in a group, methods that could be applied and aspects that describe the type of activity. By making an intuitive choice out of this list the students give emphasis to what type of activity they consider as important for multi- and interdisciplinary working. The list is presented in Table 3.

Table 3 displays the responses on the whole and per faculty. The general insight is that 'multidisciplinary' is about communication (group aspect), information integration (method) and combining (activity). Interdisciplinary is about an open attitude (personal aspect), information integration (method) and communication (group aspect). This means that the difference between 'multidisciplinary' and 'interdisciplinary' is about the personal attitude towards the project and openness to intervention from other disciplines. Also, in 'multidisciplinary' the aspect of innovation is not mentioned at all, and design is considered equally important in both.

Per faculty, for 'multidisciplinary' the engineers and architects both put communication first, but then deviate where engineers put group work aspects high on the list, while architects mention methodology and personal aspects. For 'interdisciplinary', the results of the engineers conform the group results described above, but the architects as a group consider synthesis, co-design and open attitude as the most characterising aspects. These terms emphasise how personal, methodological and instrumental 'interdisciplinary' should be.

Finally looking into the differences between the disciplines, for 'multidisciplinary' the engineers each mention different aspects first, while for 'interdisciplinary' they all agree on the open attitude. The architecture students agree on communication and information integration. Also, for 'interdisciplinary' all but urbanism agree on it being about an open attitude. Due to the high number of urbanism students in the survey the overall outcome was 'synthesised' (Table 4).

This shows how 'multidisciplinary' and 'interdisciplinary' can be better framed; 'multidisciplinary' as being independent, parallel learning assignments of different disciplines in which group work aspects are prioritised; and 'interdisciplinary' being interdependent learning assignments of different disciplines in which

Table 3. List of activities ordered according to character of the activity

Personal aspects:	Group aspects	Methods	Type of activity:
open attitude	communication	design	bridging (connect)
inspiration	co-operation	co-design	confrontation (compare and tune)
	exchange	information integration	synthesise (combine into something new)
			assemblage (collection of parts)
			juxtapose (placed next to each other)
			combine (bring together)
			integrate (unite)
			transcend (go beyond)
			innovation (make better)

Table 4. Aspects chosen as definitive by engineering students, architecture students and the total group

	Multidisciplinary	**Interdisciplinary**
Engineering	14 communication, 12 combine, 6 exchange, 9 co-operation, 7 bridging, 8 inspiration, 6 information integration, 7 open attitude, 7 design, 7 co-design, 5 innovation, 4 integrate, 4 assemblage, 3 juxtapose, 2 synthesise, 2 confrontation, 2 co-operation	13 open attitude, 13 information integration, 12 co-operation, 11 exchange, 11 integrate, 11 communication, 9 co-design, 8 inspiration, 8 bridging, 7 innovation, 6 design, 6 confrontation, 5 synthesise, 4 combine, 3 assemblage, 2 transcend, 1 juxtapose
Architecture	12 communication, 11 information integration, 9 open attitude, 8 co-operation, 8 inspiration, 8 exchange, 6 synthesise, 6 integrate, 6 co-design, 5 confrontation, 5 bridging, 5 juxtapose, 5 combine, 4 assemblage, 2 transcend, 2 design	11 synthesise, 11 co-design, 11 open attitude, 10 communication, 9 integrate, 9 information integration, 8 co-operation, 6 innovation, 6 exchange, 5 juxtapose, 5 inspiration, 5 bridging, 4 design, 4 combine, 3 transcend, 3 confrontation, 1 assemblage
Total	26 communication, 17 information integration, 17 combine, 16 open attitude, 16 inspiration, 15 co-operation, 14 exchange, 13 co-design, 12 bridging, 10 integrate, 9 design, 8 synthesise, 8 juxtapose, 8 assemblage, 7 confrontation, 2 transcend	24 open attitude, 22 information integration, 21 communication, 20 co-operation, 20 integrate, 20 co-design, 17 exchange, 16 synthesise, 13 inspiration, 13 bridging, 13 innovation, 10 design, 9 confrontation, 8 combine, 5 transcend, 5 juxtapose, 4 assemblage

Numbers indicate the number of students who indicated each word

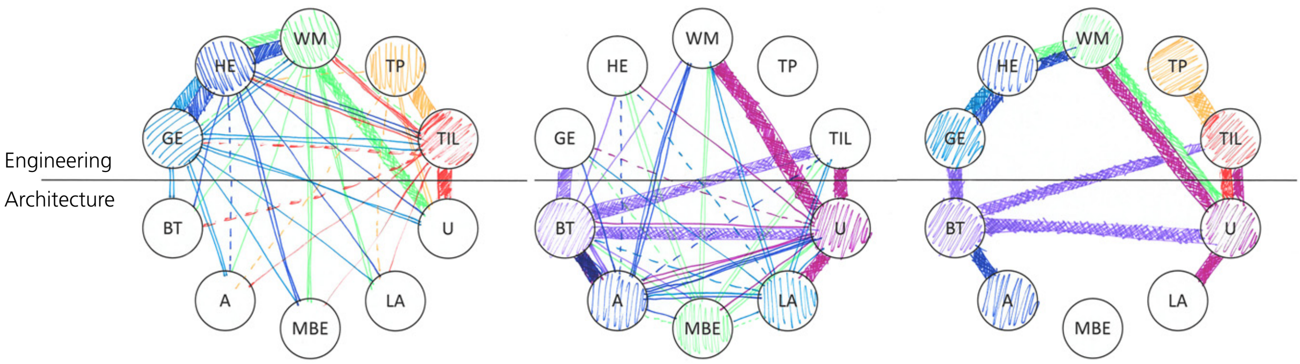

Figure 3. Answers to the question: how easy or difficult was it to 'integrate'/collaborate with (the representatives of) the participating disciplines? (QII-10). Responses of the engineering (left) and architecture students (centre), and the strongest relations (right). Strong to weakest relations are depicted by respectively a thick line, double line, single line or dotted line, in that order. Each discipline has its own colour to show the direction of the relation

a specific personal attitude is put central and group methods and activities are aimed at creating something new.

4.2 Multidisciplinary team and interdisciplinary process

The opinions of the students on how the disciplines interacted were evaluated in four questions in which they could give weight to the relation per discipline and an open part for further explanations. The answers to these questions were quantified and analysed. The analyses are visualised in a circular scheme (see e.g. Figure 3) in which the engineering disciplines are on top and the architecture disciplines are at the bottom. The connecting lines show the strength of connections as mentioned by the students. This scheme is used for the analysis of several types of relations between the different disciplines. To be able to keep the analysis readable the analysis is carried out in two parts: the first graph showing the perspective from engineering and the second from architecture students. The third graph shows only strong relations (those most appreciated or considered important) as the thick line, indicating a straightforward relation (QII-10), that is highly useful (QII-11), highly informative (QII-12) or has a large impact on the project (QII-13). Weaker to weakest relations are depicted respectively by a double line, single line or dotted line, in that order. Finally, each discipline has its own colour to show the direction of the relation.

Question II-10 relates to how easy or difficult it was to 'integrate'/collaborate with the (representatives of the) participating disciplines. Engineers found collaborating with the 'hard' engineering disciplines of hydraulic engineering (HE) and geotechnical engineering (GE) much easier than architects did, while both engineering and architecture students found collaborating with the 'soft' engineering disciplines of transport infrastructure and logistics (TIL) and water management (WM) easy. Architects had a much easier time collaborating with urbanism (U), landscape architecture (LA) and architecture (A) than engineers did. Both groups collaborated well with students from building technology (BT). Interestingly, engineering students had a much easier time than architecture students in collaborating with students from management of the built environment (MBE), while the transport planning (TP) students related easily with only TIL. The stronger and weaker relations between the specific disciplines as visualised in Figure 3 illustrate the easy, reciprocal relations such as GE–HE, HE–WM, WM–U and U–TIL. BT is strongly connected to multiple disciplines, while MBE is not strongly connected to any.

Question II-11 relates to which other disciplines were the most useful to the project/thesis (Figure 4). Engineers felt more strongly than architects that the 'hard' engineering disciplines of HE and GE made a useful contribution to each project. Interestingly, the contribution from the 'soft' engineering disciplines was viewed as more useful by architects than by engineers. U was considered useful by both. LA was appreciated much more by architects than by engineers, while A and BT were appreciated slightly more by architects than by engineers. As before, the contribution of MBE was appreciated much more by engineers than by Architects.

Question II-12 relates to how much was learned from the other disciplines (Figure 5). Engineers responded much more positively than architects did about HE, while engineers felt that they learned slightly more from GE than architects did. Engineers learned slightly more than architects did from TIL,

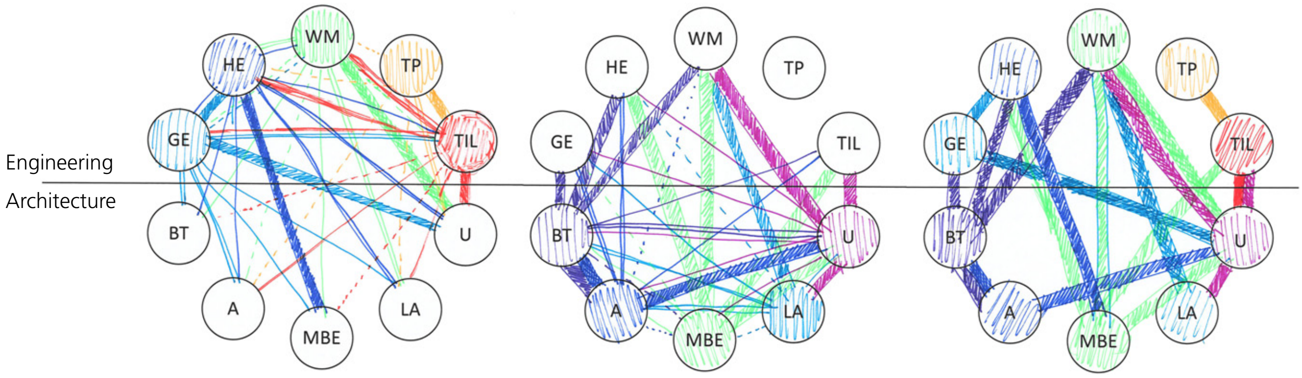

Figure 4. Answers to the question: which other discipline was the most useful to your project/thesis? (QII-11). Responses of the engineering (left) and architecture students (centre), and the strongest relations (right). Strong to weakest relations are depicted by respectively a thick line, double line, single line or dotted line, in that order. Each discipline has its own colour to show the direction of the relation

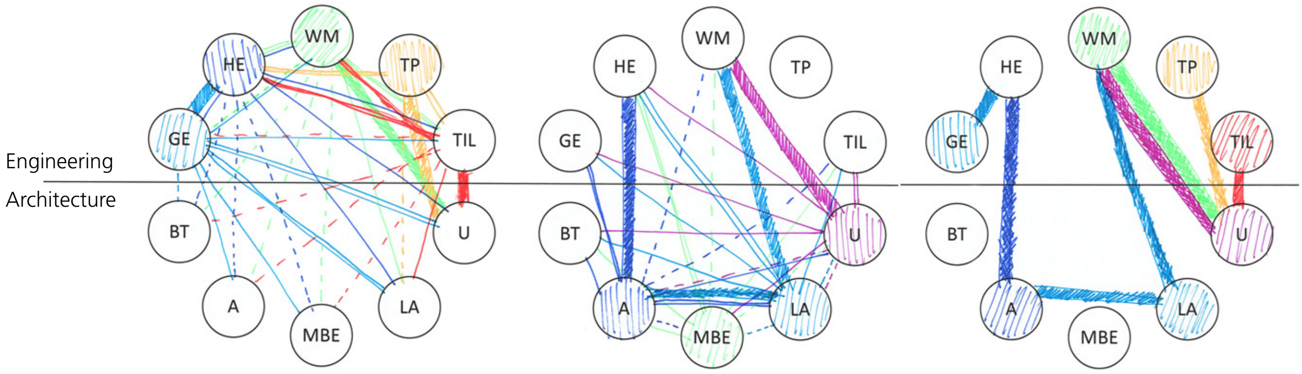

Figure 5. Answers to the question: how much they learned from the other disciplines (QII-12). Responses by the engineering (left) and architecture students (centre), and the strongest relations (right). Strong to weakest relations are depicted by respectively a thick line, double line, single line or dotted line, in that order. Each discipline has its own colour to show the direction of the relation

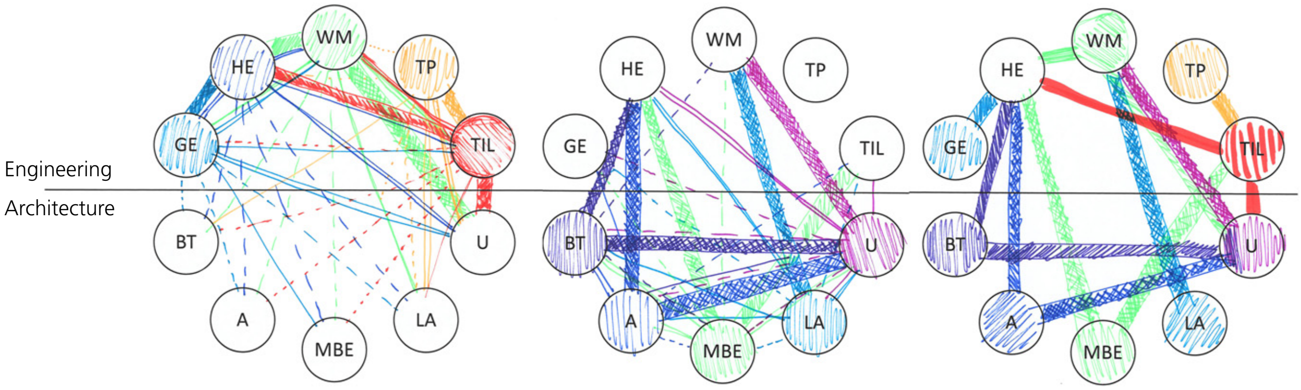

Figure 6. Answers to the question: which other discipline had the largest impact on the project? (Q II-13). Responses by the engineering (left) and architecture students (centre), and the strongest relations (right). Strong to weakest relations are depicted by respectively a thick line, double line, single line or dotted line, in that order. Each discipline has its own colour to show the direction of the relation

while the reverse is true for WM. Engineers learned significantly more than architects did from U. Engineers learned slightly more than architects did from LA and MBE, while the opposite is true for architecture and building technology. This reveals that HE, BT and MBE do not learn strongly from other specific disciplines, LA connected the most and WM and U had a reciprocal relation.

Question II-13 relates to which other disciplines had the largest impact on the project (Figure 6). The 'hard' engineering disciplines were viewed as more impactful by engineers than by architects. TIL was slightly more impactful to engineers than to architects, with the opposite true for WM. U was equally impactful to both groups. LA, A and BT were more impactful to architects than to engineers, while MBE again showed the opposite result.

Overall, explanations by students on these disciplinary relations include:

- Some disciplines, such as HE, provide clear boundary conditions to the project.
- Some disciplines, such as LA, provide novel framing of the project (e.g. ecological sustainability and psychological effects) that led to exploring new measures and design approaches.
- The connections between some disciplines, such as TIL/TP/WM and U/LA/MBE, are well understood, due to the shared focus on liveability of the built environment.
- The connections between some disciplines, such as WM, U and LA, are easily made by way of concepts such as 'building with nature'.
- Some connections were unexpectedly discovered in the process, such as how new technologies in GE (regarding subsurface stability) can affect the design of public space and the built environment.
- Disciplines from the architecture faculty provided new insight, especially into non-technical issues, and emphasise how engineering solutions have a social impact.

Each student group also developed a model for how they relate their disciplines to the total planning process they have conducted with their team. As an example, Figure 7 shows this model for the Yuriage project. As can be observed, the relation between the disciplines differs in the order of appearance, time and scale.

Overall, the group performance (question II-15) is assessed as 7.4/10; the engineers gave it an average of 7.5/10 (answers range from 5 to 10) and the architecture students a 7.4/10 (answers range from 5 to 9). Overall, participants felt that it was possible to give open feedback to the group members (question II-16). There is no deviation between engineering and architecture students in what they found the most challenging part of the project (question II-5), the whole group felt the process (deciding on the steps) was the most challenging, in particular decision making within the team on the steps. The next challenging was the content (integrating the knowledge) and the least challenging was the organisation (getting the group together). The indicated reasons behind these challenges are listed below.

Process:

- Personality clashes;
- defining a shared project aim/goal/ambitions/target/outcome;
- defining project steps, what iteration should be done and the role of design.

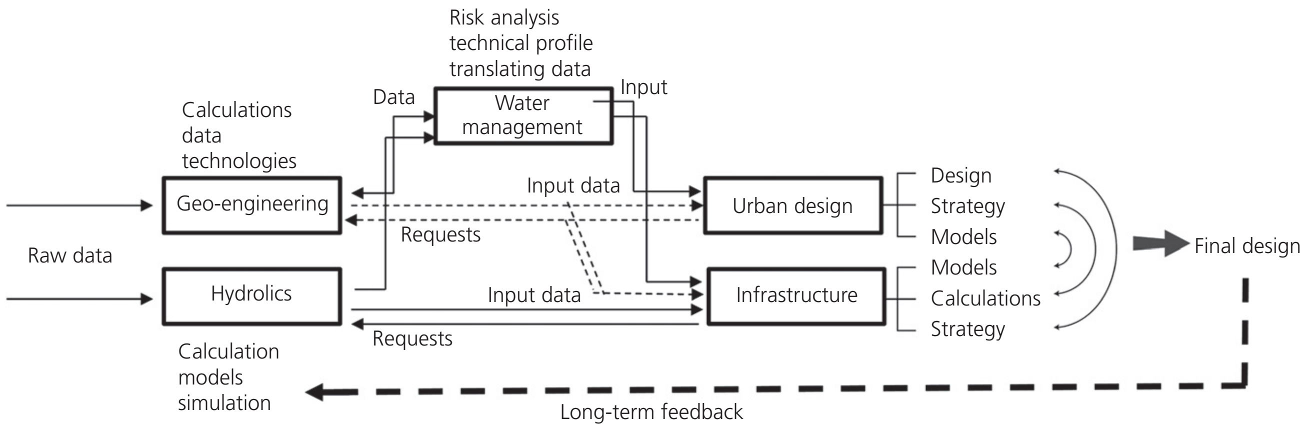

Figure 7. Model that the students developed showing the relation between the disciplines for project Yuriage ('hydrolics' is the combination of hydrology and hydraulic engineering)

Content:

- Domains have different ways of organising and integrating information.
- How to give equal weight to inputs from all domains. Qualitative assumptions (research by design as a method) were taken relatively less seriously.
- Requirement to acquire knowledge about the other disciplines first.
- The iterative approach of the project is possible due the lack of a specific goal/outcome; this lack is however difficult for engineering students, as they are used to problem solving.
- Negotiating goals without clear criteria to start from, so the common goal was in constant flux. This allowed exploring and developing new findings or solutions, but it takes time and makes part of the work redundant. This negotiation process highlighted how different values (safety, sustainability, efficiency, conviviality, etc.) are attached to the different disciplines, and was the most fundamental thing to align before designing a proposal.

Organisation:

- Organising meetings or discussions on short notice,
- matching academic calendars of the different faculties,
- larger groups have less focus,
- commitment.

On question II-6 (what the most challenging phase was of the project), opinions were almost evenly spread over the four options: analysis, synthesis, design and production. All phases run into issues such as lack of time and maintaining motivation over time, lack of information and communication, agreement on a storyline and establishing a narrative or clear story between the disciplines seemed fragmented at times. Initiation is difficult, as architects seem to 'waste time' discussing and not producing, while engineers start producing without enough discussing/designing or consensus on boundary conditions and goals. The major obstacles to working with other disciplines are vocabulary/concepts (i.e. the meaning of 'design') and perspective, and after that aim/goal, methods and instruments are mentioned only a few times (II-7). The following quote from student responses illustrates this result:

> Different disciplines work on very different levels of detail. Architects wait to the end before they start actually working on content. The attitude of engineers is to make a problem as clear as possible, without too many variables, while architects try to keep the whole context in mind. As an engineer we are used to expressing 'everything' in numbers where it became clear that some other disciplines had a more abstract approach in their goals. Sometimes architecture students are very rigorous in the methodology to follow. In terms of conceptual framework, I have learnt a lot from Architecture (ABE) students, but their proposals sometimes lack practical application, what leads to lack of agreement.

Question II-10 (what part of the project could have improved to reach a better group performance as a whole) points out that the content (integrating the knowledge), the process (deciding on the steps) and the organisation (getting the group together) are equally important. When asking more into aspects (II-8) the students overall agree that individual personalities and the size of the group have the most effect, culture and local counterparts some effect, and gender has least effect on the interdisciplinary work.

4.3 Survey results: products of the projects

The six case studies resulted in three scientific papers (one published (Krishnan *et al.*, 2019), two under review), seven group reports, one preliminary thesis and 12 MSc graduation theses (Areso Rossi *et al.*, 2018; Broere *et al.*, 2019; Claassen *et al.*, 2018; Dobbelsteen, 2018; Filipouskaya, 2019; Glasbergen, 2018; Höller and van de Wiel, 2019; Li *et al.*, 2019, Möhring, 2018; Mujumdar, 2019; Mustaqim, 2018; Nederlof, 2019; Prida Guillén, 2019; Rao, 2019; Roubos, 2019; Salet, 2019; Vafa, 2018; Van den Berg *et al.*, 2019; Van Dijk, 2018; Van Driel, 2018; Van Klaveren *et al.*, 2019; Yasaku, 2018, 2019). The group reports either focused on the interdisciplinary process or the results, while projects carried out as graduation theses go more in depth than in breadth across the interdisciplinary scope. Thesis students do mention that even though this is the case, they do find that their research study was grounded in the mindset developed in the multidisciplinary project.

Question II-9 asked if the result of the project could be considered an interdisciplinary design and how the students would asses that. The 23 engineering students scored their project with an average of 7/10 (responses varying between 4 and 10 and hydraulic engineers being most positive) and the 13 architecture students scored a 6.5/10 (varying between 4 and 8). On the question how to assess interdisciplinarity the following answers were given:

- presence of shared story telling (intertwined ideas),
- presence of intertwined solutions (serving multiple disciplinary goals),
- showing connection between problem solving and problem seeking, with a set of aspects presented in the end product,
- presentation of integrated design and roadmap,
- showing response to disciplinary boundaries, with boundary spanning actively present in analysis.

These answers clearly give insight into how interdisciplinary design can be achieved and assessed. It is about developing a shared story of ideas that actively make use of employing their disciplinary boundaries and goals in urban development.

5. Conclusions

Interdisciplinary and international research and education projects were focused on urban development in disaster reconstruction areas that had suffered from pluvial, fluvial and coastal flooding. The condition of a disaster is important because it provides current and active cases in which, due to actual experience, the aspect of safety and the role of infrastructure is quite important. A second important issue is that for experiential learning, a structured activity that focuses on participation and interaction, urban development is a multidisciplinary arena and an interdisciplinary design by nature, balancing out interest of sectors or stakeholders. For example, interdisciplinary design can be found in urban spaces that meet goals of multiple domains: a green space for urban amenity and health (urbanism), an important space for nature (landscape architecture) providing a good environment (architecture) that holds water but prevents flooding (water management) and that involves roads and transport (transport).

This paper reflects on experiences with multidisciplinary teams of students from six projects and provides insights that were acquired by asking the 38 participants to fill in the questionnaire enquiring into the process and content of their project. For the interpretation of the results it should be noted that there is an imbalance in numbers of students from different disciplinary groups; hydraulic engineering and urbanism have a larger cohort and are thus more representative. However, this imbalance is partly addressed by using the coarser classifications of civil engineering and architecture, rather than individual sub-disciplines. The analysis shows that especially the engineering disciplines reach out to each other, being comfortable with ‘narrow’ interdisciplinarity, and from the architecture disciplines the urbanism and landscape students operate well in the ‘wide’ interdisciplinary fashion.

The main questions posed in this paper are: what should interdisciplinary design entail, what are its challenges, and how these challenges can be overcome? Answers to these questions can be formulated by using the results of the survey. On the basis of an exploration of the theory on the challenges of multi- and interdisciplinary working, three aspects were considered in the analysis of the survey results: (*a*) understanding of multidisciplinary and interdisciplinary, (*b*) multidisciplinary team and interdisciplinary processes and (*c*) and products of the projects.

From the results on understanding of multidisciplinary and interdisciplinary it can be concluded that ‘multidisciplinary’ is considered a group process and not an outcome, and mainly communication skills are important. Although the projects were not focused on teamwork aspects such as negotiation, decision making and conflict management, these aspects emerged from the negotiations among disciplines that students were forced to undertake in order to create an integrated design. ‘Interdisciplinary’ is considered the outcome and intertwining of knowledge and products. Interdisciplinary design is the integration of sectoral responsibilities, goals and solutions.

On multidisciplinary teamwork and the interdisciplinary process, the survey indicates that success factors for the ability to combine sectors and interdisciplinary learning are:

- recognising the other disciplines for their role, contribution and capabilities.

- Group building is key, with clear organisations and steps.
- Methods to be able to link ideas are crucial.
- Acknowledge that in infrastructure and environment projects in post-disaster reconstruction, which are wicked by nature, the learning process is evaluated quite differently for disciplines used to solving tame problems than for the disciplines that are used to dealing with wicked problems. There is no one best solution to the problem, there is not even only one problem.
- Relation management between the disciplines is needed, especially as not all relations are in balance or reciprocal; this is not necessarily a problem but needs to be known and accepted. Sometimes data needed by one discipline are found or generated (or is made understandable or accessible) through another discipline.
- Mutual understanding of the general scope and scale of the disciplines is to be created during the multi-disciplinary working process.
- Especially activities that increase interaction such as fieldwork (intense group work in the context of the project) and organised exchange by way of scoping and charrette contribute to interdisciplinary design.

The last batch of survey questions consider the products of the projects and how interdisciplinary these are. The students score their projects a 7/10 on average, and answer to the open question that the level of interdisciplinarity can be assessed from (1) the presence of intertwined ideas (one story), (2) intertwined solutions (serving multiple disciplinary goals), (3) connection between problem seeking and problem solving, (4) integration between design and roadmap and (5) a clear response to disciplinary boundaries.

Interdisciplinary design should entail a conscious and orchestrated process in which the disciplines present their ideas within a shared value system before systematic integration. The challenges are at personal and cognitive levels, the open attitude that is necessary to be able to perceive and react, process and understand, retrieve information and make decisions and produce appropriate responses in co-creation. This can be achieved by training and learning the value of this open attitude and the acknowledgement of the necessity and added quality of the re-integration of engineering within the spatial design process.

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