REPRESENTATIONS IN SUSTAINABILITY SCIENCE

TOOLS TO ANALYZE, ENVISION, ENGAGE, AND LEARN

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“Representation in Sustainability Science: Tools to Analyze, Envision, Engage, and Learn”

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"If you can spray them, then they are real."

The day when Ian Hacking found out that "weak interactions of small particle physics are as real as falling in love," and "he became a scientific realist"

(Ian Hacking in "Representing and Intervening" 1983)

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Summary

Supporting sustainability transformation through research requires, in equal parts, knowledge about complex problems and knowledge that supports individual and collective action to change the system. Recasting the conditions, characteristics, and modes of research processes that address these needs leads to solution-oriented research in sustainability science. This is supported by systematically analyzing the system's dynamics, envisioning the desired future target state, and by engaging and designing strategic pathways. In addition, learning and capacity building are important crosscutting processes for co-producing required knowledge. In research, we use sophisticated representations as mediators between theories and objects of interest, depicted as visualizations, models, and simulations. They simplify, idealize, and store large and dense amounts of information. Representations are already employed in the service of sustainability, e.g., in communication about climate change. Understanding them as tools to facilitate processes, dialogue, mutual learning, shared understanding, and communication can yield contributions to knowledge processes of analyzing, envisioning, and engaging, and has implications on the design of the sustainability solution. Therefore I ask, what role do representations and representational practices play in the generation of sustainability solutions in different knowledge processes?

Four empirical case studies applying rough set analysis, multivariate statistics, systematic literature review, and expert interviews target this research question. The overall aim of this dissertation is to contribute to a stronger foundation and the role of representation in sustainability science. This includes: (i) to explore and conceptualize representations for the three knowledge processes along selected characteristics and mechanisms; (ii) to understand representational practices as tools and embedded into larger methodological frameworks; (iii) to understand the connection between representation and (mutual) learning in sustainability science. Results point toward crosscutting mechanisms of representations for knowledge processes and the need to build representational literacy to responsible design and participate in representational practices for sustainability.

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CHAPTER 1
Introduction

Represented: Mediators for Solutions

It is increasingly clear that, in supporting sustainability transformations through research, we do not necessarily lack knowledge about the complex problems we face, but rather knowledge that can support individual and collective action in changing our socio-ecological systems, intervening in these systems, and implementing adequate solutions so that we do what we do sustainably (Fischer et al., 2012; Robinson and Sirard, 2005). Recasting conditions, characteristics, and modes of research processes that address this need requires "science to be harnessed more effective to this task" and more critical reflection on methodology (van Kerkhoff and Lebel, 2006, p. 446). We need solution-oriented research in sustainability science that focuses on real options in decision-making and the development of pathways by which actors learn and adapt continuously to new technology, practices, and knowledge (Miller et al., 2014; Sarewitz et al., 2012).

The widely accepted insight that generating solution-oriented knowledge requires the information to be not only credible and evidence-based, but also applicable and legitimate, presupposes adequate communication and negotiation among a wide range of actors with contrasting beliefs and values (Cash et al., 2003; Wiek et al., 2012). Subsequently, a new procedural understanding in sustainability science has emerged that sets up methods and research modes at the science-society-policy interface, e.g., in transdisciplinary case studies, transition management approaches, and real-world laboratories (Lang et al., 2012; Loorbach, 2007; Nevens et al., 2013). These take into account a long-term perspective about systems change; this process envisions the researcher as a facilitator and mediator who manages knowledge generation democratically and transparently (Brundiers et al., 2013; Cash et al., 2003; Miller et al., 2014; Wittmayer et al., 2014). Within innovative research processes, the concept of learning has gained an importance beyond education. Learning refers to the continuous mutual interaction of kinds of knowledge from different actors and backgrounds to increase social relevance and saliency of the solution created in research processes (Polk and Knutsson, 2008). The interaction also builds the necessary capacity in actors to leverage their knowledge for planning and implementing solutions, thereby driving action toward sustainability (Keeler et al., 2018; Wolfram, 2016).

In order to support the generation and implementation of sustainability solutions, we have to analyze, envision, and engage. "Analyzing" stands for the genesis of the complex system dynamics that underlie sustainability problems as well as respective solutions, including different stances of framing, interpreting, and perceiving (Fiksel et al., 2013; Hjorth and Bagheri, 2006). "Envisioning" stands for one approach to generate an evidence-based image of a sustainable future to guide behavior and action, opening up to social innovation and transformation while adhering to the pluralism of norms and values spanning generations (Shipley and Newkirk, 1999; Wiek and Iwaniec, 2014). “Engaging” captures the application, implementation, and experimentation of tangible strategies that take into account the institutional, technical, cultural dimensions of change (Abson et al., 2014; Urmetzer et al., 2018). In this order, these three processes resonate with the three knowledge types of system knowledge, target knowledge, and transformation knowledge that are researched in concerted processes in order to generate sustainability solutions (Hirsch Hadorn et al., 2008b; ProClim, 1997; Urmetzer et al., 2018).

Originally bearing the meaning “to imagine,” (German: vergegenwärtigen, vorstellen) representation is the “description or portrayal of someone or something in a particular way or as being of a certain nature.” (Oxford English Dictionary, 2019). In science, we use sophisticated tools—models, images, and simulations—to make sense of the world (see Figures 1 A, B, C, and D), as well as visualizations, which are generally described as representations and which are generated and modified in representational practices (Suárez, 2008). These different tools mediate between theories and their targets, that is, the objects of interest from the real world (Hacking, 1983). Thanks to representations, we can encode large amounts of complex information (Mößner, 2018). In that regard, the following work is advanced: (i) landscape planning for climate adaption with studies about effective communication and demonstration of local climate change through visualization and place-based experiences (Sheppard, 2015; Warren-Kretzschmar and Tiedtke, 2005); (ii) interactive climate change visualizations and simulation that drive decision-making and participatory engagement (O’Neill and Smith, 2014; Zyngier et al., 2017); (iii) gaming approaches (see Figure 1 C) that include simulations and narratives utilizing learning approaches for sustainable urban planning (Withycombe Keeler et al., 2017). Such approaches are translated into practical urban planning applying paper-pencil visualization, gaming, and geo-spatial data analysis to real-world settings, as in the NextHamburg initiative (von Hoff, 2016).

In philosophical discourse, representations are critical in organizing scientific knowledge and are increasingly valued for their experimental and “explorative creative activity [that bring] an immediate contrast and possible comparison […] (Frigg, 2003; Latour, 2000; Mitchell, 2004; Morgan, 2005, p. 318; Morgan and Morrison, 1999). Nevertheless, users require some capacities to apply and utilize representations effectively and ethically (Bailer-Jones, 2008; Latour, 2000; Mößner, 2018). In addition to the academic discussions, representational practice (pictorial, audial, or tactile) is an inherent human ability and an object of sociocultural developments (Hacking, 1983, p. 133). Despite their importance in scientific practice, representations and their use in supporting the generation of sustainability solutions have not been scrutinized.

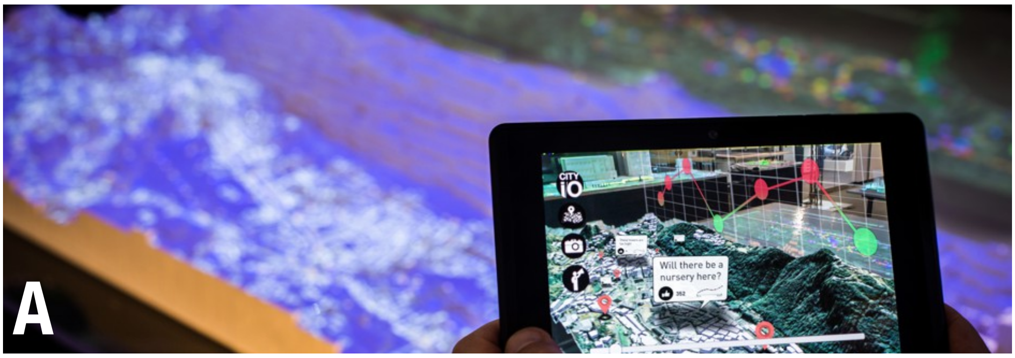
Scope of this Dissertation

This dissertation aims to shed light on the role of representations in solution-oriented sustainability science by asking the question, "what role do representations and representation practices play in the generation of sustainability solutions in different knowledge processes?"

To answer this question, four studies were conducted. Three of them correspond to the processes of analyzing, envisioning, and engaging. These studies sought to uncover the patterns and functions of representations and representational practices in current research. The last study was conducted with a focus on representational practices in a learning context in order to enhance mutual learning methods about sustainability, carried out with a collaborative group of actors. Conducting the studies in the context of cities facilitated the identification of participatory settings and the usage of strong representations in the form of models, simulations, diagrams, and photographs. However, representational practice is not only pertinent to developing sustainable urban systems; its tools can also be applied to learning processes across a wide range of fields.

This dissertation highlights several benefits of representations and representational practice that serve as tools for building applicable sustainability solutions embedded into larger processes. The dissertation also shows that widely applied representational practices can already be found in current knowledge processes for sustainability, and that these practices are rooted in mechanisms for recognizing, understanding, and exploring sustainability. Additionally, this dissertation emphasizes that representational practices support activities of communication and exploration, mediating between different perspectives in heterogeneous, collective, and cooperative groups to foster engagement. The thesis leads to representational literacy that integrates into learning processes and thereby enables actors to utilize representations effectively in sustainability problem-solving effectively.

Representations in the Urban Context



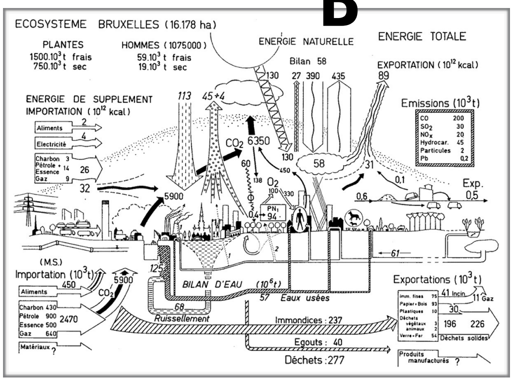
AUGMENTED REALITY WITH LEGO BRICKS

Representation integrating modeling, augmented reality visualization and a physical object built from Lego bricks; applied for infrastructure planning, e,g., “Finding Places“ HCU Hamburg

MIT MediaLab, CityLab; https://www.citylab.com/perspective/2018/08/ar-is-transforming-tech-what-can-it-do-for-cities/566618/

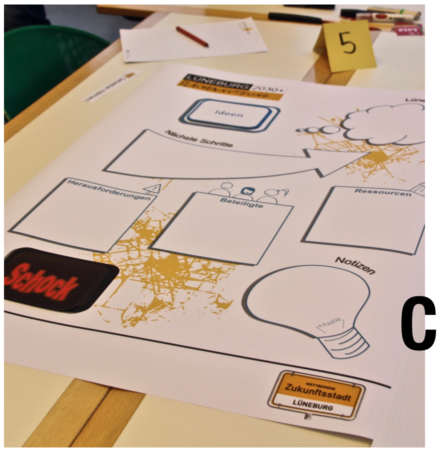
Finding Places; https://findingplaces.hamburg

B



FLOWS IN THE CITY

Representation of the urban metabolism of Brussels, Belgium in the early 1970s; Informal Sankey diagram of the material and energy flows (Duvigneaud and Denayeyer-De Smet, 1977).



DIGITAL DYNAMIC MANIPULATION

Representational practice of agent-based modeling mobility patterns and decision-making options. Dynamic manipulation during life event with experts and practitioners. Bridging the great Divide (Leuphana, Global Climate Forum, Berlin)

PAPER-PENCIL GAME

Paper-pencil based representational practice to develop solution strategies through a gaming approach, mediating between experts knowledge and desired urban vision of Lüneburg. (Student project seminar “Facing the changing climate“ Lüneburg 2030+)

Figure 1 Examples of representations A) Augmented reality and Lego B) Flows in the city, C) Paper-pencil game, D) digital dynamic manipulation

CHAPTER 2
Background

Knowledge Processes: To Analyze, To Envision, To Engage

In order to support sustainability transformations through research, programs have experienced a significant shift, moving away from developing a comprehensive and detailed understanding of problems to a solution-orientation approach for developing intervention strategies for mitigation or adaptation in real-world systems leading to a sustainability transformation (Miller, 2013; Miller et al., 2014). For this transformation, there are three tasks that contribute the necessary body of knowledge: developing an understanding of the problem, developing a future state, and designing transformative actions. These analysis units resonate as system knowledge, target knowledge, and transformational knowledge (Hirsch Hadorn et al., 2008a; ProClim, 1997) and come with distinct research questions in the diverse fields of sustainability science, for example, transdisciplinary and transformational sustainability research, innovation research, social-ecological systems research (Abson et al., 2014; Urmetzer et al., 2018; Wiek and Lang, 2016),

Within this basic categorization, methodological frameworks have evolved that integrate all knowledge types to address the complex system dynamics of real-world problems with tangible and actionable solutions (Caniglia et al., 2017b; Spangenberg, 2011; Wiek and Lang, 2016). Analysis, envisioning, and engagement are the knowledge processes particularly characteristic of the different method families that provide evidence for sustainability problem-solving (Wiek and Lang, 2016).

“To analyze” refers to research that generates an understanding about underlying system dynamics requiring descriptive-analytical knowledge about social and natural systems as well as respective interactions, mechanisms, and rules (Fiksel, 2006; Meadows and Wright, 2009). Theories and models are applied to concrete cases, and their problem is interpreted from different angles (e.g., priorities, interests, understanding). For example, modeling approaches are often applied in urban metabolism research, where comprehensive methodological advancements (emergy analyses, mass balance, or material flow approaches) develop a profound understanding of the resource systems in a city and their impact on the natural and social interaction in the urban environment (Baccini and Brunner, 2012; Broto et al., 2012; Fischer-Kowalski, 1998; Odum, 1996). These approaches also encompass use-inspired and design-inspired contributions that link the problem understanding to important management and planning approaches (Binder et al., 2009; Engel-Yan et al., 2005).

“To envision” refers to research that generates a desired future state that requires target knowledge about sustainability standards to be achieved and the normative knowledge about the desired system states; comprised therein is the rationale behind the deliberation, the value judgments, and the interpretation of the common good (Hirsch Hadorn et al., 2008a; McDermott et al., 2013). Legitimacy, justice, and responsibility pertain to this goal definition, as well as the rules for trade-offs and negotiations (Gibson, 2006; Schlaile et al., 2017). Visioning exercises are applied in the field of community planning to create a sustainable shared future of a city or community. This method family transforms scenarios that elaborate on target and normative knowledge in a way that allows the community to deliberate value judgments in order to reflect the community’s culture and identity. Ultimately, these methods guide operational planning and monitoring (Börjeson et al., 2006; Shipley and Michela, 2006; Wiek and Lang, 2016).

“To engage” describes research for designing and testing actions that require transformational knowledge. Such actions encompass technical, legal, cultural, and other qualities appropriate to its specific context and carriers, an understanding about the flexibility of institutional settings, cultural systems, and main agents of the actions(Hirsch Hadorn et al., 2008a; Kay et al., 2014). Through experimentation and exploration, solutions and strategies are formed, adapted, tested, and deeply understood so they can be acted upon (Schäpke et al., 2018). Decision-visualization environments are infrastructures within solution development, strategy building through experimentation, and exploration are facilitated by big data processing as well as visualization of system structures and dynamics. Planning and design processes of urban layouts are supported by geo-spatial visualization and facilitated by exploring the subsequent effects on budgeting, infrastructure, or ecological systems (Boukherroub et al., 2018; Isaacs et al., 2013).

Following one of those interdependent research processes requires explicit assumptions about the other two types**,** namely, that they are mutually dependent. These mutual dependencies cannot be described by a mechanistic and simplified understanding of problem-solving, but are embedded in a reflective and integrative process at the science-society-interface (Lang et al., 2012). The participatory involvement of actors from these different spheres seeks to coproduce knowledge processes of increased relevancy for real-world challenges and to craft system innovation that encompasses contested values, forms of equity, and justice regarding the normative notion of a sustainable state (Prell et al., 2010; Salas-Zapata et al., 2017). These new research modes push for toward salient, legitimate, credible, and actionable knowledge and involve researchers with a transformative mindset, and core competencies (Popa et al., 2015; Wittmayer and Schäpke, 2014).

Representation and Representational Practice: General and for Sustainability

Ian Hacking describes the role of representation in science as "[…] first there is representation, and then there is real [and representations are] not in general intended to say how [something] is" (1983, p. 233). Representations constitute a relationship between theories and their targets, that is, the objects of interest in real-world systems. Theories are abstractions of the world and specific contexts and aim towards explaining what the world is made of. We produce representations of observable phenomena through our own particular lenses and for specific purposes, to apply a theory to a certain target system, to demonstrate insights or conclusions about that target system, and to interpret the results about the target system for the world (Giere, 2004; Suárez, 2008). Representations are, as Hacking says, mediators between a theoretical description about the world and an empirical approach in which we experiment, intervene into our target systems, and generate new knowledge (1983, p. 60). At the same time, he describes the representational practice as inherent to human culture and also critical for sense-making. The most important characteristics and mechanisms this dissertation draws on are listed in Table 1 and contextualized in the following sections.

Representations utilized in science are both internal, such as mental images, and external, such as models, simulations, visualizations, physical objects, language, and calculations. They simplify, idealize, and store large and dense amounts of information and propositional knowledge (Mößner, 2018; Perini, 2005). As knowledge systems in science become more complex and diverse, competing alternative representations of the same phenomenon often coexist within the same field. The alternative representations increase a phenomenon's evidence and serve the progress of research in the field without necessarily ending in one true universal theory (Hacking, 1983; Mitchell, 2004). This is evident in the advancements of multiple and parallel ecosystem service research (Abson et al., 2014). At the same time, comparability is not eliminable, because representations address different levels, questions, scopes, and scales of analysis. Maintaining this diversity under an "integrative pluralism" can be seen as innovative and creative, serving to generate knowledge about the complex system, its drivers, and its relationships (Mitchell, 2004).

By becoming a tool in scientific inquiry, Giere (2004, p. 743) formulates representational practice as a four-way relationship, "S uses X to represent W for purposes P," in which X denotes the representation and W the target system. Within this understanding, representational practice becomes a purposeful activity (as opposed to a mere translation of information) in which different types of representations develop different qualities of representational force in their usage. For example, certain types of representations are better adapted to serve surrogate reasoning, interpretation, demonstration, or explanation (Suárez, 2008). The work about models and modeling (Frigg and Reiss, 2011; Giere, 2004; Morgan and Morrison, 1999) has lifted the strict separation between representing and intervening postulated by Hacking (1983), among others. Models "partially independent of both theories and the world" are conceptualized as "autonomous agents […] with a function as instruments for exploration" (Morgan and Morrison, 1999, p. 10). The less strict separation highlights that representational practices can serve equally to explain, explore, and interpret phenomena.

Consequently, a meaningful, effective activity of a representational practice is not a single translation, but a construction. Latour (2000) as well as Lynch and Woolgar (1990) see the representational practice as a step-wise, active, agent-centered mediation between theory and the object of interest. This construction requires to bridge a large series of gaps between theory and the real world. Such practices are integrated into larger methodological frameworks that also allow for interactions like hands-on manipulation and redaction. The (re)constructions are socially and culturally embedded and the products value-laden. The act of encoding in order to describe knowledge, as well as decoding in order to infer and draw conclusions, is highly dependent upon individual background knowledge and guiding principles. However, it is also dependent upon a sort of design literacy in order to organize effective practices (Bailer-Jones, 2008; Mößner, 2018). In the latter example, computerized and digitalized practices are taken as a standard, and their decoding almost as granted; however, the related clean-up of data and software skills for production requires as much background knowledge as the research field itself.

Representations have already a place in knowledge processes for sustainability (see Figure 1): Examples include different types of models that develop a comprehensive understanding of the problem while serving as an integration method in transdisciplinary processes (Bergmann et al., 2010). Furthermore, images and metaphors are used to communicate impactful, complex, innovative images of the future (Beers et al., 2010; Shipley and Michela, 2006). For example, Sheppard (2005, 2001) differentiates between visualization techniques to communicate informative, persuasive or deliberately; This differentiation raises ethical implications of visualizations in the context to achieve transformative behavior and a decision-making response in climate change (see Figure 1, A). Lastly, gaming (see Figure 1, C) is a stepwise representational practice that supports the goal setting and strategic planning of sustainability solutions (Withycombe Keeler et al., 2017).

On the one hand, the different uses and purposes of representations mediate knowledge processes for sustainability by explaining social-ecological phenomena and their interplay, demonstrating technical innovations, reasoning about strategic decisions, and integrating contested perspectives (Gill et al., 2013; Lange et al., 2017; Manzo, 2017; Sheppard and Meitner, 2005). On the other hand, the act of creating representations is a fundamental feature in human culture; it involves an agent and an activity and is not just a translation of a theory (Giere, 2004; Hacking, 1983; Hall, 2013). This comes to the fore in all cases where knowledge is generated (including the varied personal realities and experiences of participating actors); the representations that are placed into larger methodological approaches are not just mechanistic translations. For complex sustainability problems that are place-based, contested, life-threatening, and require an immediate solution, representations can mediate knowledge generation for sustainability to include an iterative (re)construction and discovery for both science and practice (Pässilä et al., 2013; Popa et al., 2015).

Table 1 Overview core characteristics, mechanisms of representations, and representational practice

Mechanisms, Characteristics	Description	Main Literature
Representations		
Type	The type describes the different mediators that are mostly understood as representation in sciences (mostly but not exclusively natural sciences). Archetypes broadly differentiate into (but are not limited to) physical objects (e.g. statue, paper-pencil prototypes, Marquette); models and simulations; images and visualizations.	*Hacking, 1983; Beers et al, 2010; Mößner, 2018; Morgan and Morrison, 1999;*
Purpose	The mediating relationship of the representation between the theory and the real-world is not longer exclusively understood as a denotation to be as similar and alike as possible. A constructivist understanding for the task of sense-making ascribes to representations additional purposes which include: explanation (i.e. demonstrate and communicate); exploration (i.e. as the object of research for interpretation, inferences, and surrogate reasoning).	*Suarez, 2008; Mößner, 2018;*
Organizational Role	The organizational role describes the relationship between representations that are interconnected through the same theory or target. Since representations focus on a specific section of a target, they simplify or idealize the target by chosing preferred or salient features (e.g. models of particular ecosystem functions). Several representations can exist next to each other. This relationship is either competitive taking different stances (e.g. epistemic values or social acceptance) to increase evidence and robustness of a theory; or comparable to increase the comprehensive view from different levels of analysis. Integrative pluralism organizes this diversity for a meaningful, productive co-existence.	*Mitchell, 2004;*
Representational Practice		
Relationship	A constructivist understanding attributes meaning to the representational practice (in contrast to a translational, bilateral relationship) making it an activity. A four-way relationship takes further into account who employs the representation, the type of representation, and the purpose of the activity. The relationship then reads: "The Actor ***S*** uses the representation ***X*** to represent the target ***W*** for purposes ***P***".	*Giere, 2004;*
Functional Role	Encoding and decoding are functions within the representational practice that characterize the act of purposefully selecting, simplifying and portraying information (e.g. statistical data) with a representation; and subsequently, the act of seeing, reading, analyzing the whole and segments of the representation. These functions are discussed in relation to skills of visualizing information correctly, effectively, ethically (i.e. visual literacy); To background knowledge about context (e.g. expertise, experiences, education) as requirement to correctly infer about insights; and to guidelines and principles that direct decoding.	*Mößner, 2018; Bailer-Jones, 2008;*
Process	Representational practice with a constructivist understanding requires a procedural reconstruction. Embedded into larger methodological frameworks this procedural reconstruction subsumes the functional roles (i.e. encoding, decoding) into a step-wise iterative, intentional abstracting, constructing, and discovering of a phenomenon (i.e. theory).	*Lynch and Woolgar, 1990; Latour, 2000;*

Learning Processes

Learning has a particular position in sustainability science. In addition to academic higher education, it includes social learning processes to develop core competencies and practical capacities that enable practitioners or researchers to understand challenges spanning from a local to global level and their respective solutions. These processes are employed to succeed across all societal spheres and across all spatial scales, down to one's individual behavior change (Caniglia et al., 2017a; Wiek et al., 2011; Wolfram, 2016). For researching this science-society-policy interface, learning can be seen as a collective approach. We learn with and from one another in a style called "mutual learning," one that is essential to problem understanding, interpretation, and transformation (Polk and Knutsson, 2008; Scholz, 2011).

Three basic learning processes are differentiated in this dissertation: (i) Topical and factual learning, or "learning about," which enables actors in knowledge processes to combine and compare different sources of knowledge, interdisciplinary knowledge, and contextualized information to frame the boundaries of a problem, the possible desired sustainable future, and the strategic intervention for a change (Caniglia et al., 2017a; John et al., 2017). "Learning about" recognizes representations to serve an important role whether it is for students in curricula, but also fundamentally in their function as mediators (Evagorou et al., 2015; Mößner, 2015). (ii) "Learning through" stands for processes that help to generate knowledge by actively engaging in (re)searching, exploring, experimenting, and developing experiences to generate new knowledge, resources, and skills. These processes add on appropriateness, significance, credibility, saliency, and effectiveness to factual knowledge about the given context for the benefit of those involved. What problem-project-based-learning settings usually take on in sustainability science (Brundiers et al., 2010), has no equivalent per se in representational theory. However, representational practices can support a setting that allows for engaging with knowledge in an iterative practice of reconstruction. (iii) All learning processes are collaboratively "learning with" and from each other, and all require that participating actors possess the skills to steer effective and inclusive communication, employing mutual understanding, procedural fairness, and that they value intercultural, normative, and other diversity (Brundiers and Wiek, 2017; Caniglia et al., 2017a). During these learning processes, engaging in individual critical reflection (comparing one's personal perspective with those of others) promotes new experiences and background knowledge and serves to change one's mindset (Brundiers and Wiek, 2011; Lotz-Sisitka et al., 2015). Achieving effective mutual learning requires navigating heterogenous collaborative settings and negotiating contested values (Sipos et al., 2008). Among researchers, representations in which the interdisciplinary exchange for the process predominate, while the interpersonal skills are not considered to be essential to engage in representational practice (Latour, 2000).

Learning processes already utilize mechanisms that representations and representational practices provide on several levels. They facilitate perceptual and interpretation processes and enable the actors to acquire factual knowledge and understanding, and at the same time, they help to explicate connections and allow for comparisons through exploration (Mößner, 2015).

Gap and Research Question

The role of representation is widely acknowledged in science. Representations serve as indispensable mediators between theory and the real world, and they are used to explore and understand concepts and their functioning in the real world. Due to the complexity of problems undertaken within sustainability science, the field has recently seen a convergence of representations that seek to support multiple endeavors: to analyze, to envision, to engage, and to learn or to (comprehensively) generate all three types of knowledge in order to produce actionable and practicable sustainability strategies.

Representations in sustainability are converging from diverse fields to capture the complexity of the challenges and solutions, and these representations are equally important for the exchange and mediation of knowledge types at the science-society-policy interface. Although there is an increasing quantity of research about individual types of representation (visualization, pictures, models, etc.) in sustainability, there is no systematic understanding of what role representations can take and how they contribute to a sustainability transformation (see Table 2). This dissertation therefore asks the following questions:

What role do representations and representation practices play in the generation of sustainability solutions in different knowledge processes, and how can different characteristics and mechanisms be used as tools to contribute to a sustainability transformation?

This dissertation aims to contribute to a stronger foundation of representation in sustainability science. This includes:

(i) to explore and conceptualize representation for the three described knowledge processes, along selected characteristics and mechanisms of representations and representational practice.

(ii) to understand representational practices and their mechanisms as they are found embedded within knowledge processes. This includes meaningfully connecting representational practices to methodologies to uncover innovative sustainability solutions.

(iii) to understand the connection between representation and (mutual) learning in sustainability science. This addresses the importance of the diversity of actors and their contributions at the science-society-policy interface as well as learning as an integrative element to enable action.

Table 2 Overview of gaps organized after knowledge processes and learning

		Paper 1 To Analyze	Paper 2 To Envision	Paper 3 To Engage	Paper 4 To Learn
Gap	Knowledge processes to produce sustainability solutions requires interdisciplinary theories and methodologies that are able to integrate contested norms and values, and increase legitimacy and transparency to make solutions more salient and credible and thus actionable. Knowledge processes, such as to analyze, to envision, to engage, as well as the three generic knowledge types are mutually dependent. Currently, individual types of representations are rather applied and valued for their effectiveness in specific contexts of knowledge processes, while learning throughout the knowledge processes is considered a crosscutting approach utilizing selected types of and mechanisms. However, representations and representational practice have a broader set of characteristics and mechanisms that are able to universally mediate and organize between theories and real-world, between disciplines, and between different kinds of actors at the science-society interface.				
Characteristics and mechanisms of representations and representational practice	*Type* *Purpose* *Organizational Role* *Relationship* *Functional Role* *Process*	**Challenge:** To adequately describe the complex system dynamics, in particular, identify, describe, frame, and interpret the (un)sustainable status quo. **Role of Representation/ Representational practice:** Mediating between global drivers and local manifestations; between different perspectives onto the problem and underlying causes and effects by exploration. Organize diversity of parallel manifestations.	**Challenge:** to anticipate a sustainable state that is desired and motivational while negotiating normative implications for the future in reference to the present. **Role of Representation/ Representational practice:** Mediating between internal individual images and external collective manifestation of the desired future through different functional roles, purposes, and organizational role; unlocking future-thinking and increase tangibility mediating between simplified information and complex target system.	**Challenge:** to facilitate and experiment with solution strategies, related processes; to describe necessary changes and their implication for cultural, institutional, administrational spheres. To allow interaction and application prior to implementation. **Role of Representation/ Representational practice:** Mediating changes required by solutions in a step-wise approach through the purpose of exploration; mediating between evidence-based solution and tangible, applicable local intervention and action; to use representational practice in a functional role that fosters transparent and democratic debate and interaction.	**Challenge:** to interconnect knowledge processes with the learning at the science-society-interface, equally supporting understanding and recognition of (un)sustainability; to conduct, and participate in active knowledge generation, and to mutually learn from and with others. **Role of Representation/ Representational practice:** Mediating in cognitive processes and sense-making through functional roles of simplification and idealization. Mediating a fair access and participation through a process that builds expertise and background and through actively engaging in practice.

CHAPTER 3
Concept and Design

Conceptual Framework

Four empirical studies align around the concept of representations and representational practice, and thus approach the primary research goal of this dissertation (see Figure 2). While three of these studies each look into one knowledge process, the fourth study is dedicated to learning as an integrative process. The main types of representations are identified and then analyzed through applicable characteristics and mechanisms. These characteristics and mechanisms address (i) different purposes of representations, (ii) the application and understanding of organizational roles and integrative pluralism, (iii) insights into the framings of relationships, (iv) arrangement and requirements in the functional roles of representational practice, and (v) the procedural operationalization of the practice (see Table 1). Together, this provides a substantive view on current applications and conceptualizations of representation and representational practice as a tool and builds a basis for further research concerning sustainability problem-solving.

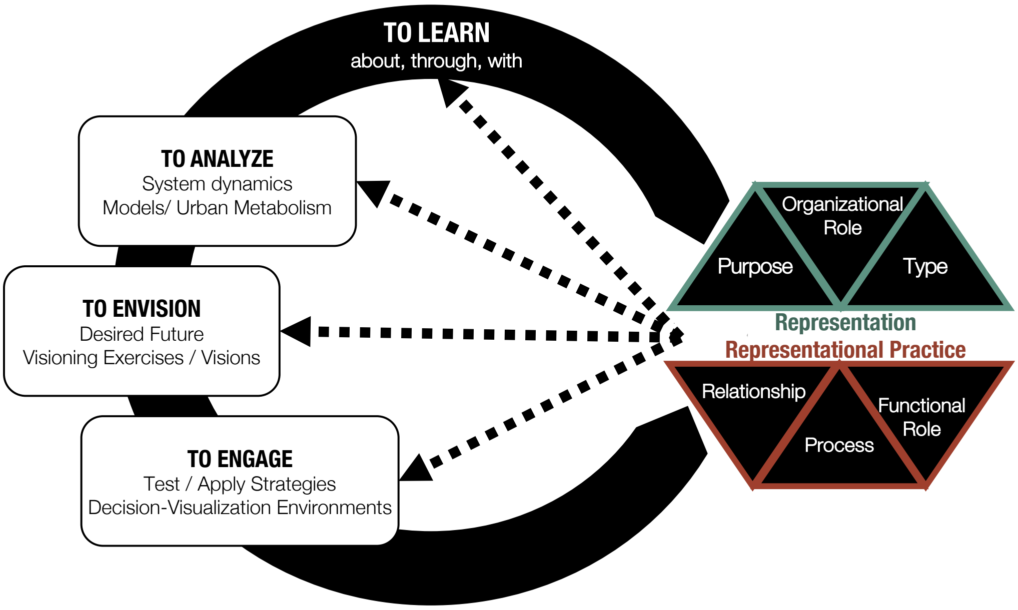


Figure 2 Conceptual Framing with three knowledge processes to analyze, to envision, and to engage; interconnected through learning; characteristics and mechanisms of representations (green) and representational practice (red) considered as tools to enhance all four elements.

"To analyze" represents descriptive-analytical knowledge about complex system dynamics, i.e., the problem identification, description, framing, and interpretation of the status quo (unsustainable or sustainable). One important aspect of the role of representation in this knowledge process is to capture an understanding of the system by exploring its complexity from the different perspectives and levels that underlie sustainability (see

“Purpose and Organizational Role” in Table 1). To this end, the field of urban metabolism research provides a robust framework for addressing the material basis of sustainability solutions. This study applies a multivariate statistical approach combining a cluster analysis and a systematic review of 221 publications (John et al., 2019).

“To envision” relates to the process of generating target knowledge and focuses on the anticipation**,** shape, and imagining of sustainable desired future states. Essential to the role of representation is to capture the diversity of normative implications in different futures by increasing tangibility, evoking a shared and motivational character of the imagined future with simplified information (see “functional role” and “organizational role” in Table 1). Visioning exercises provide an empirically informed activity with large-scale participation that can be widely applied to craft a plan for long-term community development. This study applies a rough set analysis of nine cities with such a participatory urban visioning exercise (John et al., 2015).

“To engage” is a knowledge process important to transformation knowledge highlighting the importance of applying and experimenting in order to build actionable strategic solutions. The role of representation is critical in fostering a transparent and democratic debate and in exploration; at the same time, representation serves to provide information about sustainability practices and the conditions of their implementation (see “Relationship,” “Functional role,” and “Process,” in Table 1). Semi-immersive digital decision-visualization environments (see Figure 1, D) demonstrate facilitation and visualizing in an infrastructure and allow for the visually supported design of human-computer-content interaction. This ultimately facilitates participatory, design, planning, experimentation, and decision-making processes. Visually supported, the environments test sustainability solutions prior to their implementation. This study conducted a survey and expert interviews of seven decision-visualization environments (John et al., submitted).

“To learn” focuses on learning in all described knowledge processes to enable diverse actors at the science-society-policy interface to understand and recognize (un)sustainability; to be capable to design, conduct, and participate in active knowledge generation; and to collectively learn from and with others. Representations are critical for cognitive processes and sense-making, and are an inherently human activity. They provide the potential for fair access and participation in learning processes (see “Purpose”, “Relationship”, “Functional role” in Table 1). This study contains the application and evaluation of an experience-based framework with 70 interdisciplinary students in a transatlantic program (Caniglia et al., 2016).

Table 3 Overview of research articles, publication status, and contribution

Knowledge Process	Publication	Status and Journal	Contribution
TO ANALYZE	John, B., Luederitz, C., Lang, D. J., & von Wehrden, H. (2019). Toward Sustainable Urban Metabolisms. From System Understanding to System Transformation. *Ecological Economics*, 157, 402–414. https://doi.org/10.1016/j.ecolecon.2018.12.007	published 2019 in *Ecological Economics*	1.0
TO ENVISION	John, B., Withycombe Keeler, L., Wiek, A., & Lang, D. J. (2015). How much sustainability substance is in urban visions? – An analysis of visioning projects in urban planning. *Cities*, *48*, 86–98. https://doi.org/10.1016/j.cities.2015.06.001	published 2015 in *Cities*	1.0
TO ENGAGE	John, B., Lang, D. J., von Wehrden, H., John, R., & Wiek, A. (submitted.). Mobilizing and advancing decision- visualization environments – Empirically-informed design guidelines. *Futures*.	submitted to *Futures* (Dec 2018)	1.0
TO LEARN	Caniglia, G., John, B., Kohler, M., Bellina, L., Wiek, A., Rojas, C., … Lang, D. (2016). An experience-based learning framework. Activities for the initial development of sustainability competencies. *International Journal of Sustainability in Higher Education*, *17*(6), 827–852. https://doi.org/10.1108/IJSHE-04-2015-0065	published 2016 in *International Journal of Sustainability in Higher Education*	0.5

All four case studies are self-contained, but they should be understood within the context of representation and representational practice. While taking different perspectives, they also approach the research by using established quantitative or qualitative methods; the case study concerning learning (Caniglia et al., 2016) applies both methods as well as evaluation. The spatial and topical focus is on the urban context and cities, because the urban scale is considered to be a primary driver of sustainability challenges as well as also a hub for innovative solutions. Additionally, at this scale, many systemic processes interlink from the global level into everyday practices and behavior, providing a tangible illustration of why the development of urban sustainability solutions requires an active collaboration at the science-society-interface. In the study concerning "to engage," the urban focus is, at first glance, less prominent. In many cases, decision-visualization environments are infrastructures that require a high financial investment; however, it should be kept in mind that they are not used exclusively for community planning, but also for primary research, resource, and landscape planning. While expertise about current practices may have already been transferred across fields, it has only gained in robustness through the process. All together, these studies present valuable and empirical insights into the foundation of representations and representational practice in knowledge processes to advance sustainability solutions.

CHAPTER 4

Results

Toward Sustainable Urban Metabolisms. From System Understanding to System Transformation

Beatrice John, Christopher Luederitz, Daniel J. Lang, Henrik von Wehrden

Abstract

Within the next two decades, large areas will be converted into urban environments, a process that will include enormous transformations in economic activity, environmental health, and social justice**.** To address these complex problems, scholars use the metaphor of the "urban metabolism," describing an understanding of the interdependencies and dynamics of cities and the ecosystems they rely on. Research on urban metabolism has achieved important methodological advancements, such as descriptive analytical frameworks, decision-making models, and resource flow models. However, these contributions have rarely engaged with the transformational potential of designing sustainability solutions for socio-ecological dynamics. This study aims at investigating the current state of the urban metabolism discourse in linking material flows to human well-being, ecological integrity, and social justice, as well as the transformational potential of interventions. To accomplish this, we conducted multivariate statistics of 221 scientific publications, seeking to clarify the normative and transformational aspects considered in the design, context, and products of urban metabolism research. Results differentiated eight clusters of urban metabolism research highlighting the diversity of research along disciplinary and methodological dimensions. We identify pathways to strengthen the conceptualization of a "sustainable urban metabolism" and conclude with suggestions for collaboration between urban metabolism and sustainability research.

Introduction

Within the next two decades 60% of the global population will live in cities. Consequently, large areas will need to be converted to urban environments (Seto et al., 2012). Cities, which rely on enormous amounts of energy and resources, are increasingly dependent on surrounding ecosystems. Due to these immense inflows of resources, cities have become "barely sustainable but paradoxically resilient networks" (Batty, 2008, p. 769) that, in fact, degrade the capacity of Earth's life support system (Grimm et al., 2008; Rockström et al., 2009). To cope with these challenges, scholars have described the cities' resource and energy systems with the metaphor of "urban metabolism" (Odum, 1996; Wolman, 1965).

“Urban metabolism” is defined by for all physical stocks and flows of energy and matter that form the material basis of a city (Baccini and Brunner, 2012).

Devising future pathways for sustainable urban areas is challenging given the complexity of the ongoing environmental pressures and social dynamics driving them (Holling, 2001; Steffen et al., 2007; Wiek et al., 2015). Originally, the field was shaped by Wolman’s (1965) and Odum’s (1959) work and received broad application using different terminologies e.g. “societal” or “industrial” metabolism (Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998; Weisz and Steinberger, 2010). In recent years, urban metabolism research has become an interdisciplinary field addressing the complex dynamics of cities and, more recently, has sought to identify possibilities to foster sustainability (Ferrão and Fernández, 2013). Research perspectives as diverse as industrial ecology, political ecology, and urban ecology have converged with the interest of reaching a more profound understanding of the urban metabolism and specifically the interactions between natural and social systems, as well as resource systems, and their impacts on the urban environment (Broto et al., 2012; Fischer-Kowalski, 1998). This field has developed the metaphor of urban metabolism into a descriptive framework including comprehensive methodological advancements, namely emergy analyses, mass balance, or material flow approaches (Baccini and Brunner, 2012; Odum, 1996). Furthermore, use-inspired urban metabolism research (Binder et al., 2009; Kennedy et al., 2011) has explored ways to better understand its contributions to urban planning and development (Baccini and Oswald, 2008). In other areas, such as civil engineering, the urban metabolism concept has been applied to support environmental friendly design (c.f. Engel-Yan et al., 2005).

Building upon those advancements, researchers have started to use the urban metabolism framework to identify sustainable urban solutions. In doing so, some argue that cities need to develop circular models of resource use in which outputs serve as resources for other processes (Agudelo-Vera et al., 2011; Barles, 2010; Bogunovich, 2002). Such contributions have also prompted the increased use of the term “sustainable urban metabolism,” (Chen and Chen, 2015; Codoban and Kennedy, 2008; Ferrão and Fernández, 2013; González et al., 2013) which underlines the city’s role as a “motor” and a “hub of innovation” (Bai, 2007; Ernstson et al., 2010). These are indicators for a shift in the field toward methods and designs that engage explicitly with sustainability. A wide array of fields such as ecological economics, political ecology, and industrial ecology contribute to the topic, and inter- and transdisciplinary approaches are recognized as essential (c.f. Barles, 2010; Ferrão and Fernández, 2013).

Sustainability science has advanced in a way that allows it to integrate disparate disciplines, explore innovative approaches, foster transformation processes, and systematically include the underlying normative ethical dimensions into academic research (Jerneck et al., 2011;

Kates et al., 2001; Spangenberg, 2011). However, sustainability science challenges its researchers with questions that (i) address systemic transformation knowledge production and support the empirical solution-oriented design and implementation of effective, radical sustainability solutions (Abson et al., 2017; Wiek and Lang, 2016); (ii) seek to co-produce this transformation knowledge and system innovation with actors outside academia to encompass contested values, forms of equity, and justice regarding the normative notion of a sustainable state (Prell et al., 2010; Salas-Zapata et al., 2017); (iii) enhance the reflexivity of researchers through a transformative mindset, capacity, and literacy (Popa et al., 2015; Wittmayer and Schäpke, 2014);

Research on urban metabolism that matches sustainability with the transformational potential of designing, transferring, and up-scaling solutions remain at its infancy (John et al., 2016). In response, with this article, we review how normative and transformational principles from sustainability research are considered in urban metabolism literature pertaining to research designs, topical contexts, and the research results. In order to do so, we address the research question: how strongly and in what ways does urban metabolism research engage in sustainability transformations? We address this question with a multivariate statistical approach and a systematic literature review of urban metabolism research in order to propose a set of future pathways.

In the following sections, we first introduce our research design before presenting the results of both approaches. Based on this we then discuss the status quo of sustainable urban metabolism research, and conclude by listing potential areas where these methodologies and conceptual advancements may serve to situate the concept of a sustainable urban mechanism within the larger endeavors of sustainability as a field.

Research Design: Clustering and Systematic Review of Urban Metabolism Research

In analyzing the systematically accessed literature on scientific sustainable urban metabolisms, we took a two-pronged approach. First, we made a multivariate statistical analysis following Abson et al (2014), consisting of an ordination as well as a cluster analysis (detrended correspondence analysis) of a word by paper matrix consisting of 221 peer-reviewed articles on urban metabolism (research and review articles); significant cluster groups were identified based on an indicator species analysis (Dufrene and Legendre, 1997). In a second step, we conducted a systematic literature review utilizing quantitative statistical and qualitative content analyses following Luederitz et al (2016), focusing on 152 case studies of the database.

For the detailed description of data preparation and both methods, see supplementary material S-1. A complete list of publications can be found in supplementary material S-2. The following section clarifies the analytical framework used for the systematic review.

Analytical Framework for The Systematic Review of Case Studies in Urban Metabolism Research

We limited the systematic review to case studies, as they address and explore issues in specific urban conditions with practical relevance. We defined case studies as empirical studies that were location-specific and that collected quantitative or qualitative data on different temporal dimensions with one or more levels of analysis (Yin, 2012).

We developed an analytical framework representing sustainability research principles for the literature review to capture qualitative and quantitative information from the analyzed full-text publications (coded as numerical data, free text, or at ordinal scale). The framework serves as basis for the entire coding scheme that was pre-tested for practicability and comprehensibility, and modified accordingly to ensure validity. In general, the coding scheme is structured according to four categories and contains 12 criteria (see Table 1; full coding scheme listed in supplementary material S-3). Origins of criteria and operationalizations are explained in the following sections.

Table 1. Analytical framework of sustainability research principles and respective review criteria and their operationalizations

#	Category	*Criteria*	*Operationalizations*
1	General	Publication year	
		Country of case study	
		City of case study	
2	Research Approach and Design	Approach	problem-oriented research; solution-oriented research
		Design	disciplinary/ interdisciplinarity; participatory/transdisciplinarity
		Actors	actors and their activities in disciplinary/interdisciplinary
		Method	methods in case study
3	Boundaries	Focal spatial scale	building; neighborhood; city; region
		Focal temporal scale	historical; present; future
4	Knowledge Types	Systems knowledge	kinds of system understanding
		Target knowledge	definition of sustainability; sustainability assessments; sustainability design criteria; sustainability principles; justice, fairness and equity; subgoals 11 of UN Sustainable Development Goals 2030
		Transformation knowledge	practical outlook; concrete recommendations; pilot projects

Research approaches and designs

In the pursuit of sustainable development, the identification and sound analysis of complex challenges in coupled human-environmental systems are essential to create an understanding about the status quo of a system, as well as to provide information for society about past, present, and future processes and potential vulnerabilities (Spangenberg, 2011). This *problem-oriented* **approach** predominates several fields of research, converging on the mutual interest to understand risks for society and enable sustainable development. A *solution-oriented approach* focuses with its research on practically contributing to solve these challenges (Wiek et al., 2012a). It takes on a transformational perspective and addresses normative and strategic questions with theoretical and empirical research to enable change toward sustainability (Miller et al., 2014). This includes crafting desired future target states and creating experiments for testing innovative solution pathways as well as building capacities with societal actors and institutions to operate on these pathways (Cumming et al., 2013; Nevens et al., 2013; Wiek et al., 2012b; Wiek and Iwaniec, 2014).

The selected approach influences the **research design.** Consensus exists that interdisciplinary designs are key to address complex challenges that interlink various disciplines. The epistemological and ontological diversity is an important source of innovation for the researchers (Jerneck et al., 2011). *Transdisciplinary designs* expand the collaboration between academic research with non-academic actors throughout the research process. Engaging academics and non-academics is critical for constructive discussions about contested goals and norms; increases the legitimacy and ownership of solutions; builds capacities for interventions and transformation; and enables combining different types of knowledge (Brandt et al., 2013; Lang et al., 2012). In order to capture related efforts, such as participatory designs, collaborative designs, or action-research, we have included them under the category of participatory designs. Both approaches and designs allow for the use of versatile *methods*, and mixed-method combinations that produce different types of knowledge are also captured in the analysis (von Wehrden et al., 2017). They also allow societal *actors and their activities* to be included in this analysis in order to generate a comprehensive system of understanding including power relations (ProClim, 1997; Wiek and Lang, 2016). This criterion was also considered in interdisciplinary research processes without its being an integral part of the research design, as in transdisciplinarity. The information on data sources, collection, and sampling strategies were excluded. No attention was paid to the sequence of methodical steps in mixed-method approaches.

Focal spatial and temporal boundaries

Space and time are taken into account here because both scales, due to their systemic properties, are crucial in approaching the challenges of sustainability (Coenen et al., 2012; von Wehrden et al., 2017; Weiser et al., 2017). The **spatial scale** comes into play when a sustainability problem is analyzed with regards to cause-effect relationships. The complexity of sustainability problems and their solutions, need to be captured comprehensively as they reach from different local, place-based situations, bioregion, and societal spheres, to the global level. The **temporal scale** captures the urgency, futurity, uncertainty, and the transformational aspect of the sustainability concept (van der Leeuw et al., 2012; Weiser et al., 2017). Problems and interventions cut across different time scales with indirect cause-effect relationships, and time delays, e.g. short-term measures with long-term effects. This also covers the aspect of intergenerational equity that explicitly addresses the need to account for how today's decisions affect the opportunities of future generations (Gibson, 2006). For the analysis, we operationalize the focal spatial scale with administrative units of building, neighborhood, city, and region; and the focal temporal scale with chronological understanding of past, present, and future each relative to the data points and publication dates of the case studies.

Knowledge types: system, target, transformation

We differentiate three types of knowledge created in research processes, namely system, target, and transformation knowledge (Abson et al., 2014; ProClim, 1997). These knowledge types are important, because they structure the process of research and the kinds of output and products that are generated and verify a problem or solution orientation (Wiek and Lang, 2016). Producing **system knowledge** means to describe the upstream and downstream drivers of the sustainability problem being investigated as well as their systemic interrelations. Here, we look for different framings and methods for problem analysis that allow for a systemic and comprehensive analysis. Producing **target knowledge** focuses on the development of coherent sets of sustainability targets and the application of sustainability principles within sustainability assessments, as well as the use of design criteria (Gibson, 2006; Luederitz et al., 2013). This includes reconsidering values and norms: attributing meaning to parameters, goals, targets of justice, and equity across generations throughout the research process by, for example, using visioning (Gibson, 2006; Jerneck et al., 2011; McDermott et al., 2013; Wiek and Iwaniec, 2014). **Transformation knowledge** encompasses robust knowledge for sustainability transformations, comprising strategic knowledge about practical operationalization, intervention points to induce change, and the capacity of respective actors to operate this change. Hence, transformation knowledge goes beyond simple outlooks for further research and unprecise recommendations for decision makers (Wolfram, 2016), in order to translate into strategies that are researched, tested, implemented, and evaluated (Luederitz et al., 2017; Wiek et al., 2012b). For the analysis we differentiate the range of transformation knowledge with three operationalizations (i) outlooks with relevance for outside academia, (ii) strategic recommendations, and (iii) stepping stone or pilot projects.

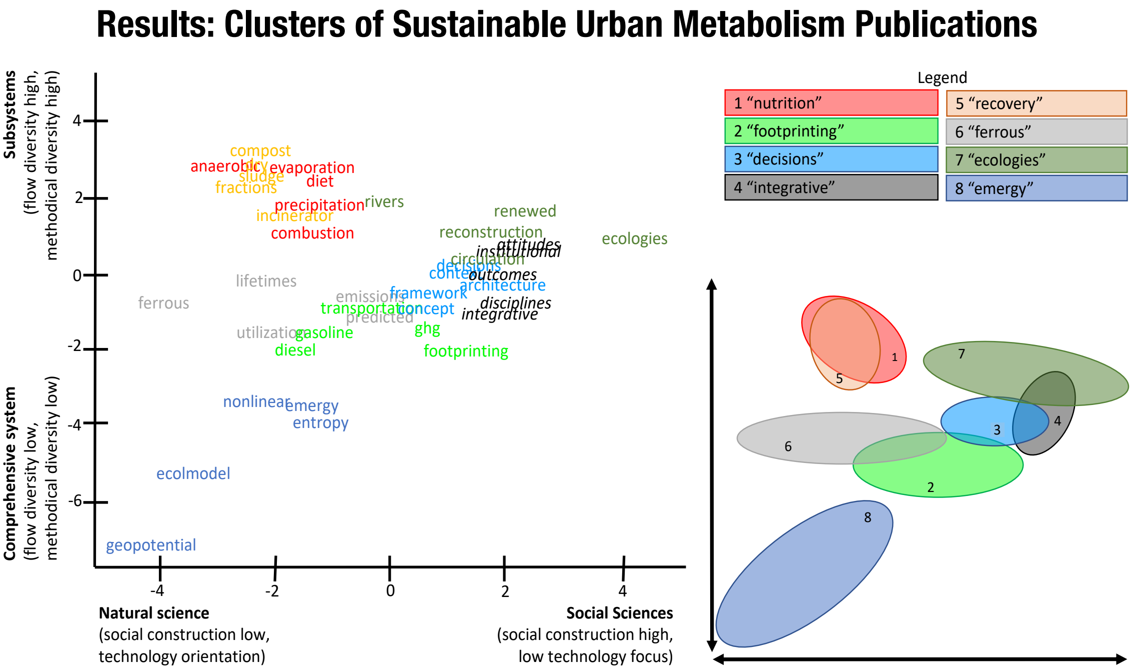


Figure 1. Cluster distribution with indicator words, Ward's cluster with cluster numbers and colors.

The multivariate analysis of 221 research and review articles resulted in eight distinct clusters with a shared vocabulary, with an agglomerative coefficient of 0.84. Most significant indicator words are plotted in Figure 1, where the x-axis describes the gradient from natural science (i.e., chemistry and engineering) to social science (i.e., economics, political science, and planning), with integrative approaches in the center. This axis shows a gradient increasing in societal metabolism and decreasing in technology focus. The y-axis ranges from comprehensive complex system dynamics that exclusively focus on the city scale on aggregated emergy analyses to the dynamics of specific subsystems, e.g. at the neighborhood or building scale, applying diverse research designs a variety of flows. Therefore, this axis is also characterized by a gradient from low to high diversity of methods (i.e. Life cycle assessment, scenario analysis, etc.) and a flow/substance diversity (i.e. carbon, nitrogen, water, etc.). The clusters distribute roughly above the median toward the gradient "flows in subsystems" and overlap there in compartmentalized clusters; The overlapping clusters share the focus on the spatial scale and interdisciplinary approaches. Natural science clusters are very distinct. The clusters are described in detail in Table 2, the clusters' titles are based on indicator words.

Table 2. Cluster descriptions with title, color, number of articles, and description of contents.

#	Cluster Title	Color and Number of Publications	Description
1	"nutrition"	red 19	Issues of nutrient flows and cycling, food sourced nitrogen and phosphorus, fossil and solar energy sources, biogeochemistry and atmospheric pathways, urban water. Related to human activities, origin and fate of substances, system behavior e.g. resilience of energy stocks or effects and efficiency of urban water systems in the entire urban system. Threatening practices and flows to built sustainability of the city are identified. Analyses in relation to urban from, across varying sectors; technologies are assessed towards their positive impact on green economy and environmental benefits. Case studies (USA, Canada, Sweden, UK, China) work with aggregated flows and aim for comprehensive views on the city, are conducted on various the spatial scales (from neighborhood to megacity). Methodical diversity (balance method, material flow analysis, multi-sectorial system analysis).
2	"footprinting"	green 34	Issues of GHG emissions with energy consumption, material consumption and transportation. The consumption and flexible demand side, the development status of household is taken into account as well the environmental and health effects. A strong focus is put on life cycle assessments and footprint analyses in relation to indicator development also over varying time scales and durations. Case studies are spanning over the United States, Europe, China and Latin America. It connects to cluster 8 to the material and resource efficiency and accounting, yet it diverts the perspective to the material basis of economic activities.
3	"decisions"	light-blue 54	Issues on cities as secondary resource source of energy, water, and nutrients and relate these to changing flows and fate due to urban layout and urban land use. Another subgroup in this cluster deals with socio economic processes and activities, consumption patterns, influencing flows across scales (building, neighborhood, city) and distribution of effects. Resilience of infrastructure, rebound effects and limits of efficiency in these closed cycle systems. Strong management and planning perspective which divides roughly into two ideas: First, planning and decision support systems including developments of historical and future planning trends or policy scenarios. Second, variations of indices or computational models supporting the performance assessments and benchmarking for decision makers. Besides the resource management, other interdisciplinary perspectives come from urban political ecology, thermodynamics, all with a strong systemic perspective and on integrative multi scale and multi sectoral system analyses.
4	"integrative"	black italic 24	Issues of conceptual and discursive relevance converging on different perspectives of integration. In planning a strong focus is about understanding types of governance and policies, types of methods creating utility, transparency and access points for planners and advancing, as well as advancing planning through innovative decision support tools, and integrating these with ongoing research. The interdisciplinary integration is applied in conceptual and framework development discussing interlinkages and mutual advancements between ecological economics and industrial ecology but also comparing and critiquing paradigms and the quality of their usage of urban theories and ecological theories. A third share of articles deals with methodical developments and reviews of current state of research fields and approaches in urban metabolism. Method designs with approaches of sustainability assessment and indicator development.
5	"recovery"	orange 22	Issues with focus on water and waste recycling (and separation) systems in relation to nutrient and phosphorus recovery but also in relation to heavy metal contamination, air pollution and carbon emissions and eventually health impacts. Discussion on technology transfer options of drainage systems, waste management systems, waste separation, and urban mining for different context globally. Method design with cross-case comparisons supported by substance flow and material flow analysis, and life cycle inventory. The overlap with cluster 1 are obvious, however, it is more specific on the type of flows and subsystems in the city as well as less methodical diverse.
6	"ferrous"	grey 29	Issues are focused on urban mining, recycling, eco-efficiency and CO2 emissions of building and construction waste, urban solid wastes. The building level is in articles of this cluster more prominent, but it also includes specific sectors of economy, such as shipping and logistics and a political dimension. Case studies in this cluster are geographically mostly (not exclusively) located in Chinese cities, working with dynamic material flow analysis and input-output analysis methodologies. It relates with cluster 2 and cluster 8 and contributing to the optimization and efficiency of resource flows, yet for a very specific set of material flows.
7	"ecologies"	dark green 16	Issues of water, energy and waste flows related to their social construction and types of labor. With perspectives from history of technology and local history understandings of long-term socio-ecological transitions are explored. It also includes questions about distribution of urban inequalities, access, and power as well as alternative models that have the potential to reconfigure these flows. Disciplines of (urban) political ecology and urban ecology are here mostly represented. Case studies from Europe and conceptual discusses are relatively balanced in this cluster.
8	"emergy"	dark blue 23	Issues of measurement of urban material and energy flows, the metabolic capacity of urban areas, and ecosystem health in the context of building and construction materials, sludge and waste, and indicator development for ecosystem health. Analyses with complex emergy methods in combination with network analyses of individual and comparative case studies in Chinese cities and Chinese urban areas.

Results: Review of Sustainable Urban Metabolism Case Studies

Below, the results are presented by the percentage of the total number of case studies followed by absolute numbers in parenthesis. The number of case study publications increased exponentially over the time period between 1994 and 2015. Of all case study publications clusters “footprinting”, “decisions”, and “emergy“ make up 58% (88); 48% (103) of all case studies were published between 2010 and 2015.

Among the total number of cases, comparative case studies were described in 12 publications covering a total of 35 locations. To illustrate the geographical distribution of research, these 35 locations were treated as individual data points resulting in 187 data points in total. These case studies were distributed across 42 countries, of which 44% (84) were located in Europe, 33% (62) in Asia, 12% (23) in North America, 3% (7) in Africa, 3% (7) in South America, and 2% (4) in Australia. The geographical distribution showed hotspots of case studies in China (49), Great Britain (13), the United States (13), and Sweden (10). Europe was predominantly represented in cluster “decisions”. Looking more closely into the cities represented, Beijing (26) contributed the most observations, followed by London (10), Shanghai (7), Stockholm (6), Toronto (6), Vienna (6), and Barcelona (6).

Research Approaches, Designs, and Methods

Overall, 67% (102) of case studies followed a problem-oriented approach and only 33% (50) followed a solution-oriented approach. Combining the criteria research approach and design (see Figure 2a), of the interdisciplinary/disciplinary case studies only 22% followed a solution-oriented approach and of the transdisciplinary/participatory case studies, 10% followed a solution-oriented approach. Some of the case studies with an interdisciplinary design mentioned different kinds of involvement of actors weaker as participatory, but indicate a trend towards participation: these cases make up 8% of the solution-oriented, and 13% of the problem-oriented.

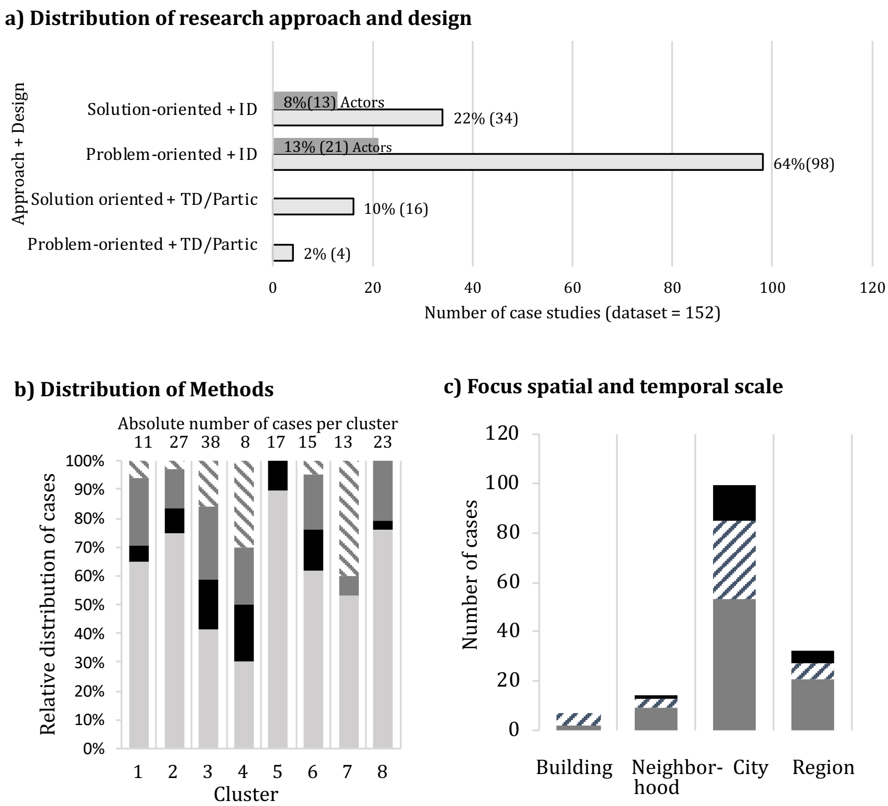


Figure 2. **a)** Research approaches and designs, dark gray = number of cases with interdisciplinary design and explicit involvement of actors **b)** Distribution of methods per cluster (from bottom to top); light gray = flow analyses, black = scenario analyses; dark gray = analytical methods with spatial dimensions, patterned = qualitative methods; **c)** Focus spatial and temporal scale of case studies in relation to each other: gray = historical development (>-5yrs since pub); patterned = present (-5yrs>pub>+10 yrs.); black = future (pub >+10yrs).

Overall, four method categories can be derived from the diversity of methods applied in the case studies: (i) different kinds of flow analyses and life cycle assessments (e.g. material flow analysis, mass balance analysis or ecological footprinting) (ii) scenario analyses (e.g. qualitative scenario planning, model based scenario analysis) (iii) analytical methods focusing on spatial dimensions (e.g. GIS), and (iv) qualitative methods (e.g., interviews, workshops). Only 13% (20) of cases used a mixed-method design. Flow analyses methods were fairly evenly distributed across all clusters. Cluster 7 “ecologies” contained no scenario methods, clusters 5 “recovery” and 8 “emergy“ had no qualitative methods, and cluster 5 “recovery” no spatial analysis methods (see Figure 2b).

Focal Spatial and Temporal Scales

The focal spatial scale extends across the building level up to the regional level; case studies existed for all of these spatial scales (see Figure c). 65% (99) of all case studies were conducted on a city scale. At least 21% (32) related or extended the focal study area to the regional scale. In comparison, only 14% (21) of the cases considered the neighborhood and building scales. All three focal temporal scales, historical, present, and future perspectives were represented. Studies predominantly took on a historical perspective and made up 56% (85) of the total. They were represented by cases with data points (both singular events and those covering a period of time) taking place more than 5 years before their publication date. These cases were followed by 31% (47) with a temporally present perspective. The smallest group, comprising only 13% (20), was made of case studies with a future perspective.

Looking at temporal and spatial scales combined (absolute number of cases): Both historical and present perspectives contributed cases on all spatial scales; however, for both time frames, the city scale was best-represented, with 53 and 32 cases respectively. At the regional scale, 21 cases employed a historical perspective. From the future perspective, there were no case studies on the building level; on the neighborhood level, 1 case; and on the regional level, 5 cases. However, in 14 cases, research on the city scale offered a future perspective.

Knowledge Types: System, Target, Transformation

The analysis of system knowledge revealed, to some degree, the multiplicity of frameworks that are applied in urban metabolism case study research. 97% (148) of all case studies had a stocks and flows understanding; 22% (34) referred to complex system approaches (i.e., complex-adaptive systems, indirect cause-effect chains), 20% (30) used or integrated a socio-ecological systems perspective, 5% (7) dealt with concepts of resilience.

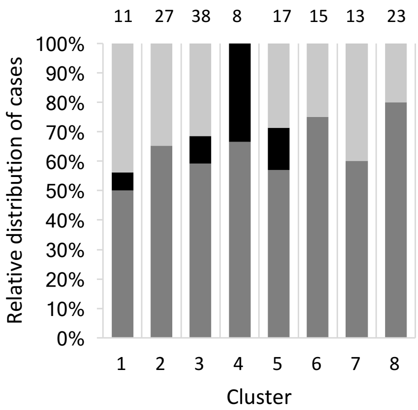
In the operationalizations of target knowledge, the envisioned contributions of the case studies to SDG 11 “Sustainable Cities and Communities” showed 5 recurring targets: 64% (97) reduced environmental impact, 26% (39) positive economic links between scales, and 5% (7) integrated policies with regards to climate change, 5% (7) supported housing and basic services, and 1% (2) contributed participatory settlement planning. The analysis showed a balanced result with regards to defining sustainability: 49% (75) of the papers provided no definition, and 51% (77) provided one at the beginning of the article. Looking into the variety of definitions (see the first column in Table 3), case studies used combinations of four general types of definitions together with design and assessment criteria. As described in Table 3, there are: (i) very broad definitions referring to general principles of dimensions and pillars; (ii) definitions from an institutional and policy perspective, e.g., Agenda 21 or the Brundtland Report; (iii) definitions revolving around the ecological dimension of sustainability; and (iv) definitions revolving around economic definitions, e.g., the steady state economy, limits to growth. The highest variability was found in the cases of clusters “decisions” and “integrative”. In contrast, the cases of clusters “nutrition”, “footprinting”, “recovery”, and “emergy“ used fewer combinations and were more focused on the definitions from an ecological perspective. The next category of justice and equity, was only present in 19% (29) of the cases. Of these 29 cases, 10% (15) actively integrated justice aspects in the analysis, and 9% (14) mentioned or discussed justice in relation to the case. Most cases with any aspect of justice were found in cluster "decisions" with 6% (9) and cluster "footprinting" with 5% (7), whereas no justice aspects are addressed in the case studies of cluster "emergy". Sustainability design or assessment criteria appear with a similar frequency in 18% (28) of all case studies, with 9% (14) appearing in cluster "decisions". Combining these results shows that (i) only 3% (5) of the total cases include a definition, sustainability assessment/design criteria, and deal with justice aspects; (ii) clusters "decisions" and "integrative" host most of the case studies engaging with target knowledge via several criteria.

Table 3. Only those cases are listed that have sustainability definitions and assessment criteria; Each column is one case study, "X" indicates the definition as used.

Type	Definitions	Cluster 1	Cluster 2		Cluster 3												Cluster 4					Cluster 5	Cluster 8				
Number of cases with definitions and assessment criteria		1	2		12												5					1	5				
1	Complementary definitions of sustainability pillars, aspects or categories					x				x		x			x	x					x						
1	Integrated definitions of social, ecological economical dimensions												x														
2	Procedural definitions emphasizing participation, agency, or social aspects							x				x			x					x	x						
2	United Nations Millennium Development Goals																										
2	WCED Brundtland Report						x	x			x						x	x		x							
2	UNCED, Rio Declaration, Agenda 21										x							x	x			x					
2	Triple Bottom Line (People Planet Profit/Prosperity)	x		x																							
3	Definitions emphasizing unspecific ecological aspects or dimension										x																
3	Definitions with focus on maintaining ecosystem (services), biodiversity, or ecosystem health		x											x						x						x	x
3	Ecosystem's carrying capacity, planetary boundaries																										
3	Connecting ecosystem functioning with human wellbeing							x				x			x		x		x	x			x	x	x		
4	Definitions with reference to Club of Rome, limits to growth, sufficiency, decoupling				x			x				x									x						
4	Daly; Steady state economy, balanced economy	x							x									x	x				x				

There were three operationalizations representing transformation knowledge (i) outlooks with relevance for non-academia, (ii) strategic recommendations, and (iii) stepping stone or pilot projects. These were not mutually exclusive, however, only 3% (5) of cases in clusters "recovery" and "nutrition" included all three categories, and 19% (29) cases did not mention transformation knowledge at all (see Figure 3). A practical outlook, the simplest way of referring to transformation knowledge, was the most prominent across all clusters, with 64% (98), followed by strategic recommendations, with 31% (48). Projects operationalizing transformation knowledge were coded in clusters "nutrition", "decisions", "integrative", and "recovery", but only made up 7% (12) of all cases.

Figure 3. Cases with transformation knowledge for each cluster; Absolute number of cases per cluster on top Categories in %; gray = outlook; black = projects, light gray = strategy recommendations.

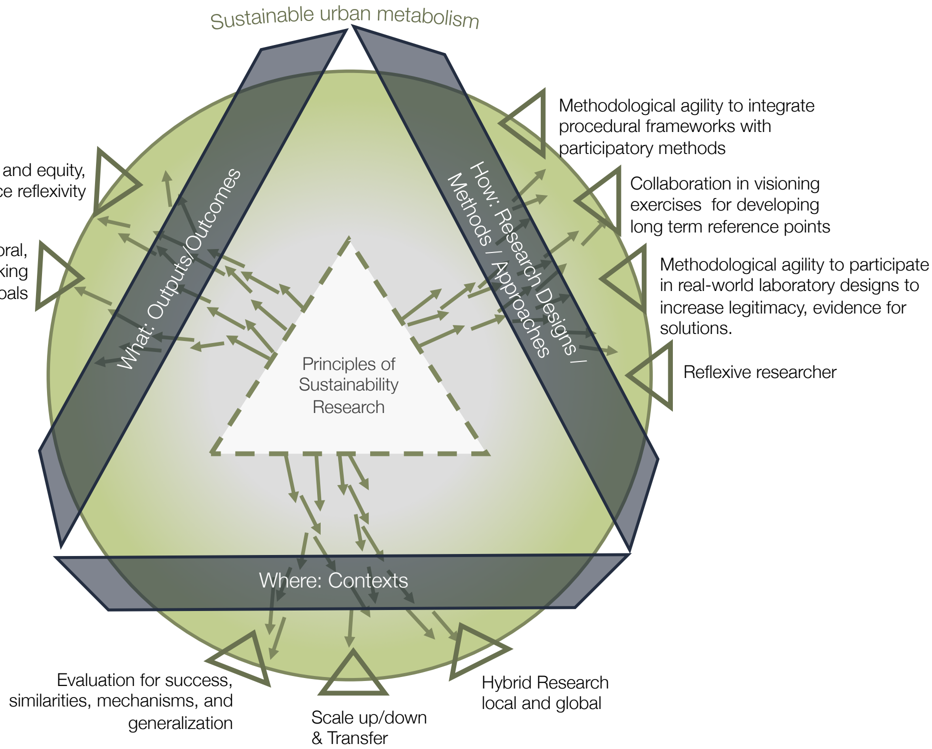


Challenges and Potentials of Urban Metabolism in Sustainability Research

Urban metabolism research has started to shift focus from a primarily analytical and descriptive perspective to one that engages increasingly with sustainability issues in general and sustainability transformations in particular.

In the following sections, we identify and discuss the possible foundations of a sustainable urban metabolism concept and identify opportunities for informing and developing systemic and evidence-based sustainability solutions. To do so, we organize the discussion in three areas (see the edges of the triangle in Figure 4) including the "where" (contexts of research), the "what" (products of research), and the "how" (methods and research designs). We use these lenses, stemming from the analytical framework of Table 1, to organize and present pathways, represented by the arrows in figure 4. These arrows were identified with a multivariate analysis, to demonstrate how sustainability research principles (the dotted triangle) can support moving a sustainable urban metabolism from system understanding to system transformation. These pathways can serve as push factors to enlarge the number, type, and quality of sustainable urban metabolism research within the community. Hence, these are also important connecting points across the interdisciplinary fields involved in urban metabolism research and sustainability research, and can also serve to embed sustainable urban metabolism contributions toward a larger sustainability endeavor.

Figure 4. Pathways (rep. by arrows) to realize sustainability research principles (dotted triangle) through the



areas of how, where, and what (edges) within the field of urban metabolism research (circle).

Where: Broadening the Contexts of Sustainable Urban Metabolism

Context is bounded by spatial and temporal system features. Contextual conditions determine the way sustainability problems and solutions are observed and explained, hence steering the meaning of a given issue (Manson, 2008; Parris and Kates, 2003; Seghezzo, 2009). This is notable, because research and science policy agendas, e.g., the SDGs and FutureEarth, frame these contexts and meanings as topical fields and targets in which sustainability contributions are urgently expected (Future Earth, 2014; ICSU and ISSC, 2015). For example, in relation to the Sustainability Development Goal 11, "Sustainable Cities and Communities," urban metabolism research contributes a large share of case studies aiming to reduce environmental impact (64%). In contrast, only 1% explicitly supports housing and basic services. The number and distribution of clusters emphasize the broad range of contexts to which urban metabolism research contributes. Whereas the clusters "decisions" (3) and "integrative" (4) might share the most overlaps in linking directly with sustainability principles, the distribution of the clusters "emergy" (8), "ferrous" (6), "recovery" (5), and "nutrition" (1) displays the flexibility in system focus that guides the research across several spatial scales.

In the field of urban metabolism, there is a shared understanding and terminology of systems, frameworks, as well as large national databases, such as EUROSTAT, that facilitate the application of accounting and assessment methods across these many contexts. The majority of them are geographically located in the Global North, where data collection and access are standardized and continuous. Acknowledging this systemization is an important milestone toward combining local insights from case studies and global generalizable results for understanding the transfer of, for example, energy management strategies across urban areas or downscaling them to then neighborhood level. Although limited access to such national databases constrains work outside of the Global North, case studies from the Global South demonstrate considerable innovation to achieve similar standards. They fill local data gaps and address topics of culturally different practices with, for example, mixed-methodological frameworks or intense stakeholder involvement (Guo et al., 2014).

Pathways: Transfer, scaling, and evaluation

Both innovation and systematization point toward broadening the contexts of sustainability topics in urban metabolism research. Innovation through methodological diversity allows researchers to capture configuration of sustainability problems that are specific to the local area and develop solutions that can surmount the cultural, institutional, and political challenges found in that particular context. This place-based research is a crucial small-scale tool for changing behavior patterns, business practices, and living conditions within a larger sustainability transformation (Wittmayer et al., 2014). Additionally, systematization organizes, archives, and makes collective research insights available. For example, open access databases can allow to access for conditions of upscaling and downscaling solutions, or for characteristics that indicate feasible transfers of solutions (c.f. Engler et al., 2018). Hence, the collaboration between "hybrids" such as the urban metabolism community and sustainability research can deliver important steps toward generalizing, scaling, and transferring solutions, as well as increasing their sustainability impact (Lang et al., 2017).

Evaluative research efforts comprise a third pathway interlinking the above. They have been developed in sustainability research in order to gauge and interpret the success of solutions (Forrest and Wiek, 2014; Luederitz et al., 2017). Integration serves two important intermediary steps: first, application of evaluative frameworks can help structure results from case studies along their outputs, related processes and inputs, as well as clarifying impact on sustainability targets. For example, reducing household water consumption is often considered to increase sustainability without clarifying the broader contextual implications or justifying how lower water use is accomplishing sustainability targets. Evaluative frameworks could help to organize activities related to resource use and they offer structured ways to assess generated outputs regarding their sustainability contributions. Second, urban metabolism case studies provide an effective way to determine a status quo or baseline which is required for rigorous evaluative research. Using existing data sets and methodologies from urban metabolism studies could support evaluative research in scoping contextual dynamics prior to interventions. As these efforts uncover similarities and mechanisms that help create processes for a sustainability transformation, they also act to strengthen the connection between urban metabolism research and the sustainability community.

What: Diversifying the Products of Sustainable Urban Metabolism

Interdisciplinary research efforts have increased our understanding of the Earth's functioning, its carrying capacity, and the anthropogenic drivers of global environmental change, and it has helped to conceptualize the immediate and long-term challenges of current societal practices and behavior (Reid et al., 2010). Products of urban metabolism research, the types of knowledge thereby developed, as well as the way that knowledge currently links and contributes to addressing sustainability problems is of particular relevance, as research alone does not automatically contribute to societal and policy changes (Future Earth, 2014; Reid et al., 2010; Wiek et al., 2012a). Through the social components in the urban metabolism it is possible to generate valuable information for target and transformation knowledge which links the system understanding to concrete transformational interventions. An adaptation in the current concept of stocks and flows is suggested by Pincetl et al. (2012, p. 201) by "linking […] flows to the complex set of institutions, organizations, and societal relations that shape and guide economic activities, politics, and cultural norms […]." Connecting stocks and flows with individual and collective actors is one way to link upstream drivers, e.g. rules, regulations, behavior, to actor-specific actions and hence to their role as polluters or victim. Currently, this connection to the social component of the system can be found mostly in cluster "decisions" (3) where they fill this gap by extending their system frameworks with political and institutional factors (c.f. Mehta et al., 2013; Svane and Weingaertner, 2006); or in clusters "nutrition" (1) and "foot printing" (2) for studies addressing policies of low carbon cities (Lin et al., 2013), demand-driven transportation emissions (Hillman et al., 2011). The actions of actors in effecting the sustainability target are also central when conceptualizing the normative dimension of a sustainable urban metabolism.

Target knowledge elicits information about the social components of a system that is driven by ideology, inequality, and power relations. Such information includes ethical and value judgments that appear in descriptions of future sustainable states and respective actions, perceptions, and causes of sustainability problems (past, present, or future). However, explicitly integrating sustainability into a methodological approach requires a certain level of conscious operationalization, such as a respective working definition and of related design or assessment criteria (Gibson, 2006; John et al., 2015). These operationalizations make up 17% of the case studies and were mostly found in clusters "decisions" (3) and "integrative" (4) with many studies focusing on policy, planning, and decision-making.

Justice and equity are core principles of sustainability (WCED, 1987). They appear as the (economic) distributive equity of costs and benefits (i.e., distributional justice); however, there are two more key constituents for evaluating them. Procedural justice focuses mainly on achieving fair outcomes through inclusive and participatory decision-making. Lastly, contextual justice focuses on the relative circumstances of culture, beliefs, and power in which "just" outcomes are placed. Seen through these lenses of distributional, procedural, and contextual justice, urban metabolism research has been contributed studies about (i) unequal distribution of access to resources or infrastructure, distribution of related costs, and risks due to (neo-liberal) management practices. Connected to procedural equity (ii) are the decision-making modes of powerful social groups (e.g., the middle class, elites), the role of power relationships and control over these modes, and their historical evolution (Broto et al., 2012). In contrast to this research agenda, the results of our analysis show that justice is only apparent in 19% of all case studies—of which only 10% actively use justice aspects in their own analyses. Cases that deal with this approach ask questions, for instance, about the eco-efficiency of a certain technology and who it benefits (Villarroel Walker, 2012). Others address downstream and upstream distributional effects of certain management practices (Fragkou et al., 2014; Park and Gupta, 2015) or how they integrate into urban planning and development (González and de Lázaro, 2013; Svane and Weingaertner, 2006). Procedural equity is highlighted in case studies exploring niches of standardized national datasets, e.g., food or water cycling in informal, marginalized, and hence vulnerable settlements (Saravanan et al., 2015; Shillington, 2013; Yates and Gutberlet, 2011). In the interest of understanding the trade-offs between equity, effectiveness, and efficiency of urban energy and material flows, aligning the research topics to equity, as well as developing a "just society", interdisciplinary research and collaboration is critical to help to operationalize equity targets, such as in the Sustainable Development Goals, including all three constituents coherently (Jerneck et al., 2011; McDermott et al., 2013).

Creating outputs that translate into practice, in the form of **transformation knowledge,** is part of a continuous debate and part of systematic efforts in sustainability research (Clark and Dickson, 2003; Sarewitz et al., 2012; Wiek et al., 2012b). Generating transformation knowledge relates to research investigating the operational and strategic issues of addressing challenges in coupled socio-ecological systems (Wiek et al., 2012b). Although the implementation of results into practice has not yet become prominent in analyzed urban metabolism research, there is increasing consensus among scholars regarding the necessity of doing so, as well as efforts made to go beyond simply analytically describing and tracing the metabolic functioning of the city (Binder et al., 2009; Chen and Chen, 2015). Various streams of research engage in the need to draw upon regulatory solutions offered through interdisciplinary collaborations with political ecology (Pincetl et al., 2012), and some downscale the flow accounting to the level of the individual acting within the city (Keirstead and Sivakumar, 2012; Svane and Weingaertner, 2006). As 64% of case studies show, having a practical outlook is almost programmatic for many case studies; however, they often lack concrete, actionable recommendations tailored to specific actors, application modes, and contexts (Forrest and Wiek, 2014). Defining this kind of product (without providing for transfer possibilities or practical application) as transformation knowledge, the researcher tolerates the risk of remaining on an informational level only, without system feedback and thus transformational effect (Meadows, 1999). Results that are transferred into a project for testing require and include more complex information on procedures, operations, and intended changes. There are cases in cluster "decisions" (see Figure 1) that pay attention to the analysis of data and the transfer and communication of results (c.f. Blečić et al., 2014; Chrysoulakis et al., 2013). They mainly deal with planning and decision-making tools such as those for climate change mitigation/adaptation or local energy, water, food, and carbon fluxes. The efforts to inform practical application and change toward sustainability are manifold but unsystematic across these case studies, both in clusters with a stronger natural science focus and those with a social science focus.

Pathways: Impact evaluation and systematic justice

Further evaluative efforts are an important aspect for pathways toward more sustainability in urban metabolism research. One way to pool and structure these efforts is to utilize sustainability goals as external organizing principles, which explicates a societal discourse and provides a future perspective for discussions. In order for urban metabolism research to derive the necessary socio-ecological practices to shape resource flows (and therefore new foci of research), a fundamental idea of desirable future outcomes must be developed. In-depth project evaluations can address the question of how case study results contribute to solving sustainability problems, and what their impact on sustainability is (Forrest and Wiek, 2014; Wiek et al., 2012b). Systematizing efforts according to current policy goals and conceptual frameworks, as well as debates, can show how results link to action and change in sustainability from a practical perspective (Future Earth, 2014; Miller, 2013; Sarewitz et al., 2012).

A third way that is relevant to research products for a sustainability transformation is the systematic alignment of contextual justice and the researcher reflecting about the way justice is addressed. The question of "equity among whom?" has to be posed from an urban metabolism perspective. On a temporal and spatial scale, this challenges how the individual, the household, the community, the value-chain, the global system, and future generations are considered, both conceptually and methodologically. Across research products, this helps also to uncover those trade-offs that occur over time and geographically, such as the parallel (water) metabolisms in the city (McDermott et al., 2013). Highly relevant in this context is the projection of the material basis of the Sustainable Development Goals e.g. the interaction between gender equity (SDG 5) and food security (SDG 2). Urban metabolism research connected to actor and network analysis would for instance allow to dynamically trace the effectiveness of women empowering policies back to household consumption and regional agricultural activity.

How: Expanding the Method Canon of Sustainable Urban Metabolism

Addressing the complexity of sustainability problems requires strong interdisciplinary and transdisciplinary approaches, increased reflexivity, and communication across disciplines, as well as methodological pluralism. Consequently, the selection of a general research approach, a sound design, and appropriate methods is demanding and crosses disciplinary boundaries (Spangenberg, 2011; von Wehrden et al., 2017). Aspirations toward interdisciplinarity within the urban metabolism community are well-represented in methodological discussions and reviews (Fischer-Kowalski, 1998; Pincetl et al., 2012; Zhang, 2013) and confirm that the field offers space for vital debates and negotiations (Robinson, 2008). The field of urban metabolism addresses crucial aspects, such as: (i) how to integrate socioeconomic drivers and causes for people's preferences, priorities, and decisions into urban metabolism research; (ii) how to transfer results and insights into practical applications (iii) how to close data gaps, increase access, and availability of flows linked to local residents' activities (Kennedy and Hoornweg, 2012; Pincetl et al., 2012; Zhang, 2013). These areas correspond very well with calls in sustainability research to shift from problem- to solution-oriented research designs that inform social action (Robinson and Sirard, 2005; Sarewitz et al., 2012). Sustainability research aims to deliver place-based information, uncover mechanisms of upstream drivers, and determine relatable products of transformation knowledge for practice (Lang et al., 2012; Spangenberg, 2011). Currently, only 13% of urban metabolism case studies follow a solution-oriented design, yet 38% supposedly produce outputs with advanced transformation knowledge, namely strategic recommendations or pilot projects. This is an apparent mismatch between intended and actual products and points to difficulties in the comprehensive interplay of general research approach, sound design, and appropriate methods.

Transdisciplinary research is a method-driven scientific principle that answers to the demand to generate transformation knowledge addressing complex sustainability problems. The interdisciplinary collaboration of researchers and the co-production of knowledge at the science-society interface are among the core concerns of transdisciplinarity (Hirsch Hadorn et al., 2008a; Lang et al., 2012). The integration of actors and stakeholders into research is a critical step, not only when the intention is to close the gap of access to and availability of data, but also in supporting the application of research findings in administration, urban planning, and decision-making. In so doing, the actors' involvement reveals a more comprehensive view of a city's social system. The use of spatial analyses, scenario development methods, and different kinds of multilateral qualitative methods in cooperation with local actors is promising as case studies of the clusters "decisions" (3), "integrative" (4), and "ecologies" (7) show (in Figure 1); They underline ways to fruitfully complement established accounting and measuring methods. In European, Kenyan, Colombian, and Chinese case studies (c.f. Arboleda, 2015; Lin et al., 2013; Lombardi and Trossero, 2013; Pauleit and Duhme, 2000), these methods enable the integration of informal flows and explore new ways of data collection. (Sima et al., 2013; Svane and Weingaertner, 2006). Additionally, studies in cluster "nutrition" (1) (Saravanan et al., 2015; c.f. Shillington, 2013; Yates and Gutberlet, 2011) offer innovative participatory approaches to operationalize sustainability criteria for urban metabolism research and engage in the contested topic of ethical and normative predicaments that are urgently relevant to attain sustainability (Fischer et al., 2007).

Pathways: Visioning, experimental settings, and Reflection

Moving toward a solution-oriented perspective in urban metabolism research is a challenge; one way to address this challenge is to support research methods based on stakeholder participation, such as "visioning" that can be used to integrate target knowledge. Visioning exercises belong to a group of methods that explore *desired* future states (in contrast to scenarios, which play out *possible* future states), that then serve as frameworks for judging the desirability of interventions and their impacts. In research as well as in planning, visioning exercises are substantial components in sustainability solution development, for example procedural frameworks (Komiyama and Takeuchi, 2006; Loorbach, 2010; Morioka et al., 2006; Ravetz, 1999; Weaver and Rotmans, 2006) and comprehensive urban development plans (Iwaniec and Wiek, 2014; John et al., 2015). Visioning exercises in sustainability aim to design long-term normative reference points, explore desirable future states, and make value orientation explicit; they are designed as participatory processes (Wiek and Iwaniec, 2014). For urban metabolism research, visioning could provide a methodological component for embedding target knowledge more systematically. For example, a resulting urban vision can incorporate desired future resource flows as well as their just and equal distribution across cities. In so doing, they also complement urban metabolism research. However, visions often insufficiently address the systemic complexity of urban areas; for instance, they often only partly consider linkages between different targets, and hence fail to meet quality criteria for coherency or plausibility (John et al., 2015). However, this kind of participatory research connects back to the aforementioned discussion of justice and equity. This approach requires expanding existing methodological toolkits to explicate power relations, hierarchies, the relationships between social groups and their ability to influence processes, behavior, and outcomes (Jacobs et al., 2016; Pooley et al., 2014).

The forms of transformation knowledge, i.e. outlooks, strategic recommendations, projects come with a varying degree of accountability, legitimacy, and eventually, impact. Hence, we might ask how we can embed urban metabolism research into "real world" research settings in order to produce highly accountable, legitimized, and impactful transformation knowledge**.** For instance, real-world laboratories are settings that create spaces for experimentation to bring about and assess system changes and produce empirical evidence about the functioning and effectiveness of interventions in practice (Broto et al., 2012; Schäpke et al., 2017; Voytenko et al., 2016). These experimental settings are intended to create evidence-based actionable knowledge that cater to the complexity and context dependency of sustainability solutions (Caniglia et al., 2017b). Furthermore, they can complement current outputs with insights on procedures and instructions and increase the concreteness (and likeliness) of application (Caniglia et al., 2017b). In return, advanced modeling and monitoring methods of urban metabolism research could provide important evidence on interplaying niches, regimes, and landscapes in transition processes. Hence, real-world laboratories can induce another quality of system and transformation knowledge generated in urban metabolism research for sustainability that goes beyond pure strategic recommendations or practical outlooks.

Finally, a principal pathway between products and research designs is the changing understanding of the role of research into these processes. The reflective researcher develops the ability to recognize important (historical) path dependencies of knowledge production, including access to and benefits of resource infrastructure, how power relations also affect the research process itself, and the provision and legitimacy of outcomes (Jacobs et al., 2016). This takes on greater importance as experimental settings and participatory designs grow in number, requiring the objective researcher to take on a more interactive position.

As the number of case studies and the results of this study show, efforts have been increased to better understand and foster a sustainable urban metabolism and to reflect and collaborate on complex sustainability challenges. The high diversity and activity of research that converges under the umbrella of the urban metabolism framework offers great opportunities to work on strengthening the linkages to other areas of sustainability research and elaborate on connections in order to achieve sustainable urban futures. Nevertheless, establishing a new culture that moves from analytical understanding into real-world applications requires a transdisciplinary effort as well as conceptual and methodological agility and respective frameworks.

Conclusion

Acknowledging the role of urban areas as motor and hub of innovation, we have provided an overview of the current state of urban metabolism research in the context of sustainable development. We investigated how links between urban metabolism research and sustainability can be structured, how strongly they are intertwined, and what gaps and possibilities offer space for further advancements. To that end, we applied a multivariate statistical analysis and a systematic literature review involving the quantitative and qualitative analysis of 221 scientific publications.

From this analysis, we first created eight individual clusters of urban metabolism research spanning disciplines from the natural to the social sciences, covering a broad spectrum of energy, material, and resources, and exploring the urban area across various system scales. Second, we highlighted interlinkages with transformative and normative principles of sustainability research according to research approaches and designs, spatial and temporal boundaries, and knowledge types. Third, we outlined pathways of how, where, and what to address in the methodological and conceptual gaps between urban metabolism and sustainability research.

We found that the field of urban metabolism research comprises several diverse approaches that align with different aspects of sustainability research. However, there is a lack of connection to the ongoing developments in sustainability research, and lack of alignment of metabolism contributions toward larger sustainability endeavors. Consequently, we conclude with the following recommendations to provide substance to the “sustainability” aspects of a sustainable urban metabolism and to further connect this research with the sustainability discourse:

We recommend a stronger integration of complex system dynamics underlying urban metabolisms and their sustainability transformation. Urban metabolism research can provide substantial insights with regards to system complexity and its legacies, especially related to material flows. Such insights can help coping with complexity in diverse sustainability research efforts and are critical for evaluating success and impact to a sustainability transformation. However, they require that system understanding be the means and the starting point to conduct further research, rather than being the end product.

Second, we recommend stronger collaboration within and across the interdisciplinary communities regarding the development of transformation knowledge, the practical application of research results, and engagement in strategic and operational change to support the transfer and scaling of solutions for cities. Such collaboration and organization from a solution-oriented perspective should address innovations in research designs, identify the role of social action, and reconsider (historical) leverage points for change outside the policy realm.

Third, we suggest more dialogue between the fields about the role of actors and stakeholders in research processes in order to bridge data gaps, and tailor solutions more strategically. Such exchange should include discussions regarding the value of participatory processes and transdisciplinary research, as well as experimental research settings. It should capitalize on ongoing and future urban metabolism research in the Global South and encourage capacity-building among actors in society. Such capacity-building should be aimed at training these actors to understand and apply urban metabolism research.

Lastly, stronger engagement in normative discussions about sustainability, justice, the desirability of alternative futures, and trajectories is critical. Setting definitions and standards explicates issues of poverty and implicit equity goals. Such discussions can help to valorize research results, highlight contexts in which further research occurs, and reveal barriers to implementation.

How Much Sustainability Substance is in Urban Visions? – An Analysis of Visioning Projects in Urban Planning

Beatrice John, Lauren Withycombe Keeler, Arnim Wiek, Daniel J. Lang

Abstract

Cities are hubs of social interaction, trade, and innovation. Yet, they face sustainability challenges of economic decline, social injustices, and environmental degradation. Urban planning is a critical instrument to cope with these challenges. Visioning, the process of constructing desirable future states, can provide direction for sustainability-oriented planning and decision-making and is increasingly used in this capacity. However, there is ample evidence that urban visions are often not designed along a robust set of sustainability principles. We analyze nine explicitly sustainability-related urban visions from Sweden, Germany, Ireland, Canada, USA, and Australia with respect to their sustainability substance, i.e. in how far they, broadly and in detail, adhere to sustainability principles. Using rough set analysis, we identify a number of procedural components that enable or obstruct the inclusion of sustainability substance in urban visions. Results indicate that the sampled urban visions do not substantially and comprehensively include sustainability substance, instead narrowly focus on optimizing the built environment, for example. Furthermore, the sustainability substance of visioning processes benefits from stakeholder engagement that includes capacity building, whereas some other types of participation obstruct the inclusion of sustainability substance. The study concludes with recommendations for visioning processes to yield urban visions with sustainability substance inclusive of a diverse and integrated set of sustain- ability principles.

Introduction

Cities are hubs of innovation in social interaction, technology, ways of living, and possibly sustainability (Grimm et al., 2008; Weisz & Steinberger, 2010). However, cities also host intensive consumption, production, and trade that impact water resources, land use, and biodiversity, among others, at local, regional and global scales (Bolund & Hunhammar, 1999; Ernstson et al., 2010; Weisz & Steinberger, 2010). In 2008 urban areas released 71 per- cent of the global carbon emissions and consumed 60 to 80 percent of the world's energy (International Energy Agency, 2008). During last centuries, the inflow of ecosystem services and the consumption of direct material per capita has outpaced population growth in most cities (Ferrão & Fernández, 2013; McGranahan & Marcotullio, 2005: 805). Detrimental health effects, social segregation, and access equity issues threaten the well-being and quality of life of the urban population. Sustainability transitions are needed within cities to meet the demands of growing urban. populations amid resource scarcity. This requires leadership com- mitted to sustainability and knowledgeable about its implementation (Grimm et al., 2008; WBGU, 2011).

Urban sustainability efforts are increasingly initiated and led by municipal planning departments and often aim to build capacity within a city to endure dramatic changes, while fulfilling the basic needs of all residents, and reducing resource consumption and improving efficiency (Ernstson et al., 2010; Roseland & Connelly, 2005; Smith & Wiek, 2012). Around the 1960s, a significant shift in the planning paradigm occurred, which, in the past, strove to build physical cities based on architectural ideals, such as LeCorbusier's 'Ville Contemporaine'. Today, planning is strongly tied to community development, facilitated in part by the urban form. Since the 1990s visioning has been an important tool to define community priorities and, increasingly, to develop sustain- ability goals for cities. These approaches in urban planning can pro- mote and direct innovation and decision making within cities on a variety of topics, and are apt to address sustainability challenges and facilitate sustainability transitions (Ferguson, Frantzeskaki, & Brown, 2013; Minowitz & Wiek, 2012; Swilling, Robinson, Marvin, & Hodson, 2011; UN Habitat, 2010). Visions, defined as desirable future states (Shipley, 2002; Wiek & Iwaniec, 2013), can orient strategic operational planning as well as monitoring and adaptation of implemented plans. Interested communities can use visioning (i) to engage diverse publics or incorporate community perspectives and expertise in planning (Hammer, 2010; Weisbord & Janoff, 2008); (ii) in collaborative set- tings with different forms of participation (Rowe & Frewer, 2004); (iii) using different media – such as pictures and other visuals – to stimulate engagement; (iv) to generate target knowledge to guide strategy development (Kaplan & Norton, 2008; Wiek, Binder, & Scholz, 2006) which is (v) communicated to the broader public in a variety of ways, including visioning reports, videos, or newspaper articles (Eickhoff & Geffer, 2007; Lennertz, 2007).

Conceptual and empirical studies have been conducted to strengthen the theoretical underpinnings of visioning and to understand, in particular, how visioning works, when and with what outcomes (Shipley, 2002; Shipley, Feick, Hall, & Earley, 2004; Wiek & Iwaniec, 2013). These studies provide evidence that visioning serves communities through tangible and intangible out- comes. For participants of visioning processes, intangible outcomes include: the capacity to engage in large group deliberations, consensus about targets for city development, and support for and willingness to participate in strategies to achieve visions, which can extend to the broader community. Tangible outcomes include visioning documents that are salient and legitimate to the community and which can be linked to internal city administration and documentation to facilitate implementation of strategies derived from visions (Costanza, 2000; French & Gagne, 2010; Lachapelle, Emery, & Hays, 2010; Moss & Grunkemeyer, 2010).

These empirical studies highlight the benefits of different visioning approaches for a broad range of applications. Some visions and visioning processes have positive, innovative effects on the dynamic of change within cities (Beers et al., 2010). Despite these benefits and the increasing application of visioning in general urban development contexts, sustainability remains an elusive goal for most cities. If visions are tailored to help facilitate urban sustainability transitions, they must draw from best practices and successful sustainability solutions in order to add sub- stance to and flesh out principles of sustainability (Opschoor, 2011; Wiek & Iwaniec, 2013). This evidence-based ”sustainability substance“ can act as target knowledge to orient planning and policy-making when incorporated into visioning processes that bring together different stakeholders from the community and yield shared visions that are sustainable, substantive, and reflect the communities' culture and identity so they can assume owner- ship and accountability (Beers et al., 2010; Uyesugi & Shipley, 2005).

To inform sustainability transitions within cities, this research employs an exploratory case study to determine how much sustainability substance is in nine urban visions and what conditions of visioning processes contribute to or impede generating substantive sustainability visions. Results indicate critical methodical components that are intended to help urban planners design and implement visioning processes that bring about greater sustainability substance to guide urban sustainability transitions.

Method

An exploratory comparative case study was conducted, analyzing nine cases in cross-comparison using rough set analysis. The research design subdivides into (i) case sampling and database construction, (ii) the analytical-evaluative framework to categorize the qualitative data of the cases, and (iii) datamining with rough set analysis.

Database Construction and Cases Sampling

We performed a web-based search using snowball technique and organizations' platforms (e.g. ICLEI, APA), which yielded an inventory of 92 future-oriented urban planning activities in 13 countries. Following Schreier (2010) and Patton (2002), a purposeful sampling protocol was applied to this inventory using predefined criteria to select as cases those sustainability-oriented visioning activities that best illustrate the heterogeneity of methods, objectives, and city backgrounds while meeting comparative requirements for analysis. Selection criteria were: (i) adequacy of a single case, defined as a city-wide vision with existing and accessible detailed (administrative) documentation of outputs, processes and procedures in language spoken by the authors; and (ii) sufficiency of the set of cases, defined as variance in visioning methods, time horizons, city sizes, and intent for sustainable development. Based on these criteria, nine cases were selected (see Box 1).

Box 1

Case #1 (GOT) the Gothenburg 2050 project in Sweden developed from 2002 to 2005 long-term future images of the city and region aiming at a sustainable society. Initiated by Chalmers University of Technology and Gothenburg University, the project team developed a back-casting methodology and involved partners from local and regional governments and the local energy utility. Citizen participation occurred through workshops, surveys and exhibitions. The vision document included technical descriptions and short narratives of living situations (Ramnero, 2005).

Preceding a new land use development plan, the city of Ahrensburg (Case #2, ABG), Germany, organized in 2008 a future workshop following the methodology by Jungk and Mullert (1987). This process aimed to define common goals, wishes, and interests until 2030 toward a sustain- able growth and development based upon a broad spectrum of societal actors. The project team included the planning department, and external consultants on regional economy, mobility, architecture, project management and communications. Citizens were involved through workshops, simulation games and sightseeing tours. The outcome was a 16-page vision document with descriptions and lists structured into four topics (Raum & Energie, n.d.).

The community visioning process from 2010 to 2011 ”Saskatoon Speaks, Shape Our Future“ (Case #3, SKN), in Canada, was initiated to found shared values and define future opportunities and challenges until 2060 to inform Saskatoon’s strategic plans. Selected city staff of all departments formed the project team with consultants on urban design, landscape architecture and project management. Using their own visioning methodology, 7000 to 10,000 residents participated through online questionnaires, summits and roundtable discussions. A ‘do-it-your self-toolkit’ was provided to empower citizens to continue discussions independently from official events. The result of the process is a 30-page vision document describing the future and sustainable development of Saskatoon with lists of ‘success factors’ related to eight topics (City of Saskatoon, 2011).

The community visioning ”Portland 2030: a vision for the future“ (Case #4, PDX) aimed to build a core set of shared values, involving four sustainability dimensions, to guide and prioritize actions of groups from all societal spheres to unify their efforts in light of the upcoming city development plan. The project team consisted of a management team, a steering committee, diverse task-specific sub-committees and, further, associated partners such as non-governmental organizations, businesses and universities. Residents were engaged via surveys, self-organized group discussions and fairs. The result of the process from 2007 to 2011 was a visioning document, addressing nine topics with descriptions and narratives of future living-situations (VisionPDX, 2007).

A methodology of strategic visioning and sustainability assessment was used in the visioning exercise Dublin - A city of Possibilities 2012 (Case #5 DUB). The goal of the exercise was to develop a strategy linking social, economic and cultural issues on local and regional level leading to an enhanced integration of institutions and services. During the process from 2000 to 2002, the team was composed of city planning staff, members of local government, local economic development groups, and social groups. Citizens and interest groups participated over surveys, roundtables and community forums. The vision document consists primarily of technical descriptions, tables, and lists (Krawczyk & Ratcliffe, 2006).

Case #6 (IGS), Visions for Ingolstadt in Germany evolved from the city's procedural 'Local Agenda 21' processes and took place from 2000 to 2002. The existing processes were combined adhering to initial public involvement activities in order to achieve long-term goals for city planning until 2020. The project team included city staff, council members, and external consultants on communications and methodological development (Stadt Ingolstadt, 2002). Their own methodological approach (Bürgerkonferenzen) comprised panel discussions, hosted workshops and exhibitions. The resulting visioning document is subdivided into five topics.

The visioning process Mining the Future: A Vision for Canmore (Case #7, CMO), Canada, for the year 2030 revolved around the question 'what kind of community can we as citizens imagine Canmore becoming in the years ahead?'. It complemented the pre-existing Natural Step community-wide engagement program that trains and empowers community leaders in sustainability decision-making (Mackrael, 2008; The Natural Step, 2008). The main team consisted of external consultants who liaised with the city staff. In the process from 2005 to 2006, residents were engaged by online questionnaires and hosted workshops. The vision document consists of tables and lists (Town of Canmore, 2006).

The project, York Region Vision 2051 (Case #8 (YK), in the Regional Municipality of York south of Toronto (Canada), updated two earlier versions 'Vision 2021' and 'Vision 2026: Creating Strong, Caring, Safe Communities', in accordance with the Region's Sustainability Strategy, in order to address new significant regional changes. The team was comprised of regional planning staff and used a back-casting methodology. From 2010 to 2012 citizens were engaged through online questionnaires and group discussions. The vision document is primarily a list (York Region, 2011).
The purpose of the visioning exercise "The Sustainable Sydney 2030 Vision" (Case #9, SYD), Australia, was to set the course to more sustainable work and life in the city. The team included city staff and an external consultant group with broad expertise and their own methodological approach for the visioning process. During 2006 through 2008, a series of participatory actions involved citizens. The vision document is thematically subdivided and written in form of descriptions, using lists and maps, as well as futuristic drawings and pictures (City of Sydney, 2009).

Adopting an Analytical – Evaluative Framework

A literature review was conducted to develop an analytical-evaluative framework that categorizes the relevant generalized and case study specific data and evaluates the level of sustainability substance for each case. The framework is composed of two types of attributes: (1) condition attributes, hereafter Critical Condition Criteria, and (2) decision attributes, hereafter Sustainability/Resilience Criteria.

The Critical Condition Criteria (CCC) are mainly derived from practical method guidelines and case studies, describing general surrounding factors and procedural structures under which visioning exercises take place. The CCC cover three major themes: (1) external conditions including all city specific characteristics, (2) attributes describing process and organization of the visioning exercise, and (3) specificities about participation and actor involvement during the visioning process. Overall 25 criteria were used to describe the visioning process. To cover situational differences and variations each attribute has 2–3 different manifestations (see Table 1, codification matrix).

Sustainability/Resilience Criteria (SRC) operationalize general sustainability principles (Gibson, 2006) for the urban scale. They contextualize general sustainability criteria with specific aspects related to urban areas (Gibson, 2006; Jenks & Jones, 2010). Specific criteria may address more than one general criterion and general criteria may be specified in more than one specific criterion. The criteria were compiled from three perspectives: practitioner (BioRegional, 2012), researcher (Bunting & Filion, 2010; Jenks & Jones, 2010), and decision maker (Roseland & Connelly, 2005; Clark, 2010; Lehmann, 2010). While the specification and operationalization of sustainability and resilience criteria is necessary for the analysis, the specification requires that some, alternative but potentially important, operational definitions of criteria are not included (Gibson, 2001). Three sub-criteria for resilience in urban systems were added (Ernstson et al., 2010; Resilience Alliance, 2010) to cover a broader and more comprehensive perspective on transformation of urban areas (Redman, 2014). Overall seven feasible sustainability/resilience criteria were synthesized. In order to address the different levels of detail and extent to which sustainability issues are addressed in the final vision the attributes are coded with three nuances: (1) not an issue (i.e. the sustain- ability category was not mentioned at all), (2) only marginally referred to in the vision, or (3) important (i.e. discussed intensely and with high level of detail (see Table 2, codification matrix).

Table 1 Codification matrix for condition attributes including abbreviation, codes for manifestation and short description. This table shows all CCC sorted in three major themes, including the abbreviation that is used within the ROSE 2 software to denote the attributes, a short description of the attribute itself, and a translation for what the codes 1, 2, and 3 stand for.

	Criteria	Abbr.	Definition	Codes 1	2	3
CCC: External conditions	City Size	SIZE	City specific characteristics could influence which sustainability/ resilience challenges are predominant, the way they are approached and how visioning methods are selected and operationalized. Considered to be important are: the ***city size*** (Walter & Scholz 2006), a shrinking or growing ***demographic development*** (Commission of the European Communities, 2008), ***age characteristics*** and ***migration background*** of population (Uyesugi & Shipley, 2005).	small <50,000	medium >50,000	big >500,000
	Demographic development	DEMO		shrinking	growing	
	Age characteristics	AGE		median ages (30-34)	median ages (35-40)	median ages (41-45)
	Migration Background	MIGR		<10%	>10%	
CCC: Process and Organisation	Timeframe of vision	TIME	The ***timeframe of vision*** indicates how far into the future the vision is laid out for (Shipley et al 2004). A long-term vision might include certain measures to adapt to arising circumstances (Stevenson, 2002).	short (10 years)	medium (20 years)	long (30-50 years)
	Duration of process	DURA	***Duration of process*** and ***costs of process*** give some indication on the intensity and effort of the process. (Helling, 1998).	short (<6-1month)	medium (~1-2 year)	long (several years)
	Costs of process	COSTS		<100.000 EUR	>100.000 EUR	>500.000 EUR
	Composition project team	TEAM	The composition of **project team** and associated **project partner** (Shipley et al., 2004) distinguishes whether only city staff is involved or to what extent citizens, external consultants or other societal spheres are involved in steering processes.	city council members	city citizens	none
	Project partner	PART		external experts/consultants	local societal spheres	both/none
	Starting themes	START	***Starting themes*** indicate if main issues are pre-selected during preparation of the visioning process through council decisions, regional guidelines, etc.; or if they are selected in an open process with participants.	pre-selected	developed during process	
	Situation Analysis	SITUA	With a thorough ***situation analysis*** and ***clear outcome objectives*** set in the beginning a definite scope, common ground and understanding is expected to have a guiding influence throughout the process and facilitate to locate main issues (Helling, 1998; Resilience Alliance 2010).	none	simple	extensive
	Clear outcome objectives set	OUTC		no	yes	
	Concept sustainable development	SUST	The ***concept sustainable development*** specifies whether a sustainabil-ity understanding, as a preparatory activity, was explicitly defined as starting point, developed among participants, or marginalized as a topic (Berke & Conroy, 2000).	no	implicitly	explicitly
	Lenght of vision	LENGTH	***Length of vision*** and ***type of vision*** (Shipley et al., 2004) differentiate the forms and appearances of vision documents in terms of number of pages as well as text and illustration.	short	long (>15 pages)	
	Type of vision	TYPE		bulletpoint list	description	narrative story, pictures

	Integration of vision into daily use	USE	A visioning process should lead to the **integration of the vision into daily use**, by e.g. strategic plans for municipal planning, measurements, follow up processes, etc. (Shipley et al., 2004, Helling, 1998). This would be an indicator for the practicability of the resulting vision document.	no	yes	
	Transparent reporting of process	REPORT	**Transparent reporting of process** indicates, if information and details about the visioning exercises is sufficiently transparent and communication strategies are chosen to reach the general public (Fricker et al., 2010).	no	normal	extensive (new media)
CCC: Participation	Higher level of involvement	INVOLV	***Higher level of involvement*** indicates especially the collaboration and empowerment at one point during the visioning process. It is expected that various involvement strategies throughout the process phases will be combined (Stauffacher et al., 2008).	none	collaboration	empowerment
	Actor Diversity Selection	ACTOR	***Actor diversity selection*** deals with the issue 'who' participated and how carefully were the participants chosen (general interested public, systematically ensuring diversity, systematically very specific). High actor diversity implies the provision of diverse resources (knowledge, authority) affecting the vision's result (Walter & Scholz, 2006: 199) and is required to address the stakeholder's interests sufficiently, and influence the choice of method (Mathie & Green, 1997; Holman & Devane, 2008).	low (interested public)	medium (diverse public)	high (specific group leaders)
	% of Participants/ population/year	PARTIC	Due to the varying characteristics of cases the comparison of number of participants and participatory events (Shipley et al., 2004; Holman & Devane, 2008) is facilitated by ***% of participants/population/year*** and denotes the number of participants relative to city population normalized to one year duration of process.	<1%/a	<5%/a	>5%/a
	Unilateral Methods	UNI	***Uni-/bi-/multilateral methods*** differentiate between methods that use a one-way communication (e.g. questionnaires, online surveys), or involve a kind of dialogue (e.g. interviews, exhibitions), or call for a third party (e.g. workshops, roundtables) and how often they were applied during the process (Walter & Scholz, 2006). The methods require differing levels of actor involvement, increasing towards the use of multilateral methods.	none	1-2	3 or more
	Bilateral Methods	BI		none	1-2	3 or more
	Multilateral Methods	MULTI		none	1-2	3 or more
	Types of thinking - intuitive	THINK	***Types of thinking*** indicates a method design that includes stimuli for intuitive understanding and interpretation. All participants are supposed to provide intuitive thinking without being entitled experts. (Scholz & Tietje, 2002: 41, 194).	no	yes	
	Method organization	ORGA	Participatory methods are suitable to be mixed and organized repeatedly (Scholz & Tietje, 2002, Holman & Devane, 2008: 19). ***Method organization*** indicates different approaches of such repetition: one single block, without any repeated involvement; ping-pong, cyclical organization; or a continuous independent stream aside to the process.	one block	ping pong, cyclical	continuus

Table 2 Codification matrix for Sustainability/Resilience attributes including abbreviation used within the ROSE 2 software, and short description. The codes translate for all decision attributes as 1 = not an issue, 2 = marginal, 3 = important

Criteria	Abbr.	Definition
Built Form Processes	SRC 1	On *housing* level this criterion accounts for 'green' design principles, long building life-cycles and flexible usage. On a city wide level this criterion deals with functions and balanced mixture of land use as well as high density settlements. The latter includes retrofitting existing districts with mixed-use urban infill and choosing a pattern of growth with viable, connected, permeable layout and polycentric set-up. Sustainable *transport infrastructure* comprises aspects such as as means for transport, traffic management strategies, including street layout, connectivity, and walkable communities. Sustainable *energy* comprises renewable sources, measurements of reductions and efficiency, as well as an energy management (Baker et al., 2010; Weisz & Steinberger, 2010; Newman et al., 2009; Roseland & Conelly, 2005: 114ff; Perrels et al., 2008; Bramley et al., 2010, Lehmann, 2010: Colding, 2007).
Ecosystem Services	SRC 2	Local-to-regional ecosystem services are the building blocks for human well-being. The criteria address the careful handling of regional inflows of services as well as those generated within the urban area, such as: *Air filtering* and *climate*, *water systems* and management strategies, *soil*, and *food* production (Bolund & Hunhammar 1999, Millennium Ecosystem Assessment 2005: vi).
Consumption, Production, Economy	SRC 3	This criterion indicate the change towards a carbon neutral lifestyle, zero waste and behavioral changes of consumption patterns. The strategies of the community's *economy* include short supply chains, sectorial diversification for local self-reliance, cooperative and local ownership models, high social performance of business practices, as well as municipal support for innovative local entrepreneurship and employment (Billharz & Schmitt, 2011; Newman & Jennings, 2008: 188; Fischer et al., 2012; Lehmann, 2010; Williams et al., 2010; Roseland & Conelly, 2005: 168; Deller et al., 2009; Shuman, 2009).
Social and Cultural Processes	SRC 4	This category incorporates reduction of health risks (e.g. reducing noise emissions), happiness and wellbeing of citizens. *Culture* comprises three main points: building a sense of place and local identity, encouraging a connection between citizens, and underline the distinctive features of the city, such as heritage identity. *Education* follows the idea of cities as hubs for innovation through equal access to educational institutions, promotion of research, specific trainings and knowledge production, and strengthening social and community capital (Roseland & Conelly, 2005; Irvine et al., 2010: 230f; Newman & Jennings, 2008: 150f; Lehmann, 2010; Bramley et al., 2010: 109; Ernstson et al., 2010).
Governance	SRC 5	Good urban governance deals with new forms and qualities of leadership towards sustainability including transparency, accountability, sustainable financing, performance assessments and planning for transformation, as well as forms of community participation and collaborative management across societal spheres. Additionally, adaptive governance means the flexibility to respond, learn and adapt to changes by promoting new networks and cooperation among stakeholders as well as new organizational structures (Lehmann, 2010: 242; Roseland & Conelly, 2005: 11; Fricker et al., 2010; Rowe & Frewer, 2005: 255; Carlsson & Berkes, 2005: 66; Resilience Alliance, 2010: 37; Ernstson et al., 2010: 541).
System of City Spatial Networks hinterland	SRC 6 SRC 7	These two criteria operate on the broader and systemic scale "resilience of cities". The human settlement stands in a reciprocal relationship with dynamic landscapes and regional ecosystems, acknowledging regional climate and topography and adequate climate change adaption and mitigation strategies. The growing inner urban flows require understanding of effects on the hinterland and strategies against resource depletion and waste disposal. Further, the city is positioned in a web of dynamic *networks* across spatial and temporal scales, expanding the basic idea of nested ecological processes to cultural, social and technical networks. (Ernstson et al., 2010: 533; Olson, 2005: 227f; Bolund & Hunhammar, 1999; Kennedy et al., 2007: 43; Brunner, 2007; Rockström et al., 2009).

Data Collection

A document analysis of 82 case related documents was con- ducted. The analytical-evaluative framework was used to sort and map all available qualitative data from case documents, which included workshop materials, final vision reports, project websites, city council protocols, official statistics, as well as newspaper and scientific articles. Ordinal values on the scale {1, 2} or {1, 2, 3} were used to code the qualitative data (see Tables 1 and 2, codification matrices) in so-called Attribute– Value Pairs (this required additional sub-criteria, keywords, and a scoring system, see Appendix for further detail): The value of the pairs indicates the manifestation of the corresponding more general attribute; for example "Actor Diversity" (general) has a manifestation of "Low", "Medium", or "High". This discretized qualitative information was then presented in the information table (see Table 3).

Table 3 Collected Data – Each case described according to CCC and SRC criteria.

Type of Criteria	Criteria Abbr.	Cases #1 GOT	#2 ABG	#3 SKN	#4 PDX	#5 DUB	#6 IGS	#7 CMO	#8 YK	#9 SYD
	SIZE	3	1	2	3	3	2	1	3	2
	DEMO	2	2	2	2	2	2	2	2	2
	AGE	2	3	1	2	1	3	1	2	1
	MIGR	2	1	1	2	2	2	2	2	2
	TIME	3	2	3	2	1	2	2	3	2
	DURA	3	2	2	3	2	2	1	2	2
	COSTS	3	1	3	3	2	2	1	1	3
	TEAM	3	1	1	2	1	1	3	1	1
	PART	3	1	1	2	3	3	3	3	1
	START	1	2	1	1	1	1	2	1	1
	SITUA	3	2	3	3	3	1	3	3	3
	SUST	3	1	2	3	2	3	3	3	2
	OUTC	2	2	1	2	2	2	2	2	2
	LENGTH	2	1	2	2	2	2	1	2	2
	TYPE	3	1	2	3	1	2	2	1	3
	USE	1	2	2	1	2	2	2	2	2
	REPORT	2	3	3	3	1	2	2	3	1
	INVOLV	1	1	2	3	1	1	3	1	1
	ACTOR	1	1	2	2	3	1	3	3	3
	PARTIC	1	2	3	1	1	2	3	1	2
	UNI	2	1	2	3	2	2	2	3	2
	BI	3	2	3	3	2	2	1	2	3
	MULTI	2	2	3	2	3	2	2	3	3
	THINK	2	2	1	2	1	2	1	1	2
	ORGA	2	1	3	3	3	2	2	1	3
SRC	**SRC 1 “Built environment“**	2	2	3	3	3	2	1	3	3
	SRC 2 “Ecosystem Services”	2	1	2	2	1	2	1	3	1
	SRC 3 “Consumption, Production, Economy“	2	1	1	3	2	1	1	2	2
	SRC 4 “Social and cultural processes“	1	2	2	3	3	2	2	2	2
	SRC 5 ”Governance“	1	1	1	2	3	2	2	3	3
	SRC 6 “System of City”	3	1	1	2	1	1	1	1	1
	SRC 7 “Spatial networks hinterland”	3	1	1	2	1	1	2	3	1

Datamining with Rough Set Analysis

Following Nijkamp, Van Der Burch, and Vindigni (2002), Walter and Scholz (2006) and Blumer, Stauffacher, Lang, Hayashi, and Uchida (2013), rough set analysis, a multivariate classification method, was used to analyze the collected data. The method allows to process highly categorized qualitative data, i.e. the vision documents, with a low number of cases (Düntsch & Gediga, 2000) by organizing attributes of the analytical-evaluative framework into deterministic rules (Pawlak, 1997). New assumptions were derived elucidating causal relationships between case conditions that determine the visioning approaches and the generated outcomes (Blumer et al., 2013; Düntsch & Gediga, 2000).

The data was mined using ROSE2 version 2.2 (Laboratory of Intelligent Decision Support Systems of the Institute of Computing Science, Poznan), following Pawlak and Slowinski (1994). The assessment of approximations distinguished all clearly defined attribute–value pairs in CCC and SRC from all vague pairs. It also measured the reliability of the case description by means of those CCC and SRC. Then, the rule induction generated rules that appear as 'IF [...] THEN [...]'-statements, describing co-occurrences between one or several sequential CCC specifying certain SRC (ex: If ”Actor Diversity = 3 and Unilateral Methods = 2 then SRC 2 ”Ecosystem Services“ = 1). We set the minimal number of cases covered by the rule, i.e. the minimum relative strength, to 70 percent. Specifically for this study, the rule description process provided information on the conditions in visioning methods that lead to the inclusion of certain sustainability and resilience criteria in the developed visions.

Results

The results section subdivides into (i) an overview of the technical results from datamining (Fig. 1), and then results are grouped according to the research questions into (ii) insights on the comprehensiveness of sustainability represented in the cases, and (iii) predominant rules and patterns among SRC.

The rough set analysis generated coherent results; the data mining showed 100 percent in accuracy and quality of classification, hence no combination of conditions delivered contradicting rules and the framework proved consistent. The rule induction produced rules with a minimum relative strength of 75 percent and a length of maximum seven conditional attributes. By excluding rules that only applied to one case and linking rules with logical operators ”AND“ and ”OR“, 27 emerged as part of the final set for interpretation (see Fig. 1).

Comprehensiveness of Sustainability in Urban Visions

This section summarizes the results that give insight on how much sustainability substance is to be found in the nine urban visions. First, we looked in the cases including the most and least number of SRC, and second, we looked into the composition of the most prominent SRC and related sub-criteria.

Overall, the results showed that no city fully integrated all sustainability principles in their vision, as no case received a continuous coding of ”important“ for all SRC (Table 3). Portland, York, Dublin and Sydney incorporated the most sustainability substance in their visions, with the most SRC coded as ”important“ or “marginal“. York was the most complete, with four SRC coded as “important“. In contrast, in the Ahrensburg case five out of seven SRC were coded as “not an issue“, indicating that the vision lacks sustainability substance. The actual presence of sustainability sub- stance in existing urban visions can vary greatly between cases.

A closer look into the SRC revealed that the underlying sub-criteria and keywords also lack a balanced distribution. For clarity, sub-criteria appear in italics followed by their absolute contribution (x) to the possible points (n) achievable for the sub-criteria in brackets (e.g. density (x/n)). Higher scores indicate that more sub-criteria are addressed in this vision which leads eventually to a SRC coded as ”important“. Across the cases, the most abundant occurring SRC were: 1 ”built form processes“ and 4 “social and cultural processes“; the prominence of the built environment is ascribed to the prevalence of the sub-criteria density (38/54), land use (31/54), accessibility and transport infrastructure (63/90), and housing characteristics (52/72) in the visions. The energy (17/54) sub-criteria, however, were not prevalent and absent from cases of Ahrensburg, Canmore, and York.

In contrast, the visions did not incorporate SRC related to the broader regional context and resilience, in so lacking consideration of connections with the hinterland. So, SRC 6 “system of city“ was scarcely represented, only appearing in two of the cases, namely Gothenburg and Portland. Despite its general representation, the sub-criteria dynamic landscape (6/18) and climate change (6/18) had certain bearing in the visions, pointing to two viable sub-topics within “system of city“ that were addressed by cities, whereas material flows considered as urban metabolism was not prevalent (3/18). SRC 7 “networks across scales“, the second SRC addressing a more systemic view on the city, is represented within four cases coded as “marginal“ and “important“, namely Gothenburg, Portland, Canmore, and York. While cultural networks (0/18) did not play any role among the sub-criteria, social networks (8/18), technical networks (10/18), and ecological networks (10/18), however, were moderately represented also indicating the viability of these topics to be included in the cities’ visions.

Fig. 1. Overview technical results: approximations and sequential steps of Rule Reduction down to the 27 rules used for interpretation

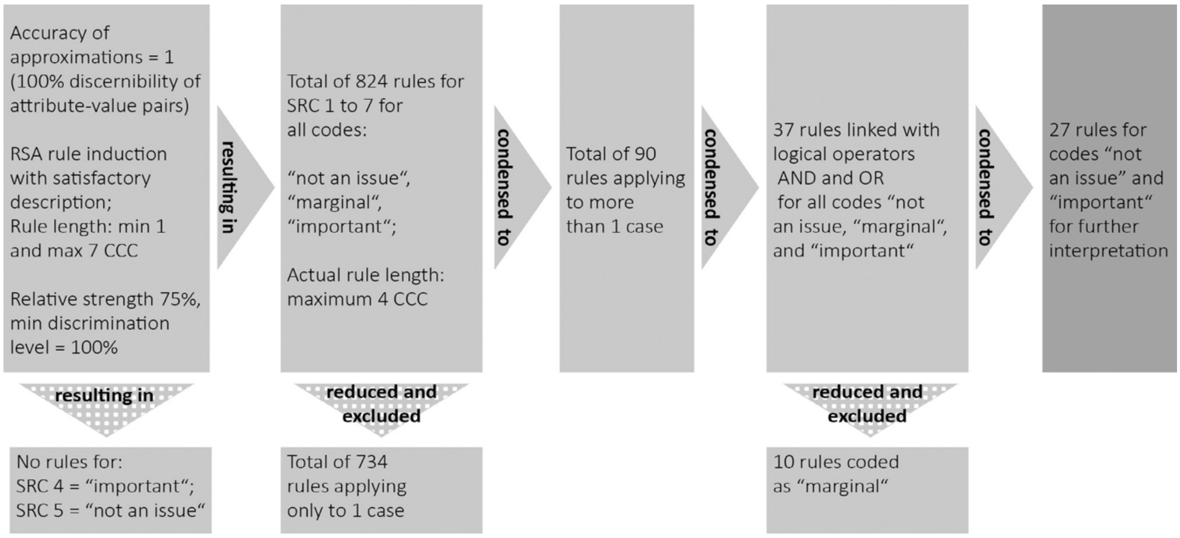


Table 4 Reduced rules sorted by codes "important" and "not an issue"; where applicable, rules have been merged with logical operators "AND" and "OR" (CCC codes in the same row are connected with AND, in the row below with OR, e.g. rule 6: if (MULTI = 3) and [(ACTOR = 3) or (INVOLV = 1)] then (SRC7 = IMPORTANT))

	Rule No	IF CCC is...	THEN the following Sustainability and Resilience Criteria are included as…	Applicable Cases
SRC with CODE "important"	1	Timeframe=2 AND (Type of vision=3 OR Costs=3 OR Method organizaion=3 OR Bilateral Methods =3)	SRC 3 Consumption, Production, Economy=3	PDX, SYD
	2	Timeframe=3 AND (Project partners=3 OR Involvement=1 OR Participation=1 OR Outcome objectives=2)	SRC 7 Spatial Networks hinterland=3	GOT, YK
	3	Explicit sustainability=3 AND (Participation=1 OR Project partners=3) (City Size=3 OR involvement=1)	SRC 7 Spatial Networks hinterland=3	GOT, YK
	4	Actor diversity=3 AND (Duration=2 OR Project Team=1 OR Involvement=1 OR Starting theme=1 OR Length of vision=2)	SRC 5 Governance=3	DUB, YK, SYD
	5	Bilateral methods=3 AND Method organization=3 AND Outcome Objectives=2	SRC 3 Consumption, Production, Economy=3	PDX, SYD
	6	Multilateral methods=3 AND (Actor diversity=3 OR Involvement=1)	SRC 5 Governance=3	DUB, YK, SYD
	7	Situation analysis=3 AND Involvement=1 AND Explicit sustainability=3	SRC 7 Spatial Networks hinterland=3	GOT, YK
	8	Situation analysis=3 AND Explicit sustainability=3 AND Project Partners=3 AND (Length of vision=2 OR Starting Themes=1)	SRC 7 Spatial Networks hinterland=3	GOT, YK
	9	Situation analysis=3 AND Timeframe=2 AND Types of thinking=2	SRC 3 Consumption, Production, Economy=3	PDX, SYD
	10	Situation analysis=3 AND Project team=1 AND (Outcome objectives=2 OR Involvement=1)	SRC 5 Governance=3	DUB, YK, SYD
	11	Situation analysis=3 AND Duration=2 AND (Outcome objectives=2 OR Involvement=1)	SRC 5 Governance=3	DUB, YK, SYD
	12	Situation analysis=3 AND Use=2 AND Length of vision=2	SRC 5 Governance=3	DUB, YK, SYD
	13	Situation analysis=3 AND Starting themes=1 AND Use=2 AND Outcome objectives=2	SRC 5 Governance=3	DUB, YK, SYD
	14	Situation analysis=3 AND Outcome objevtives=2 and Use=2	SRC 5 Governance=3	DUB, YK, SYD
	15	Situation analysis=3 AND Starting themes=1 AND Timeframe=2 and Length of vision=2	SRC 3 Consumption, Production, Economy=3	PDX, SYD
	16	Situation analysis=3 AND Involvement=1 AND Use=2	SRC 5 Governance=3	DUB, YK, SYD
	17	Multilateral methods=3 AND Outcome objectives=2	SRC 5 Governance=3	DUB, YK, SYD
	18	Costs=3 AND Method Organization=3 AND Outcome obectives=2	SRC 3 Consumption, Production, Economy=3	PDX, SYD
SRC with CODE "not an issue"	19	Type of vision=2	SRC 3 Consumption, Production, Economy=1	SKN, IGS, CMO
	20	Project team=1	SRC 6 System of City=1	ABG, SKN, DUB, IGS, CMO, YK, SYD
	21	Unilateral methods=2 AND Use=2 AND Starting themes=1	SRC 7 Spatial Networks hinterland=1	SKN, DUB, IGS, SYD
	22	Unilateral methods=2 AND Actor diversity=3	SRC 2 Ecosystem Services=1	DUB, CMO, SYD
	23	Unilateral methods=2 AND (Duration=2 OR Project team=1)	SRC 7 Spatial Networks hinterland=1	SKN, DUB, IGS, SYD
	24	Unilateral methods=2 AND Use=2 AND Situation analysis=3 AND Outcome objectives=2	SRC 2 Ecosystem Services=1	DUB, CMO, SYD
	25	Unilateral Methods=2 AND Use=2 AND Length of vision=2	SRC 7 Spatial Networks hinterland=1	SKN, DUB, IGS, SYD
	26	Use=2	SRC 6 System of City=1	ABG, SKN, DUB, IGS, CMO, YK, SYD
	27	Duration=2	SRC 6 System of City=1	ABG, SKN, DUB, IGS, YK, SYD

Finally, SRC 3 on sustainable consumption and business practices was most often incorporated into visions through the waste management (14/18), high social performance (12/18) and community self-reliance (11/18) sub-criteria, with behavioral changes (0/18) being the least coded sub-criterion. A very high scoring in sub-criteria was also found in SRC 5 "governance", in which a few cases achieved in the sub-criterion governance (64/108) nearly full points, such as Dublin, York and Sydney. Provision and distribution of public services, safety, good governance, community participation, and inclusion are here the widespread topics.

Generally, the results show sustainability substance in visions with strong emphasis on the built environment and weaknesses in considering impacts of the cities on their hinterlands. However, all SRC were addressed in some capacity, confirming their relevance for urban visioning.

Conditional Attributes, Rules, and Patterns

In this section the results focus on what conditions of visioning processes contribute to or impede generating substantive sustain- ability visions. First, we look in the SRC that appear in rules coded as "important" and "not an issue", and second we examine the combinations of contributing and obstructing conditions.

Overall, the results show that not all conditional attributes are critical for the sustainable substance in visions. 40 percent of all CCC codes appeared in the rules with the exception of demo- graphic development, migration background and transparent reporting. Of the set of reduced rules (Table 4), 18 identified insights into contributing factors (coded as "important") and 9 into obstructing factors (coded as "not an issue"). Although SRC 1 "built environment" or SRC 4 "social and cultural processes" appeared prevalently, there were no specific co-occurrences of CCC that either hindered or supported explicitly the inclusion of these sustainability principles. Co-occurrences of CCC that lead to SRC 2 "ecosystem services" and SRC 6 "system of city" were only coded as "not an issue" and so revealed only obstructing conditions. In contrast, SRC 5 "governance" was only coded as "important", reflecting general awareness of this principle among those who initiate and participate in visioning. Together, these findings indicate that sustainability substance is not entirely subject to the visioning process. However, principles dealing with urban governance, regional connectivity and consumption are present under certain methodical conditions and not others, providing transferable insights for constructing visioning processes that generate visions with sustainability substance.

Visions that include sustainability governance (SRC 5) benefit from a visioning process with participation, situation analysis, and the use of multilateral methods. For participation, this means a high diversity of individual actors, lower intensity of participatory involvement among the general public, a project team composed of city staff and/or medium duration process (rules 4 and 6 in Table 4). Extensive situation analysis will help generate visions including sustainability governance if they depart from pre-selected starting themes, set outcome objectives in the beginning, lower intensities of stakeholder involvement, and addressing sustainability explicitly in the visioning process (rules 10–14, 16, 17). For multilateral methods, outcome objectives that are set from the beginning also lead to a stronger inclusion of governance issues (rule 17). Therefore, when designing a visioning process to yield a vision that considers governance it is critical to carefully select the participating stakeholders and deliberately plan their involvement. The inclusion of regional connectivity (SRC 7 "spatial networks hinterland") is fostered by similar conditions to the aforementioned governance principle. An explicit module dealing with sustainability and the use of unilateral methods appeared to be most influential. When explicit sustainability was present in visioning processes, it also included extensive situation analysis, no higher level of involvement among stakeholders, a broader project team, and preselected starting themes (see rules 3, 7, 8). In contrast, the use of unilateral methods is the most frequent condition obstructing the inclusion of regional connectivity. However, the co-occurrence of unilateral methods with high actor diversity, extensive situation analysis, starting themes, or outcome objectives, remains ineffective for the inclusion of regional connectivity (as well as for SRC 2 "ecosystem services"). These rules emphasize how important knowledge input, techniques of knowledge management, and the expertise of project team members are for visions to include regional connectivity and ecosystem services. Despite the support of co-occurring conditions, such as the positive related ones set-outcome-objectives or extensive situation analysis, unilateral methods still seem to be an obstructing and an ineffective factor during visioning processes.

Economic activities (SRC 3, "production consumption economy") is an important principle in visions when bilateral methods are conducted (rules 1, 5); Economic activities are particularly included in visions which result from processes that (i) envision a medium-term future and use extensive situation analysis; (ii) set clear goals and use a continuous method organization; (iii) have high costs (rules 9, 15, 18). This SRC emphasizes the importance to consider project management conditions as they have important implications for the content of the visions that are generated.

The analysis provided limited insights as to visioning process conditions that lead to the inclusion of system of the city (SRC 6). The low number of rules only indicates clearly that a narrowly comprised project team is an obstructing factor (20), whereas both remaining rules with single conditions are without context and unsubstantial (26, 27). This insight concurs with the previous findings, showing the importance and success when intensive expertise and knowledge input is inserted into the visioning process.

Overall, six major groupings of conditions emerged which majorly explain the presence (or not) of sustainability and resilience criteria in the resulting visions, namely: (i) high actor diversity and low participatory involvement; (ii) different project team compositions and additional external partners; (iii) explicit use of a preparatory sustainability module; (iv) an extensive situation analysis; (v) different methods for communication; and (vi) final outcome with length and type of vision. These groupings highlight where emphasis needs to be placed when designing and implementing visioning processes. That recurring conditions in similar combinations, such as situation analysis and high actor diversity, lead to the successful integration of sustainability principles further underscores the importance of interconnected visioning conditions.

Discussion

The purpose of this study was to determine how much sustainability substance is in urban visions and what features of the visioning process and other conditional factors foster the inclusion of this substance. Among the cases, there are many good examples of visioning exercises that aim to include sustainability substance. These cases focus intensely on one or more sustainability principles while lacking a comprehensive and balanced approach to all of them. In that way, they can serve as best practices, but only to a limited extent. These insights are congruent with observations made by Newman and Jennings (2008) and Berke and Conroy (2000).

Three major findings emerge from the analysis, which have implications for sustainability visioning in cities. First, visions do not adequately consider the city as embedded within and connected to other regions (e.g., hinterland) and cities. As a result, cities miss out on opportunities to design collaborative, synergetic solutions (e.g. for renewable energy production or climate change adaptation) that would be informed by innovative technical or social networks with other cities. The latter impacts the array of solutions and strategies potentially derived from visions. Second, visions focus on narrow aspects of the urban built environment and physical programming (e.g. through transportation, housing characteristics, or density) and undervalue others. To counter this tendency, there are a series of common methodical conditions, such as different project team compositions and additional external partners or extensive situation analysis, that are successful at capturing sustainability more broadly. Third, participation of the public, inclusion of diverse actors, and varying types of project teams all aligned to contribute to a shared and tangible outcome. Yet, visions take a mostly institutional and administrational perspective on the public and do not often directly engage in detail with citizens' values and behavior (sustainability related or other- wise). This study would be well complemented by an analysis of the contribution of visions to actual processes of transformation in cities.

Some of these insights were difficult to tease out because of the interconnectedness among the conditions and across the cases. At the same time, all three major findings clearly show that this inter- connectedness of conditions is important for the effectiveness of the visioning process. The influential methodical conditions can help designing visioning processes yielding better sustainability substance.

Urban Visions with Greater Systemic and Resilience Perspectives

Visions address prominently the future of inner city systems, staying within the perspective of administrational borders. The initiating departments of city administrations, mandated to prioritize developments within their administrative boundaries, could be seen here as crucial gatekeepers. Yet, isolating long-term urban visions from the hinterlands on which they depend, among other regional and global interdependencies, reduces resilience considerations in the visions and limits the capacity of subsequent strategies to contribute to a city's resilience. Increasing urban resilience might require a portfolio of response mechanisms that depend on networks of cities to manage possible vulnerability to outside shocks and stressors, for example those related to climate change and extreme weather events (Leichenko, 2011). To comprehensively incorporate sustainability, urban visioning processes need to extend beyond administrative boundaries and even con- sider their impact on other regions or the hinterland, e.g. by embracing the concept of a cyclical and regenerative city (Girardet, 2014).

The visioning processes that (i) carefully considered how knowledge and expertise were integrated into their project teams and (ii) had dedicated space for sustainability principles were most successful at capturing regional connectivity and systemic aspects. Internally, most city departments try to incorporate the additional workload of a visioning process into their daily business. When steering committees and project teams are composed the aim should be to incorporate additional diverse expertise to the team, i.e. for organization and management for example via citizens, NGOs, community groups, or local businesses, as in the Portland case. To build procedural and sustainability expertise, teams are frequently complemented or consulted by professional process partners or researchers (Berke & Conroy, 2000; Iwaniec & Wiek, 2014; Shipley et al., 2004). This process may involve support concerning management or methodical skills that allow all parties involved to effectively deal with a broad variety of topics and perspectives, such as regional connectivity and resilience or systems thinking (Iwaniec, Childers, VanLehn, & Wiek, 2014).

Some have argued that having sustainability components is not especially effective in the process (Berke & Conroy, 2000), however, our findings indicate that these kinds of components, such as resilience, as an explicit part of the visioning process, as well as building a common understanding of sustainability, lead to more sustainability substance in the final visions. Yet, sustainability visions are more likely to consider also resilience if the visioning methods involve components that are informed by extensive local situation analysis, which sensitizes for case-specific historical con- texts as well as problems, trends, and challenges. Consequently, all parties involved get informed so compromises and trade-offs can be negotiated adequately (Moss & Grunkemeyer, 2010; Resilience Alliance, 2010). Overall, these results indicate that careful knowledge preparation on individual and group levels are important methodical components whose interactions need to be explored in greater detail and carefully crafted when aiming for more sustainability substance in visions.

Expanding on Sustainability Substance by Participation

Visions are not only limited by an unnecessary emphasis on city boundaries, but also by focusing on physical aspects of the city, for example layout and dwelling density, sustainable infrastructure, transportation systems, green building, and climate design. This perspective can have positive effects at city and neighborhood scales by, for example, reducing direct resource flows of fuels and electricity, improving material requirements, and reducing household consumption on goods and services (Weisz & Steinberger, 2010). This is often why urban development plans focus on layout, design, urban form, and patterns of growth within the city system (Berke & Conroy, 2000). For participants in visioning activities, physical aspects of the city lend themselves well to tangible visuals that can function as landmarks and reference points for urban identity and place making, and which citizens find particularly meaningful (Lynch, 1960; Stedman, 2003). Consequently, development plans that are based upon visions that emphasize the built environment and administrative roles and structures will lend themselves to strategies or comprehensive development plans that prioritize built environment issues and the administration's tasks. Addressing these strategies and comprehensive plans will come naturally to traditional city departments whose administrative duties cover these issues.

In practice, implementation strategies that were favored by administrations to realize visions such as LeCorbusier's Radiant City in Paris 1922 (Fishman, 1991) or the German town Anting in China by Albert Speer & Partner from 2000 to 2004 (Gutzmer, 2014) have the very adverse effects associated with top-down approaches of social advancement through design, principles of rational imposed order, or one-size-fits-all urban cultures. In contrast, urban planning can be augmented by bottom-up processes in which citizens are assigned a much more active role to ensure coverage of diverse needs and activities. More bottom-up approaches, which are genuinely interdisciplinary and participatory (Ling, Hanna, & Dale, 2009; McLain et al., 2013), have been applied successfully in other contexts, such as urban biodiversity and eco- logical planning. However, when it comes to visioning and the built environment, planning seems to fall back on the old paradigm.

In our cases, visioning processes that explored different participation processes successfully generated visions including tasks for the principle of sustainability governance and regional connectivity such as York, Dublin, and Sydney. In general, participation and diversity of actors are understood to create (i) a common ground, (ii) heterogeneity of inputs, and (iii) a better recognition of sustainability principles (Moss & Grunkemeyer, 2010; Shipley et al., 2004). Structurally, these processes do not necessarily bene- fit from a large number of participants, and downsizing neither prevents inclusiveness nor leads to an underrepresentation of topics (Mathie & Greene, 1997). This basic principle was confirmed by how actor diversity manifested throughout the principles in our case studies: Highly diversified teams supported by certain project partners and lower participation by citizens lead to better results in terms of good urban governance practices, planning, and assessment. Working with a small dedicated group of people during the entire process (e.g. the steering committee of Portland's VisionPDX working with a project team and community groups and businesses) over a longer period of time led to more sustainability governance in the visions and to more productive exchanges between all parties involved. Overall, our results suggest that some (more) complicated sustainability principles tend to become rich and detailed in the overall vision if they are not compromised from the very beginning and developed constructively and intensely over the course of time.

Distribution of Responsibilities and Contribution

The analysis of the visions also reveals structural weaknesses among the parties that construct them. To address sustainability principles and represent the needs of a heterogeneous public, urban sustainability visions should draft tangible and coherent desirable future target states for sustainable urban living which can guide implementation strategies (Wiek & Iwaniec, 2013). This requires diverse representation from citizen interests, but not necessarily distributing the responsibility for carrying out the vision among citizens. Despite broad participation in the processes, there is little accountability or assigning of tasks and duties for citizens with regard to changes in personal behavior toward sustain- ability or responsibilities within the community, and supporting structures are not defined to facilitate such a distribution of responsibilities. Citizens' perspectives need to be integrated into planning and decision making (Jacobs, 1961), but citizens themselves need to be seen as active, individual forces with capacities of self-organization outside the public programs administered by cities (Smith, Fressoli, & Thomas, 2014).

Re-distributing responsibilities and contributions to more participating parties and, in this way, expanding the term "diversity" to include a structural component can have several positive effects on implementation strategies. First, empowering citizens and reducing institutional dependencies adds to the portfolio of responses a city can rely on in times of crisis (e.g. when facing cli- mate change related extreme weather events (Folke, 2010)).

This enhances the overall resilience of urban areas and fosters concepts of open citizenship (John & Kagan, 2014). Second, in areas characterized by more sustainability features (e.g. areas of urban biodiversity), identity, community involvement and commitment get increasingly important, due to the meaning residents ascribe to them. This phenomenon of evolving ownership and identity cause changes in social interaction. It exists in certain areas and is promoted by measurements from urban planning approaches (McCunn & Gifford, 2014). Maintaining this phenomenon means drawing on the resources of individuals engaged. Third, the management and implementation of visions require innovation and initiatives for which partnerships can provide new roles and arrangements which combine different actors and stakeholder (groups) (Frantzeskaki, Wittmayer, & Loorbach, 2014). In our cases, preparative situation analyses, in particular, were an important method component and reoccurring pattern throughout the sustainability principles. Situation analyses can be used to collect background information such as how community groups engage in sectorial niches and how their practices are mainstreamed. This type of engagement can become apparent in an array of different community partnerships including public–private partnership settings for socio-technical innovations, local business associations (e.g. Business Alliance for Local Living Economies (BALLE, 2012)), and knowledge partnerships with local universities and research institutes (Lang & Wiek, 2013). While partnerships and community groups are greatly highlighted in sustainability visions, these visions insufficiently picture options for changes by non-institutionalized, voluntary, individual participation and contribution of citizens. Changes of values, behavior patterns and active bottom-up involvement from individuals form a significant portion of this 'non-institutionalizable' change, in particular because visions are supposed to be a common and shared future that people own, strive toward, and from which strategies are built.

Overall, at its core the analysis highlighted the complexity of visioning exercises throughout each of the subsequent methodological steps, underlying the overall validity of our explorative approach. Certain limitations in our study can be linked to these points: First, the analysis emphasizes North-American and European cases caused mainly by the sampling criterion of adequacy: Language barriers and problematic accessibility of the detailed documentation are the main reasons for developing countries and the Global South being underrepresented. This focus might potentially create a certain bias in the results; we therefore propose that a more diversified set of visioning processes in further research might generate additional insights. Second, the condition criteria of the analytical-evaluative framework focus solely on visioning procedural structures and resulting patterns disregard city specific features, i.e. size or density. A more in-depth study could expand on the city specific contexts e.g. local politics, municipal history, economic development, and national policies that alter process decision making. This would demand a wider range and number of studies, covering the city's development needs and accepted trade-offs and is outside of our scope and current approach which is limited to evaluate visions.

Conclusion

Cities need to actively steer urban development paths and use options that urbanization trends offer to find innovative solutions and embrace their role as forces for sustainability transformation. Decisions about a shared sustainability vision are vital for communities as they can pave the way for solutions and have practical implications for long-term planning.

The purpose of this analysis was to contribute to a better under- standing of visioning process conditions that lead to greater sustainability substance in urban visions. The results revealed several important insights for visioning processes, visions and tendencies for implementation strategies as they pertain to sustainability in cities:

- Approaches to include sustainability principles in urban visions are made from different angles. The missing comprehensiveness and emphasis on the built environment suggests a major difficulty to either translate or to contextualize urban sustainability principles in practice in a balanced and accurate way. Transdisciplinary settings are required in which experts, practitioners, and researcher together facilitate a common understanding of sustainability and the application of sustainability design principles to the specific urban environment.
- Context matters! Visioning processes are not only to be selected and adapted to the communities' prerequisites and needs, but also the different design options for participation, project team compositions and pre-procedural research can impede or facilitate the inclusion of especially resilience related principles in the final vision. For practitioners, it is important to consider that these design options appear as separate features, but function also as surrounding conditions that individually and in combination influence the sustainability substance of the visions. An integrated process design approach is needed in which the options for (i) high actor diversity and low participatory involvement, (ii) different project team compositions and additional external partners, (iii) explicit use of a preparatory sustainability module, (iv) extensive situation analyses, (v) different methods for communication, and (vi) final outcomes for the vision are evaluated and weighed against each others' influences considering the process goals.
- In order to use the full potential of sustainability visioning, initiators cannot see the process as an extended participatory urban planning process to further develop zoning practices and define development patterns. For practitioners it is crucial to aim for shared urban sustainability visions that comprehensively and evidence-based pictures future urban living, consisting of aspirations and contributions from both institutional and

administrational change as well as changes on a self-organized personal and individual level. This way comprehensive urban sustainability visions are borne and realized by all participants.

The explorative design of this analysis leaves several points open to further research. There is a need to develop a method module that facilitates a shared understanding of sustainability and resilience principles, builds a common ground and language, and fosters the systemic thinking of sustainability issues to inform sustainability visioning processes. Such a module would make sustainability explicit in the process and could be used as leverage in existing visions. Finally, there is a need to further bridge the science-society gap, particularly related to knowledge about sustainability issues and evidence-based solutions, to contextualize and design applicable tangible methods for practitioners

Mobilizing and Advancing Decision–Visualization Environments – Design Recommendations

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Abstract

Semi-immersive visualization facilities support research, planning, and decision-making at the science-society-policy interface. Decision theaters, visualization studios, and similar installations – here referred to as Decision-Visualization Environments (DVEs) – facilitate human-computer-content interactions to explore climate change impacts, resource management practices, and urban design solutions. This comparative study analyzes the current practices of seven DVE facilities from around the world based on expert interviews, site visits, and document review. We found common practices across 53 attributes concerning the planning, stakeholder involvement, and realization of DVE activities. DVEs need good facilitation and purposeful combination to unlock their full potential. An active network of DVEs could constitute a productive learning community to pool or coordinate activities and share insights. Based on our findings, we deduce recommendations on how to improve the design of existing DVEs, to create new DVEs, as well as to plan DVE projects or events.

Introduction

Digital tools and semi-virtual visualizations dramatically drive, challenge, and alter processes in planning, research, development, dissemination, and deployment of ideas and changes in all areas in society and affect people exposed and engaged in them. These technological innovations also facilitate transformative, open, and autonomous knowledge production processes (Barth & Burandt, 2013; John, Caniglia, Bellina, Lang, & Laubichler, 2017; Roussos et al., 1999; Trapp, 2006). They create new ways to explore and simulate complex problem, scenario, and solution analysis, and allow for decision-making based on enhanced participatory methods (Maffei, Masullo, Pascale, Ruggiero, & Romero, 2016; Roupé, 2013).

The term Decision-Visualization Environments (DVEs) covers a variety of types of approaches around the world that offer a digitally supported, semi-immersive, visual environment for research, planning, and decision-making processes. Such environments are labeled under terms such as “theater”, “laboratory”, “studio”, “center”, “institute”, “environment”, yet “decision theater”, “visualization studio”, and “command/operation center” are most prevalent. What unites these facilities is a strong visualization component, building on often novel emerging software and hardware settings, allowing for a visually supported design of human-computer-content interaction in order to facilitate participatory, design, planning, experimentation and decision-making processes.

DVEs aim to create solutions for complex problems by integrating the public and decision makers building on large data visualization of system structures and dynamics, their alternatives and solutions. This is gaining in relevance in topics such as groundwater management, community planning, resilience planning, climate change research, water security (c.f. J. D. Salter, Campbell, Journeay, & Sheppard, 2009; Sampson, Quay, & White, 2016). Prominent institutions hosting such facilities are located at Arizona State University (DTN) and the Universidad Nacional Autónoma de México (AD-LANCIS). DVEs emphasize their facility as means and research tool. Cases revolve around topics of data science and data visualizations, scientific and engineering discoveries, advancing networking infrastructure, architectural and urban planning, 3D visualization, geoscience visualization and virtual reality (c.f. Kawano et al., 2017; Park, Renambot, Leigh, & Johnson, 2003). Prominent institutions are the Electronic Visualization Laboratory at University of Illinois Chicago, the Laboratory for Advanced Visualization and Application (CyberCanoe) at University of Hawaii, or the Visualization Center C at Linköping University Campus (LAVAWP, 2018; Visualiseringscenter C, 2018). Finally, command and operation centers, also called war rooms, focus on supervision, control, and advise e.g., to increase productivity or monitor emergencies. They rely on advanced methodologies for immediate decisions supported by large real-time data analysis, e.g., for military purposes. Exemplary facilities are at Swedish National Defence College (B. Brehmer, 2007) or at Australia"s Defence Science and Technology Organization (FOCAL) (Wark et al., 2005). Most DVEs are currently located in North-American. However, facilities such as at DTN, AD-LANCIs or CyberCANOE also invest to disseminate their work into larger networks.

Boukherroub et al (2018) trace their origins back into the 1970s and 80s to a facility at Our Lady of the Lake University of San Antonio. However, war room configurations date back to 1905 (Lambert, 2005) and since then, paper, pinboards, and whiteboards have given way to computer-based data analysis. The technology setup of DVEs requires a large initial investment and comes with high cost of maintenance, while facing fast technology innovation cycles. Available financial resources and purposes of usage influence the equipment such as number and size of screens, computational power, furniture, recording equipment, and mobile equipment (e.g., VR/AR, touchtables).

The human-computer-content interaction is the core element that elicits new knowledge production and active use of knowledge in this semi-immersive environment. Highly interrelated are the role and effect of visualizations or virtual reality for improving system understanding and building planning capacities (Larson & Edsall, 2010; J. D. Salter et al., 2009). Related studies detail important elements of more comprehensive methodologies in order to provide a transformative scenario of knowledge production processes (Bonk & Graham, 2006). This capitalizes on transformative learning and König (2015, p. 107) describes it as "sensitive to 'positionality'" with a collective and action-oriented developing process, facilitates the engagement with complex real-world problems.

We realize that there is a growing demand to experiment with ways how interaction is facilitated by technology (Bonk & Graham, 2006; Schroth, Angel, Sheppard, & Dulic, 2014; Schulmeister, 2002). However, the dispersed and interdisciplinary field is challenged to integrate both the insights on individual elements, e.g., visuals, VR, 3D, about successful and social interaction mediated through technology and the insights from comprehensive settings of such environments. In addition, more knowledge about the strategic placement of the facilities and a coordinated overview of transferable products is needed.

Comparative research on DVEs aiming for such comprehensive understanding of transferable design principles is currently at its infancy. Transferrable design principles should also help to create DVEs in diverse places, facilitate mobile experimenting on solutions to complex problems and advance research at the science-society-policy interface (Wiek & Forrest, 2018; Wiek & Lang, 2016). In response, this study addresses the question: How are DVEs structurally set up, and what are the current practices in the context of their institutional settings and applied cases? We investigate this question by developing a functional framework of DVEs and empirically informed design guidelines using insights from reviewing available publications, expert interviews and on-site visits.

Research Design and Functional Framework

We used a three-step approach for data collection and derived from relevant literature a conceptual framework for data analysis. We first outlined the three steps and then present the analytical framework.

First, using google, we identified websites of existing DVE facilities and grey literature (e.g. reports, manuals) about them. Through Google Scholar, Science Direct, and Scopus, we also identified peer-reviewed publications from existing DVE facilities. The search yielded a pool of 34 DVEs with basic information on location, institutional organization, and signature projects (see Supplementary Material). From this pool, we selected 7 DVEs for our detailed study using the following criteria to enable reasonable comparison and robust generalization: located in the USA/Central America, capable of high-performance computation, in operation for more than 10 years, with signature projects on sustainability issues and with diverse stakeholder involvement beyond academia.

Second, from the identified sources and a survey, we extracted data on current practices and settings for all 7 DVEs. This included information about the institution (e.g., location, organization, founding date, budget, number of events), the signature projects (e.g., topics, sustainability topics, purpose, outputs), the infrastructure (e.g., technical equipment), and the main users/participants (e.g., businesses, governmental agencies).

Third, we collected additional data by using qualitative semi-structured interviews with representatives from all 7 DVEs (e.g., principal investigators, staff members, directors) as well as visits of 2 DVEs. The interviews focused on detailed information about processes (interaction, facilitation, and visualization) as well as evaluation of current practices and future developments (obstacles, advantages, challenges). The three-step approach of data collection created a robust data set for 7 well-established DVEs that allows careful generalizations relevant for similar DVEs around the world.

For data analysis, we created an analytical framework based on pertinent literature (Fig. 1). Building upon Sampson et al. (2016), the framework includes nine modules for human-computer-content interaction, depicting the functional interplay between data and technologies, interactions and actors, and overall purposes and outputs.

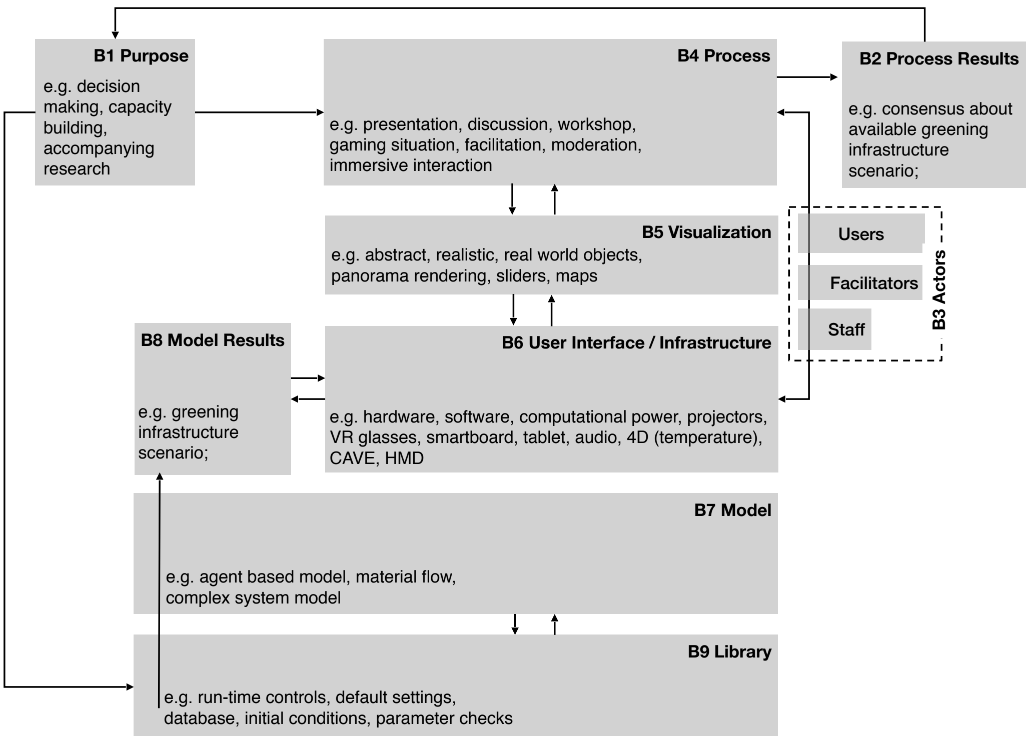

Figure 1 Framework for functional design of DVEs with nine modules.

B1 Purpose describes the objectives of the facility and respective events or cases taking place in it. It includes but is not limited to information provisioning, capacity building, and science-policy decision making (Dentoni & Bitzer, 2015; Sarewitz & Pielke, 2007; Withycombe Keeler et al., 2018). This module is the starting point and drives the entire set-up, influences the selection of the computational model, and the process.

B2 Process results refer to both the practical and scientific results that immediately follow from the process, and to larger outcomes to which the DVE case contributes (Dentoni & Bitzer, 2015; Lang et al., 2012; Rowe & Frewer, 2004). Process results are logically linked to the purpose as well as to the selected process.

B3 Users, facilitators, and staff are groups of actors involved in different functions in a case or event in the DVE. Users are characterized by professional background, gender, race, competencies, capacities, agendas, power, etc. that all influence the process, efficiency of visualization, the type of user interface and quality of results (Cai, Fan, & Du, 2017; Prell, Reed, Racin, & Hubacek, 2010). These characteristics are specific to cases and purposes and can be captured through actor analysis (Reed et al., 2009). Facilitator mediate structured or unstructured information elicitation, individual and collective learning, through a computer-supported environment (Clawson, Bostrom, & Anson, 1993; Harvey et al., 2002). There are more informal roles, e.g., networker, honest broker, change agent, or epistemediator, who can serve as important procedural lever (Brundiers, Wiek, & Kay, 2013).

B4 Process refers to the design or method of engagement during a case or event taking place in the DVE. First, engagement is characterized by the degree of interaction with users, e.g., *consultation* ascribes participants expertise that they can share vs. *citizen control* hands over decision making power to the participants (Arnstein, 1969; Stauffacher, et al., 2008). Second, participatory methods use unilateral, bilateral, and multilateral mechanisms, e.g., surveys, exhibition, round table discussions (Bill & Scholz, 2001; Rowe, 2005; Salter et al., 2010). They help to structure, plan, or experiment, e.g., whole system design or scenario planning (Holman & Devane, 2007; Withycombe et al., 2017). Third, these methods either come with a structured or unstructured facilitation to evoke information or to aggregate, integrate and summarize information (Rowe, 2005). The process connects and integrates all relevant elements of a DVE from a content or data perspective with the actors. It serves as the direct junction to the process results.

B5 Visualization is the module integrated between user interface, as the provisioning element, and the process, as the procedural element. Visualization is the targeted, meaningful translation of contents (model, results, and input) and the central element and communication tool of a DVE. Visualization includes: the effective type of data translation, different functions visualization can fulfill, and the consistent combination of several individual representations (Sheppard, 2012; Tufte, 1990). Possible visualization tools, e.g., sketching boards, are supportive methods and link to the process (Al-Kodmany, 2002; Holman & Devane, 2007). Appropriateness and effectiveness of visualizations, especially when targeting transformative experiences, also include ethical concerns (Sheppard, 2005).

B6 User interface is the platform that brings the model results from behind the scenes in an accessible and representable format for actors. It is an important element in the human-computer-content interaction and carefully includes appropriate hardware and software solutions to show, explain and allow exploration of contents, e.g., dashboard, widgets, touch tables, screen, etc. It is characterized by balanced multimodal input and output, consistency of features, terminology, and interactions, adaptability to users' preferences, and minimized user error (Reeves et al., 2004). The user interface is steered by requirements of the library and the model and tailored to the needs of actors.

B7 Model refers to a computational model with the capability to rapidly process (large) datasets. It is linked to DVE's computing power, e.g., based on complex system models, agent-based models, etc. The model is tightly connected with the library that stores input data, i.e., for large data analysis. The purpose determines whether a model is required and the functionality of the model (Sampson et al., 2016).

B8 Model results are static or dynamic results from underlying data analysis. Complex models require fast computation and step-by-step differentiation and integration of the underlying modules. If data input are pre-set conditions with optional static changes, library and model can be neglected or subsumed under model results. In both cases, the model results serve as input for the user interface (White et al., 2010).

B9 Library is the database that stores the necessary data, run-time controls, and parameters for the case and event to execute a model and visualize the results. This function makes it the link between the underlying model, consequently the model results, but also the user interface. All of these modules draw from a constant and dynamic exchange between each other (Sampson et al., 2016).

Results

In the first section, we present the results based on the modules of the framework with its strongest attributes. In the second section, we go into detail about advantages, challenges, future development, and success factors of the DVEs. The modules of the framework define the main criteria. We coded data inductively to maintain the interdisciplinary wording and aligned them with the modules.

Profiles of Different Dves

From the data analysis, we identified 53 attributes for 15 different criteria that characterized five of the nine framework modules, namely *visualization, process, purposes, participants*, and *user interface*. The modules *library*, *model*, and *model results* were not explicitly mentioned. The module *process results* was treated on a general level, so we included it in section 3.2. The DVE profiles are described on an ordinal scale of 1 (= mentioned) or 0 (= not mentioned) and presented in table 1.

Purpose

The DVEs' cases were described by two types of purposes: (i) catering to societal outcomes and (ii) involving accompanying purposes with a purely scientific focus.

Business consultation was covered under the *first type of purpose*. It was characterized by a quick turn-around time of events and focused on operational or production problems, as well to solving these by using the DVE environment. However, only #U4 and #L7 engaged in this activity. Capacity building was the largest group of that type. Capacity building described activities revolving around informing and triggering conversations to enhance understanding. Beyond this "explaining" approach, capacity building in form of converting opinions, or negotiation of issues, was only conducted by #U7. In the foreground were capacity building cases with "exploration and experimentation" leading to decisions. However, in fact, there was no DVE that engaged in decision making, only in creating an informational situation that could enable a decision at a later stage.

Accompanying purposes address different kinds of technology (hardware/software) development as well as accompanying research about human-computer interaction and dynamics e.g., from cognitive science, psychology. Only #U7 and #P1 did not engage in this type. Basic research was one major pillar of DVEs and used e.g., to generalize and analyze information of environmental, climate, or other types of data in order to identify problems, and to build interdisciplinary research question and hypotheses.

Table 1 Profiles of DVEs for all 15 criteria, green = 1 (mentioned), grey = 0 (not mentioned).

Group	#	Criteria	Attribute/Subattributes	#A2	#B5	#P1	#E6	#A3	#U4	#L7
Visualization	1	Function	summary graphs	0	1	1	0	1	0	1
			experiential visuals	1	1	1	1	1	0	1
			focus visuals	0	1	1	1	1	1	1
	2	Characteristics	simple	1	0	0	1	0	0	1
			impactful / triggering immediate response / relatable	1	1	1	1	0	1	1
			giving holistic sense	0	0	0	0	0	0	1
			attractive	0	0	0	0	0	1	0
			not misleading or distorting data	0	0	0	0	0	0	1
			explicate mental models	0	0	0	1	0	1	0
	3	Series	channel combination (audio, verbal, textual)	0	1	0	1	0	1	1
			timing	1	0	0	0	0	1	0
			problem-question oriented	1	0	0	1	1	0	1
	4	Integration	immediate interaction /manipulation/distraction	0	1	1	1	1	1	1
			physically walkable	0	1	0	1	0	0	1
			pre-set conditions / static	1	1	1	1	1	1	1
			dynamic/live /bottom up	1	1	0	1	1	0	1
Facilitation	5	Types of facilitation	time keeping	0	1	1	1	1	0	0
			guiding discussions	1	1	1	1	0	0	1
			provide information/presenting	0	1	1	0	1	0	0
			facilitate negotations	0	0	0	0	0	1	0
	6	Multilateral formats	break out groups	0	1	1	1	0	0	1
			fast forward session	0	0	0	1	0	0	1
	7	Roles & responsibility	tech intro for emppowerment	1	1	0	0	1	0	1
			champions across actor groups	1	0	1	1	0	1	0
			trust across disciplines and staff	0	0	1	1	0	1	1
Purpose	8	Secondary Purpose	accompanying research	0	1	0	1	0	0	1
			technology development	0	1	0	1	1	0	1
	9	Primary Purposes	basic research	1	1	1	1	1	0	1
			business consultation/services	0	0	0	0	0	1	1
	10	Capacity buliding	decision making	0	0	0	0	0	0	0
			negotiation	0	0	0	0	0	1	0
			experimentation/exploration	1	1	1	0	1	0	1
			information/ conversation	1	1	0	0	1	1	1
Actors	11	Staff	technical staff	1	1	1	1	1	1	1
			research assistants	0	1	0	0	0	0	0
			graduate students	1	1	0	1	1	0	1
	12	Research Team	Natural Science	1	0	1	1	1	1	1
			Social Science	0	0	1	1	1	1	1
			Formal Science	0	1	0	1	0	0	0
			applied science	0	1	0	1	1	0	0
	13	Participants	Private	0	0	0	1	0	1	1
			Municipal (Gov+Admin)	1	1	1	0	0	0	1
			Federal (Gov+Admin)	0	0	1	0	1	1	1
			Public + NGO	1	0	0	1	0	0	0
User Interface	14	Directing	extra room	0	0	0	0	1	1	0
			extra table	0	1	1	0	0	0	0
			integrated	1	0	0	1	1	1	1
	15	Room	Tiled (360 or large wall)	1	0	0	1	0	0	1
			Master (projector, screen)	0	1	1	0	0	0	0
			Half-round	1	1	0	0	1	1	1
			Table	0	1	0	0	0	0	0
			Handheld device (tablet, VR glasses)	1	1	0	1	0	0	1
			BYOD	0	0	0	1	0	0	1

Actors

Three different groups of people were typically involved in running a DVE: staff, research team, and participants. This differentiation was based on their professional function and educational background, and not regarding their capacities to work and act, or their role and responsibility during an event. Facilitators were not explicitly mentioned as a group, but rather seen as part of the process.

The *staff* had the role of preparing the event, data, visuals, the room, the equipment, etc. This group of people was represented by technicians, research assistants and graduate students. All DVEs worked with a technical staff, whereas research assistants were only part of the team in #B5.

The *research team* represented a diverse group of people with academic background approaching the DVE institution in order to design an event, while being involved as participants. The fields of research were divided into four subgroups: Overall, formal and applied science, i.e. computer science, graphic design, and urban design, were not as frequent as natural and social sciences (i.e. physics, earth science, geography, psychology, political science). *Participants* comprised practitioners from private sectors, municipal and federal governments and administrations, and the general public e.g., community groups and non-governmental organizations. Most frequent groups came from the private sector, government and administration. Only #A2 and #E6 also integrated the public or non-governmental organization.

Specific *roles and responsibilities* were needed to smoothly run a DVE event with multilateral engagement, however, these roles were not yet implemented consciously into the process. Among those was the "champion", similar to an honest broker or networker. This role and its task to mediate across different actor groups was considered important to steer the success of the case. During the preparation, the role supported an adapted process design to the respective mental models and languages. Another role was described as the interdisciplinary mediator, i.e., epistemediator, enabled to translate across sciences, and was trusted by all researchers.

Process

Processes were described in categories of mechanisms for engagement and types of facilitation, yet there were no comprehensive structured descriptions of methods.

Overall, DVEs were fairly homogeneous on *types of facilitation* such as basic timekeeping, presenting information or moderating discussions. Only the DVE #U4 clearly engaged in facilitating negotiations that require experiences in the respective field. A brief *introduction e*xplaining the user interface to participants to empower them to work autonomously was in place for #A2, #B5, #A3, and #B7. This introduction was considered relevant to break the barrier between participant and technology, and prepared the participants to shift their passive recipient attitude into a pro-active one. Overall, the facilitation of processes was relatively unstructured.

All *mechanisms* of processes were multilateral, i.e. back-and-forth interactions between content, researchers, and participants in which co-production of knowledge was facilitated. Although, intentions were not actively translated from the purpose into engagement methods, the group size was specified as (i) interaction that takes place in large groups, (ii) interaction that used smaller break out groups, and (iii) break out groups in fast forward sessions with repeatedly short meeting durations.

Visualization

Experts explained visualizations by functions, design principles, and order of visualizations. Overall the DVEs #B5, L6 and E7 share the most comprehensive view on all subcategories of visualization.

First, All DVEs had a similar understanding of which *functions of visualizations* should be integrated. They were grouped into three areas: (i) Summary graphs, usually pie charts or non-standard pictorial representations, showed overall performance or the overall process adaptive throughout an event. (ii) Experiential visuals allowed exploration of a certain issue and potential manipulations of the latter using maps, or 3D imagery. (iii) Focus visuals supported details, delivered additional background information, and were usually abstract graphs (line graphs, etc.) or photographs.

Second, characteristics of visualization focused on functional *design principles* which also competed with each other. Visualizations were supposed to be simple but impactful, attractive but not misleading, give a holistic sense, and explicate mental models of actors.

Third, narratives, *series* and *order of visualizations* were considered important to lead through comprehensive processes in the DVEs. Series were conceptualized as narratives and allowed an additional integration of multisensory data, e.g., audio, verbal and textual information, and specific timing of each visual. The close link to purpose and process was crucial for success. Integration also interlinked with the user interface. However, all DVEs except #A2 mentioned possibilities of immediate interaction and manipulation of the visuals. #B5, L6, E7 made explicit that their infrastructure included tangible and even physically walkable characteristics. Static visuals with pre-set conditions that were presented or explored was the standard usage in all DVEs. Dynamic datasets behind the visuals, that could be manipulated live, or even integrated through participants' devices during the meeting ad hoc is still impossible for #A2, P1, and U4.

User interface

The user interface was described by two aspects that focused on the larger setup instead of the software and design aspects for user interaction: The attribute of *directing* described the location where the instructions were translated for the computer which happened either in an extra directing room, at an additional table, or was integrated from anywhere within the DVE. The *room setup* was described as a spectrum spanning a relatively large sized room setup (e.g., tiled displays on 360 degree wall), to a tiled half round, to a division between master screen and individual screen, to touch tables, to handheld devices, and to individually brought devices. The design of the user interfaces differed in its *compatibility* to include participants' personal devices, which is only possible for DVEs #E6 and #L7.

General Observations

Inquiries about the categories of advantages, challenges, and future development of DVEs as well as success factors or transfers comprised eleven attributes (see Tab 2). Advantages address the usefulness and benefit of having a DVE at one's disposal; Challenges address the difficulties and barriers to install, run and maintain a DVE; Future development anticipates planned modifications, long-term adaptations, or needed innovation; Success summarizes respective indicators, of which transferrable results were considered a success. For some attributes it was possible to match advantages with respective challenges and future developments. A clear connection was found between the attributes and the modules of the functional framework, e.g., process, visualization, actors and personnel, products and outputs. However, a few attributes address linkages between these modules or beyond, such as space and technology referred to user interface. Each result is labeled with letter and number in Tab 2, and referred to in parenthesis. The observations were considered collective and general experiences that were attributed to the functioning of the entire facility or its institutional placement.

Overall, the matching of criteria showed that any holistic or creative approaches were developed for attributes of personnel, funding and strategy. The technology setup of DVEs requires a large initial investment and comes with high cost of maintenance, while facing fast technology innovation cycles. Such challenges and advantages of technology, engagement, and visualization were the ones most tangible and dominant. There was no mentioning of advantages regarding process and organization, visualizations, strategy, actors and personnel, funding, or successful products.

Most surprising, the results for products and outputs show that there is basically no practical knowledge about the fate of products developed in the DVEs from a practical perspective. Products in the academic world, such as peer-reviewed publications or conferences, were the only indicators of that kind. Furthermore, there was an imbalance between positive aspects, e.g., advantages of the DVE and successes, in comparison to required changes, e.g., challenges and future development. In particular, there were certain path dependencies between a strategy that addresses investments of infrastructure, purposes and services in a comprehensive long-term way, a funding strategy, and an efficient, continuous staffing. This could be an indicator for a necessary innovation cycle that not only pertains to the facility itself but also requires institutional changes.

Table 2 General observations of advantages, challenges, future development and success organized in eleven attributes.

#	Topic	#	Advantages	#	Challenges	#	Future Development	#	Success/Transfer
1	**Space and Technology**	A1	creating **holistic engagement** and complex understanding through physicality, tangibility by visualization, immediate interaction and engagement Space and facility changing the **roles, hierarchy and power** of participants (e.g. diminishing the role of the expert) and the hosting institution	C1	interior design, the confinement of **space &** amount **technology** are intimidating (e.g. depending on user group)	FD1	reaching **mobile** individual and collective application through **VR** and distributed network by maintaining a level of physicality		
2	**Place**			C2	**place** and vicinity of the facility affects organization, availability, accessibility and operations (e.g. staff, funding)			T2	Transfer of DVEs into **schools and museums**
3	**Process and Facilitation**	A3	attractive high **speed** of data return, analysis and reactions **seamless** interaction between content and humans via technology	C3	going beyond passive presentation and creating an enabling **engagement** between participants and **technology** (e.g. enabling change of mindset, cultural shifts)	FD3	Inclusive, integrative conversations by improving **facilitation techniques**	T3	Transfer of **communication and involvement** methods (e.g. lessons learnt)
4	**Visualization**			C4	finding the right balance between shiny, exciting **visualization** and not misleading translation from domains	FD4	Cost-effective, adaptive visuals by accompanying research and learning from **best practices** (e.g. natural language translation)		
5	**Process and Organization**			C5	time intensive **interdisciplinary preparatory** work (e.g. shared problem definition, event design and shared language development)				
6	**Strategy**			C6	having a long term **strategy** for the DVE in place (e.g. efficient and continuous investments into infrastructure and technology guided by purpose, goals and success)	FD6	creating long term, regular learning **communities** Focus and train **core competencies** of DVE and build a flexible team on site (e.g. decision making, visualization, facilitation)	T6	Creating **larger networks** that more effectively collaborate (e.g. technology development) Planning **guidance** for newcomers (e.g. operations, advisory board)
								S6	Number of **events** hold in the DVE popularity and **fame** of the DVE across disciplines
7	**Actors & Personnel**			C7	efficient and functional **staffing** and interdisciplinary collaboration to cover diverse roles and responsibilities of a running DVE (e.g. networking person, lead, technical support, visual designer)				
8	**Funding**			C8	lacking cost-effectiveness, cost-benefits, and self-sustaining **funding** (e.g. strong dependencies of institutional structures and third party money)				
9	**Products, Outputs**			C9	no assessment of long term **outcomes**, and immediate products (e.g. further use of outputs)	FD9	**certify** institutions and processes to implement them as experts and producer of quality products and services		
10	**Technology**					FD10	continuous, smart, cost-effective **upgrade and update** of technology, programming and interface (e.g. cloud-based services, matching data resolution, compatibility)	T10	multi-purpose **modular** technology settings (e.g. up- and downscale)
11	**Research**	A11	DVE used and presented as a **research tool** and instrument					S11	Number of scientific peer-reviewed **publications**

Discussion

Profiles of DVEs inform specific practices of purpose, with actors, in processes, with visualizations, and the user interfaces. Additionally, all experience challenges in their current implementation. In particular, the following discussion interlinks the insights for (i) the human-computer-content interactions created in the DVEs, and (ii) the DVEs' role at the science-society-interface.

Human-computer-content interaction in DVEs

Computerized visualizations and simulations are key elements in DVEs for a transformative human-computer-content interaction. They serve as the communication tool between hosts and participants, e.g., scientists and societal actors, but in many interdisciplinary projects also as a communication tool among the scientists themselves (Lange, 2011). This is possible due to the inherent ability of visualizations to create a common ground and reduce confusion across racial and social differences, as well as language barriers (Al-Kodmany, 2002; King, Conley, Henderson, Latimer, & Ferrari, 1989; Tufte, 1990). Given the diverse purposes of cases in DVEs, such as capacity building or decision making, the visualizations in place would need to enable transformative experiences, whether they concern community participation processes, planning processes, or they target changing mindsets, practices, or behavior.

The results show (see section 3.1.1), three aspects of visualizations namely design principles, functions, and order of visualizations are observed in practice. Ordering visualizations by including multisensory data to create a specific narrative, storyline or logical series is a crucial advantage of the DVE. Storylines can deviate from a linear or chronological order, and may be associative, distributed, and parallel. This means that visual storytelling focuses on iterating and repeating important reference points in particular ways and is ideal for constructivist learning and knowledge creation for actors with diverse backgrounds. Immediate interactions and manipulation of visuals including tangible, physical, and walkable characteristics help to give participants a "sense of being there", connecting them with previous experiences to create new knowledge (Barth & Burandt, 2013).

There are a number of possible types of information that integrate as part of such a story. A meaningful, purposeful combination of sources of information can have a cumulative effect for the recipients (Andersson & Magnusson, 2016), which play a role when a general perspective translates into a detailed and systemic one. They can also appear at the level of emotional responses to the respective story, having the negative effect to upset or overwhelm participants with excess of information (Sheppard, 2005). Storylines may be problematic when quickly switching from an abstract plan view to virtual reality simulation. Under this circumstance, the cumulative effect poses also an ethical question of balancing shiny and exciting and not misleading visual translations (see Tab 2, C4, FD4). The case of water resource management in Arizona explicates participants' critique towards legitimacy, credibility, and saliency of data based on their roles and agendas, and underlines the importance of maintaining a transparent view behind the scenes, e.g. into the production process or the data (White et al., 2010; Lange, 2011).

Al-Kodmany (2002) highlights that visualizations may not be sufficient for a meaningful human-content interaction. A process includes appropriate methods of facilitation that can steer the degree of interaction with the topical issue and guide conversations among participants effectively. The advantageous high speed data return and possibilities of seamless interaction with the content is mainly accompanied by only basic types of facilitation (see Tab1; Tab 2, A3). In DVEs these participatory approaches are not particularly elaborated and creating an enabling environment and inclusive conversation is challenging and requiring future development (C3, FD3). Though, a strong emphasis was put on a multilateral exchange with varying speeds, among larger or smaller actor groups that included contributors with different roles during the process. Valuable approaches are experimentation and exploration, instead of explanation approaches, combining scientific with practical knowledge for systems understanding or capacities for implementation (Caniglia et al., 2016; Domask, 2007). Although appropriateness and effectiveness of participatory methods are mostly defined case by case (Rowe & Frewer, 2004), all participatory designs for human-environmental problems should recognize “the interplay of uncertainty, choice, and constraints” (Salter et al, 2010). Evaluation strategies in DVEs to measure success, effectiveness of processes, collective and collaborative learning processes are missing, however these would be of high relevance to better understand the impact on implementation and policy (Pahl-Wostl, 2009; Radinsky et al., 2017; Sheppard et al., 2011).

DVEs at the science-society-policy interface

Decades of experience with application cases and involvement with people of different gender, age, experiences, and attitudes allow to support the advancement of this kind of research infrastructure at the science-society-policy interface, and to solve complex real-world problems. The combination of the experience with big data processing and a strong visualization background for this work makes a DVE unique. The purpose to support actual “decision-making”, however, was less prominent than expected. Results showed more often a capacity building approach with providing background information, negotiating options, and exercising collaborative planning, allowing for an informed decision making process at a later stage. The diverse participants, e.g. from governmental agencies or businesses, use different heuristics and formats of decision-making. Without evaluation of immediate products and long term outcomes it remains whether decision-making is aided due to the DVE.

Promising cases of decision making follow an exploration approach to capacity building using a DVE. The joint resilience planning for climate change related disaster recovery across city bureaus in Portland is one example of a complex capacity building process. Additional to the emergency recovery plan, the DVE events also aimed at cross-bureau collaborations (City of Portland et al., 2018). This example shows the power of visualizations in DVEs, empowering decision choices, offering options for safe experimentation and manipulation, and giving detailed or technical explanations for the individual actor and the entire group. Within such planning processes, evaluations of VR/AR visualizations provide insights into how highly realistic representations including multisensory information are able to evoke affective responses, and create the sense of "being there" (Lange, 2011). This kind of response can contribute to effective community planning and broader acceptance by the public (Maffei, et al., 2015; Maffei et al., 2016).

The facility of a DVE provides a space and place for knowledge production at the science-society-policy interface. The physical aspects of this space are not without their effects, since the interior design and technology set up can be intimidating for some participants. The results also show that the location of the DVE itself, e.g. at a distant university campus, also complicates accessibility for participants, or increases the emotional distance to the actual real-world problem. To counteract this issue, the idea of mobile versions become more prominent. For example, the mobility of war rooms to operating sites has been in practice and built into their original design (Brehmer, 2007). Semi-immersive domes and tent solutions, e.g. the Mobile Dome of Clockwork Ocean Project (Helmholtz-Zentrum Geesthacht, 2017), are more mobile facilities with kiosk and exhibition modes. Research that takes place at remote locations or communities underline the importance of the transportation feature (Boukherroub et al., 2018). The accelerating hardware and software development already decreases acquisition costs, allowing to transfer DVEs into schools or museums (Tab 2, T2). Mobile devices, cloud-based media, and user-friendly augmented reality applications are a targeted future development (see Tab 2, F01, T10). These approaches may achieve a new level of methods: (i) which dissolve stereotypical divisions between experts and participants regarding data provision for the case and control of an organized process (Lange, 2011); (ii) using it on-site, e.g., at a specific environmental problem, increases the tangibility of the experimentation with multi-sensory data, and democratizes the hierarchy and power a DVE space can produce (Gawlikowska, et al., 2017). A mobilized DVE increases the dynamics and requires to rethink the participation of groups, the flexibility of the room and distributed location and facilitating infrastructures to enable capacity building or decision making "within" instead of "about" an issue.

Our results show DVEs' experiences as wide-ranging shared and also segmented. The alignment of the different functional modules in the DVE underline that these facilities apply insights from interdisciplinary fields in a unique space. Current practices uncovered what differentiates DVEs from mere technical equipment with high computational power and high resolution video walls. DVEs operate at the science-society-policy-interface with a strong focus on complex real-world problems. They provide a save and innovative space for experimentation and build individual and collective capacities among the actors that may lead to decision making. Hence, DVEs utilize transformative experiences of a human-computer-content interaction and a semi-immersive experience involving all human senses increasing the complexity of the topic at hand very easily. By going beyond just explaining and creating a mode of experimenting and exploring complex problems, DVEs create interaction by purpose-oriented visual storylines, or the entire process and involvement of different actors. Consequently, this requires them also to advance facilitation methods as part of their set of tools that empower participants and ensure a save and inclusive dialogue.

Design Recommendations for DVEs

We present 12 design recommendations using the functional framework (see Fig. 3). The design recommendations address three levels: (i) the first level (green line) plans the overarching institution. (ii) the second level (green dotted line) describes the larger context of the facility and its options for transfer (green arrow); and (iii) the third level (green boxes) supports the design of the actual case in a DVE. The recommendations systematize tackling of current challenges while envisioning pathways for facilitation, engagement, and visualization techniques.

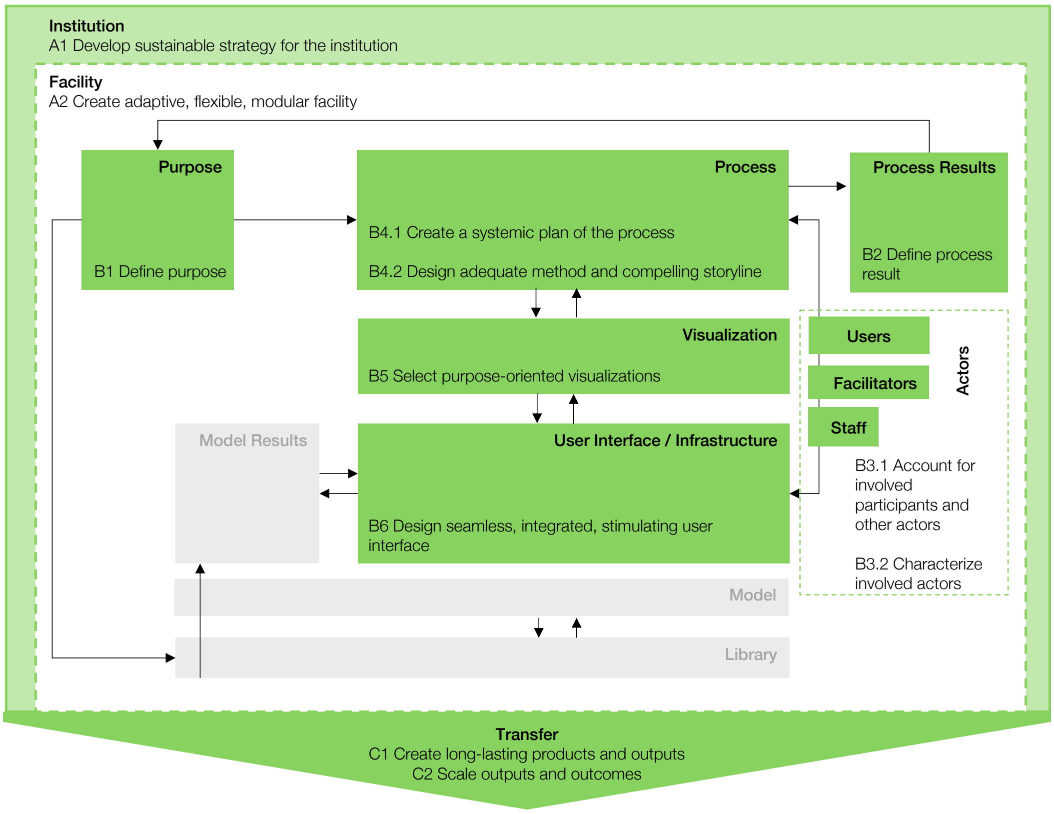

Figure 2 Twelve design guidelines anchored in the functional framework of DVEs; Design of the actual case and event (B1-B6), design of the facility (A2, green dotted line), design of transferrable products and outputs (C1, C2, green arrow), design overarching institution (A1, green frame)

A1 Develop sustainable strategy for the institution

This significant investment for a DVE requires strategic planning supported by the administration and organization. The strategic goals of the DVE should align, pertain or support the overarching strategy and institutional goals. An alignment of goals includes a clear idea of long-term funding, continuous investments, a connection to a collaborative, supportive institutional network. The strategy provides space for creative ideas, spin-offs, and services innovated by the facility, aim to fulfill an efficient occupancy rate, and support the positive image of the institution. Collaboration between the DVE, other research facilities and projects as well as partners is vital for the long-term success, exploiting the DVE as an adaptive specialist service that continuously innovates and adopts new techniques and technologies while creating a body of knowledge of best-practices, methods and technical solutions.

A2 Create adaptive, flexible, modular facility

To host heterogeneous types and purposes of cases and events requires an adaptive, flexible, and modular perspective on the facility’s technology, space, and place, demanding a high level of mobility of the infrastructure (e.g., furniture, displays, handheld devices) while ensuring cost-effective software and hardware. By allowing a holistic engagement with physicality and tangibility for the interaction with participants, cases should be adaptive, using a flexible, careful interior design that respects and anticipates attitudes of participants towards technology, power, and hierarchy. Therefore, location and vicinity (e.g., room or mobile tent) should be selected on a case-by-case basis, allowing for adaptability of a DVE that results in diverse hardware set-ups that are adjustable, using a growing toolbox of software tools that can be expanded without becoming a convoluted set of code repositories, quick fixes, and plug-ins. To avoid reinventing the wheel for each use-case the development of a mid- and long-term software strategy is advisable.

B1 Define purpose

The purpose of a case or event describes the overarching goal(s), besides the research questions or a problem-definition and drives the entire design with immediate effect for appropriateness of a process and interface. A defined purpose makes contributions to societal outcomes and/or exclusive research outcomes explicit. This should include a focus on types of individual or collective capacity building especially when engaged with practitioners in order to define the appropriate knowledge-production process.

B2 Define process result

The intended result of a process is indicated by a concrete output in the form of a specific product, combined with a long-term outcome. As the DVE is an infrastructure for research, two types of results are considered: Definition of the expected output and respective outcome provided to the practitioners and participants is vital, as well as the expected outcome for the research community. Since most projects fail at the interface between researching and societal relevance, it is advisable to address in this step real-world implementations of outputs, e.g. into planning. Overall, process results need to be linked to the measurement of success and transfer activities (C1, C2) of the facility. Indirect outcomes are also important results when considering capacity building.

B3.1 Account for involved participants and other actors

Every group involved in planning, executing, conducting, and participating requires careful accounting, including the appropriate number of participants and the variety of tasks. Different groups need to be mapped out for different stages and tasks of the case or event. This procedure ensures practical and functional staffing, starting with the preparation phase, and therefore contribute to an efficient operation of the DVE.

B3.2 Characterize involved actors

The backgrounds, needs, expectations, interests, languages, and relationships of involved parties determine the course of events in the case, its success, and its preparation. Characterizing and utilizing these aspects for the design process allows for creating a relatable and adaptive case or event, enabling participants to engage in a transformative knowledge-production process, including information on how to build trust across involved parties and ways to balance power and hierarchy. Also, several informal roles critical to the process, such as the networker, change agent, honest broker, or community champion, should be identified within the participants. This, as well as the guideline B3.1, can also be considered a requirement to successfully moderate and facilitate a process.

B4.1 Create a systematic plan of the process

Preparation of the process requires common event management and project coordination to represent the case and its purpose adequately. As each event should produce results to serve the overall purpose it needs to have a degree of interaction with the participants, the adequate mechanism for this interaction, the intention of the event(s), and subsequently the appropriate method of engagement to allow staff and research team to adapt their respective roles. Regarding the content a precise joint problem definition, interpretation, and development of shared terms and language needs to be coordinated between actors, including an introduction package to enable the participants to understand the event and the entire place and the mode of work. An integrated and systematic approach regarding guidelines B1 and B2 with a complementing set of B4.1 and B4.2 will greatly define the scope of inquiry and possible results, reduce bias, and contribute to the activation and motivation of all parties involved and hence, leads to a higher rate of successful implementations and positive long-term effects.

B4.2 Design adequate method and compelling storyline

A storyline with a visualization of contents creates a seamless human-computer interaction that to allow the participants to experience the case holistically, building on professionally developed and led artistic- and aesthetics-based processes to explore and include the setting, community, and social fabric affected by the research in an open-minded way to activate its stakeholders to interact effectively. Thereby the active engagement, building on appropriate facilitation techniques should lead to a transformative knowledge production. This should include an explicit design of facilitation that elicits, aggregates, integrates, and summarizes information. A professional presentation and facilitation will aim to present facts, avoid bias and obfuscating tactics to empower the stakeholders to understand, assess, and judge possible outcomes in reconciliation of a diverse set of interests based on a broader acceptance. A transformative experience also allows the participants to explore a variety of solutions and experiment with scenarios which requires dynamic data manipulation. This shows that a process involving a DVE is a task to incite, direct, and facilitate an inclusive and integrative communication between diverse parties and their particular interests and therefore needs the same professional preparation and execution as it does for its underlying scientific research.

B5 Select purpose-oriented visualizations

A series of visualizations, or narratives, should be combined with the process in a meaningful way. Aside from translating data, they need to generalize, experience, or detail knowledge and can work with elements to trigger immediate responses or to explicate people's mental models. A DVE is not limited to seeing but allows for a multisensory experience by adding audio, verbal, textual or tacit knowledge. Visualizations ought to be balanced between exciting and exact and follow an internal logic, as they can obfuscate possible insights and inhibit outcomes. Thus, visualization should adopt purpose-oriented design principles with respect to the intended audience and situation that also consider cumulative effects on attitudes and cognitive understanding while considering ethical concerns, such as persuasion and influencing behavior.

B6 Design a seamless, integrated, stimulating user interface

The design of a user interface reflects the purpose and process (guidelines B1, 4.1, 4.2.) of a case or event through state-of-the-art software and hardware, in respect to its audience while adhering to multimodal guidelines. Obviously, a group of researchers will need a great level of flexibility to choose datasets, graphing elements, and scenarios which inherently create a higher complexity, whereas the general public in an exhibition needs to be presented with a limited, well-explained set of controls that are easy to use in a kiosk-mode. Between these two extremes a number of gradual adaptations need to be considered on a case-by-case basis. Therefore, the integration of an interface for content interaction should be seamless, and adaptive to the participants' skill level. The user interface should address diverse groups sizes as well as individuals equally efficient.

C1 Create long-lasting products and outputs

Outputs should comprise concrete products, and research related outputs tailored to practitioners, demanding a larger expertise and a long-term investment into the infrastructure to integrate into a comprehensive set of success measures including assessments, audits, or certifications. The transfer of lessons learned from all areas of expertise should be part of this assessment in order to make a DVE more effective and efficient (see Tab 2; C9, S6, S11, FD9). It is advisable to create a repository (knowledge-management database) of methods and insights, and the expertise gained, as well as a mid- and long-term software strategy, since this knowledge represents the true long-term value of a DVE.

C2 Scale outputs and outcomes

Targeting the scaling of outputs and creating outcomes is another form of impact. Scaling aims to disseminate products, e.g., communication and involvement methods, and to increase the number of facilities, e.g., in schools, museums, or agencies. This requires a membership within a network or peer-to-peer learning community in order to share technology, organization and planning practices, and is necessary in order to improve the efficiency of the facility (See Tab 2; T2, T6). For example, interactive dashboards can be concrete products of a DVE that can be disseminated. These dashboards can be deployed in locations as informational or interactive screens, as well as data-driven plug-ins for websites to keep the stakeholders or the general public informed of a situation or a progress made.

Conclusion

Over time Decision-Visualization Environments (DVEs) have evolved into a research infrastructure based on a semi-immersive environment to support researching, planning, and decision-making processes, e.g., in architecture, forest science, urban design, and other domains.

The goal of this study was to examine current practices of such DVEs, and to understand mechanisms, advantages, challenges, and future advancements of their work. For this analysis, we created a functional framework of a DVE to describe and design the structure and interactions in nine modules. The nine modules extend existing understanding of the technical and computational power of a DVE by integrating the purpose of cases and events, the process with its relation to user interface and participating actors, and emphasize visualizations as core characteristics within the interaction. The results revealed profiles of different DVE practices as well as challenges and entry points for future development that are shared across facilities. A set of twelve design recommendations organize all modules according to the functional framework (see section 5) and provide a comprehensive approach to (i) the design of a case, e.g., planning the process and accounting for the involved participants and (ii) the strategy of the larger institutional placement and flexible facility.

It is the save space for exploration and experimentation at the science-society-policy interface that makes the DVE a unique tool. The advantage of the semi-immersive environment and strong visualization component creates a transformational human-computer-content interaction in order to address complex real-world problems. Such an interaction still needs an innovative facilitation and moderation to support and empower diverse actors in their knowledge production. At the same time, ideas of a more flexible and mobile facility evolve towards accessible cloud-based and mobile devices allowing to address problems at their original location. By recognizing these shared mechanisms and criteria, we believe that the term Decision-Visualization Environment (DVE) is adequate for framing a definition for this type of facility and infrastructure.

Further research of DVEs should foster a learning community that works across institutions. Such an interdisciplinary community would be able to develop purpose-oriented scenarios to use DVEs and ways to transfer successful solutions for collective learning in order to advance, transfer and train transformative experiences in human-computer-content interaction.

An Experience–Based Learning Framework. Activities for the Initial Development of Sustainability Competencies

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Abstract

Purpose – This paper aims to present an experience-based learning framework that provides a bottom-up, student-centered entrance point for the development of systems thinking, normative and collaborative competencies in sustainability.

Design/methodology/approach – The framework combines mental mapping with exploratory walking. It interweaves mapping and walking activities with methodological and theoretical inputs as well as with reflections and discussions. The framework aligns experiential activities, i.e. mental mapping and walking, with learning objectives, i.e. novice-level sustainability competencies. The authors applied the framework for student activities in Phoenix/Tempe and Hamburg/Lüneburg as part of The Global Classroom, a project between Arizona State University in the USA and Leuphana University of Lüneburg in Germany.

Findings – The application of the experience-based learning framework demonstrates how students started developing systems thinking (e.g. understanding urban systems as functional entities and across different domains), normative (e.g. using different sustainability principles) and collaborative (e.g. learning across disciplinary, social and cultural differences) competencies in sustainability.

Originality/value – The experience-based learning framework contributes to the development of curricular activities for the initial development of sustainability competencies in introductory-level courses. It enables students from different disciplinary, social and cultural backgrounds, e.g. in international education, to collaboratively start developing such competencies. The framework can be adapted to different educational contexts.

Introduction

Climate change, desertification, poverty and pandemics are among the typical sustainability problems which feature high degrees of complexity and damage potential and do not have obvious solutions (Kates et al., 2001; Lang et al., 2012). The goal of Higher Education for Sustainable Development (HESD) is to enable students not only to understand these problems but also to contribute to solution efforts (Barth, 2015; Wiek and Kay, 2015). To achieve this goal, contributions in HESD argue for educational settings that allow students to actively engage with real-world sustainability problems (Rowe, 2007; Brundiers et al., 2010; Scholz et al., 2006; Domask, 2007). The exposure to real-world problems enables students to develop systems thinking, normative, anticipatory, strategic and collaborative competencies necessary for engaging in problem-solving efforts and for professional careers (Remington-Doucette et al., 2013; Allen et al., 2014; Singer-Brodowski, 2015; Wiek et al., 2011a, 2011b).

To support the acquisition of sustainability competencies in higher education, functional and progressive sets of educational activities are needed (Brundiers et al., 2010; Wiek et al., 2014). This article presents an experience-based learning framework for the initial stage of competency development. This framework provides an experiential and student-centered approach for the novice-level development of systems thinking, normative and collaborative competencies suitable for introductory-level sustainability courses (Wiek et al., 2011a; Wiek et al., 2015). The framework contributes to the pool of settings for sustainability education, particularly applicable in courses with students from different disciplinary, social and cultural backgrounds, e.g. in international education (Brundiers and Wiek, 2011; Wiek et al., 2011b).

The experience-based learning framework adopts the constructive alignment approach pioneered by Biggs (1996); cf. Biggs and Tang, 2007). This approach has two main components: the constructive one and the alignment one. According to constructivist theories of learning, students learn little through passive exposure but better through active engagement (Biggs, 1996). The experience-based learning framework is therefore composed of activities that draw on students' experiences of (un)sustainability in local contexts. This supports the development of sustainability competencies better than theoretical and abstract topical introductions. The alignment component refers to linking learning objectives with learning activities (Biggs, 1996). The experience-based learning framework therefore aligns the objectives of novice-level systems thinking, normative and collaborative competencies (Wiek et al., 2015) with activities of mental mapping (Lynch, 1960) and exploratory walking (Kohler, 2014). The framework interweaves these activities with theoretical and methodological inputs as well as with reflections and discussions (Stauffacher, 2010).

The authors applied the framework in The Global Classroom, a project between Arizona State University (ASU) in the USA and Leuphana University of Lüneburg in Germany (Wiek et al., 2013). They conducted a formative assessment of the framework in two successive iterations, working with more than 70 students from both institutions (Sadler, 1989; Stull et al., 2011). The findings suggest that the framework can be applied in different educational contexts.

This article, first, presents the overall goals of the experience-based learning framework. It expands on the learning objectives of the framework and focuses on how experiential activities align with these learning objectives. It also presents the mental mapping and walking methods used to structure students' learning. Second, it introduces how the framework structures these activities with accompanying inputs, reflections and discussions. Third, it reports some of the findings from the application and formative assessment of the framework in The Global Classroom. Finally, it draws conclusions on how to adapt and further develop the framework.

Experiential Activities for the Initial Development of Sustainability Competencies

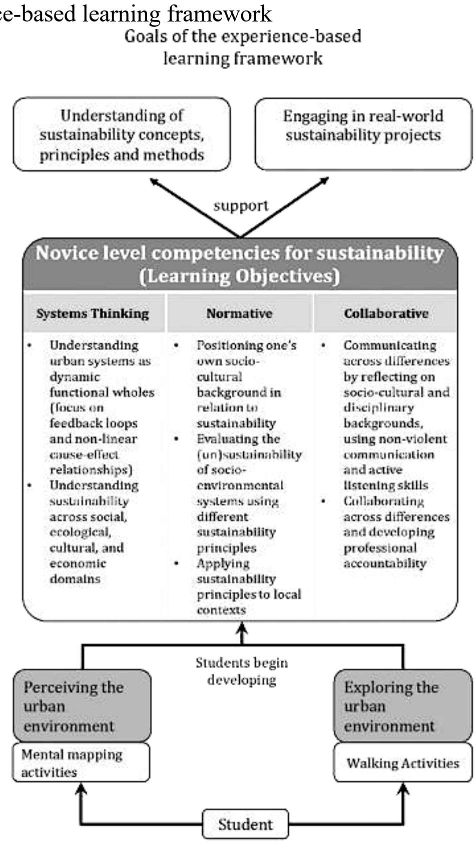
Since the early 2000s, sustainability education aims to structure activities that foster the step-by-step development of key competencies in sustainability over the course of an educational program (Brundiers et al., 2010). Yet, little attention has been paid to how instructors can facilitate the initial development of such competencies in students from different disciplinary, social and cultural backgrounds, e.g. in international education. With an experiential approach that makes use of mental mapping and walking activities, the experience-based learning framework structures the initial stage of in the development of systems thinking, normative and collaborative competencies. Figure 1 links the learning objectives of the framework (central box in the figure) with the experience-based learning activities, i.e. mental mapping and exploratory walking (lower boxes in the figure). By performing these activities as well as by reflecting on and discussing their results, students develop basic sustainability competencies. They foster students' understanding of concepts, principles and methods in sustainability as well as enable graduates to engage in real-world sustainability problem-solving (upper boxes in the figure).

Learning Objectives: Developing Novice-Level Sustainability Competencies

Increasing attention has focused on competencies as central for the development of curricula in sustainability (Barth, 2009, 2015). Sustainability scholars have identified a set of key competencies for sustainability: systems thinking, normative, anticipatory, strategic and collaborative competencies (de Haan, 2006; Wiek et al., 2011a). The experience-based learning framework operationalizes systems thinking, normative and collaborative competencies as specific learning objectives at a novice-level of competence development, say in the initial stage of competency development (Wiek et al., 2015). The novice level of competencies development characterizes many students in introductory classes to sustainability, as they are often neither cognizant nor already committed to this subject.

Systems thinking is the ability to analyze complex systems and problems across different domains (i.e. society, environment, economy) and scales (local to global) (Wiek et al., 2011a). This competence is essential to understand and engage with the complexity of sustainability issues (Clayton and Radcliffe, 1996). Taking the example of urban sustainability, systems thinking competence entails describing the basic structures, dynamics and functions of urban systems (Clayton and Radcliffe, 1996); explaining causes, indirect effects and feedback loops of urban sustainability problems (Clayton and Radcliffe, 1996); describing urban systems and their (un)sustainability across social, ecological, cultural and economic domains (Dale and Newman, 2005); and articulating the link between urban systems and their hinterland(s) as well as other urban centers. The novice-level creates the base for more advanced levels of systems-thinking competence, including mastery of complex adaptive system concepts or modeling methods (Iwaniec et al., 2014).

Figure 1 Goals of the experience-based learning framework



Note: Learning objectives (Novice-level development of systems thinking, normative and collaborative competencies) align to experiential learning activities (mental mapping and exploratory walking)

Sustainability is an intrinsically normative concept (Miller, 2012). The development of normative competencies in sustainability requires an advanced understanding of how to evaluate current situations and engage in negotiations of values and priorities in assessing sustainability issues (Remington-Doucette et al., 2013; Scholz, 2011; Wiek et al., 2011a). Normative competence is displayed in the abilities to (Wiek et al., 2015): recognize and position one's own values, habits, perceptions and new experiences in relation to sustainability in a given place and time; explain concepts of justice, equity and ethics and their relevance for sustainability; and appraise the (un)sustainability of socio-environmental systems using different sustainability principles and targets (Bell and Morse, 2008; Gibson, 2006; Schlosberg, 2007; Seghezzo, 2009; Luederitz et al., 2013). The novice level creates the base for more advanced levels of normative competence, including facilitation of negotiations among different stakeholders approaching (un)sustainability from different perspectives (Remington-Doucette et al., 2013), or mastery of sophisticated multi-criteria assessment methods for sustainability evaluations and visioning (Wiek et al., 2011a).

Due to the complex nature of sustainability problems, teams of people across disciplines, social and cultural backgrounds are needed for successful problem-solving efforts (Scholz, 2000; Beierle and Cayford, 2002). The ability to collaborate in ways that recognize, accept and positively use difference in disciplinary, social and cultural backgrounds is an important sustainability competence (United Nations Educational Scientific and Cultural Organization, 2005; Agyeman, 2005; Wiek et al., 2011a). Collaborative or interpersonal competence on the novice-level includes diversity and intercultural capabilities (Adams et al., 2007); compassionate, empathetic, non-violent communication and active listening skills; and collaboration skills and professional accountability to each other (de Haan, 2006). These skills are the basis for advanced levels of collaborative competence, a crucial element in all sustainability professions.

Experience-Based Learning In Sustainability Education

The experience-based learning framework relies on the widely supported assumption that activities building students' experiences of (un)sustainability in local contexts support the acquisition of sustainability competencies (Brundiers et al., 2010; United Nations Educational Scientific and Cultural Organization, 2005; Scholz and Tietje, 2002). Domask (2007, p. 53) asserts that:

> […] experiential learning offers an educational experience that most effectively: connects the academic with the practice, fosters an effective interdisciplinary curriculum, links students to work experience and job opportunities, and engages and empowers students.

However, most educational settings rely on the prior introduction of sustainability issues, frameworks and approaches (Alvarez and Rogers, 2006; Brundiers et al., 2010; Domask, 2007; Scholz and Tietje, 2002). Explorations of real-world sustainability issues are often taken as a way to test and confirm what has been already introduced and learnt in class. For example, “in field trips […], students experience the sustainability issue in the real world, exploring how sustainability issues discussed in classroom materialize or fail to materialize” (Brundiers and Wiek, 2011, p. 315). Introductory courses often adopt standard educational settings based on weekly lectures with accompanying readings to familiarize students with sustainability concepts and issues. Classroom-based case studies are then used for linking concepts and empirical information to increase students’ problem-solving skills by simulating sustainability challenges (Remington-Doucette et al., 2013). This approach is useful when real-world experiences are hard to organize or deliver, for instance, in large introductory courses.

Once students have acquired some familiarity with sustainability and its features, in some cases experiential learning approaches come into play, which enhance both students’ active participation and their problem-solving skills (Alvarez and Rogers, 2006). In the experiential case encounter, students attain a closer understanding of a specific situation by immersing themselves in the case they are investigating (Scholz and Tietje, 2002). The so-called pull-concept for mutual learning accounts for the way students learn in experiential case encounters (Posch and Steiner, 2006). Here, the interactions between societal stakeholders, students and instructors are organized in a way that directly generates a demand for learning. All participants jointly try to create solutions to ill-defined problems. As students become aware of their insufficient knowledge of the situation they face, they become motivated to acquire more knowledge and skills for problem-solving (Posch and Steiner, 2006).

Unlike these common experiential learning approaches, the experience-based learning framework proposed below offers students the opportunity to explore and experience sustainability issues in the real world, without prior sustainability knowledge or commitment. In this process, they learn how to identify and analyze a sustainability problem. They also start thinking about solution options.

Mental Mapping and Walking Activities

The experiential, student-centered and bottom-up learning framework uses two main learning approaches (Figure 1). The first is inspired by Kevin Lynch’s concept of mental mapping (Lynch, 1960), the second by walking concepts, in particular by transect walks (Kohler, 2012, 2014). The mapping activities allow students to reflect on their perceptions of the urban system. Second, the walking activities enable them to have a new experience of that system.

In the early 1960s, the urban planner Kevin Lynch developed mental mapping activities to capture the perception that people have of their urban environment (Lynch, 1960). As an alternative to usual bird's eye views on the city, Lynch's approach allows students' to build an experiential image of the city and enables reflections on the meaning that they attribute to different parts of it (Soini, 2001). Reflections on in how far socio-cultural backgrounds influence students' experiences and perceptions of the city are particularly relevant in international educational settings.

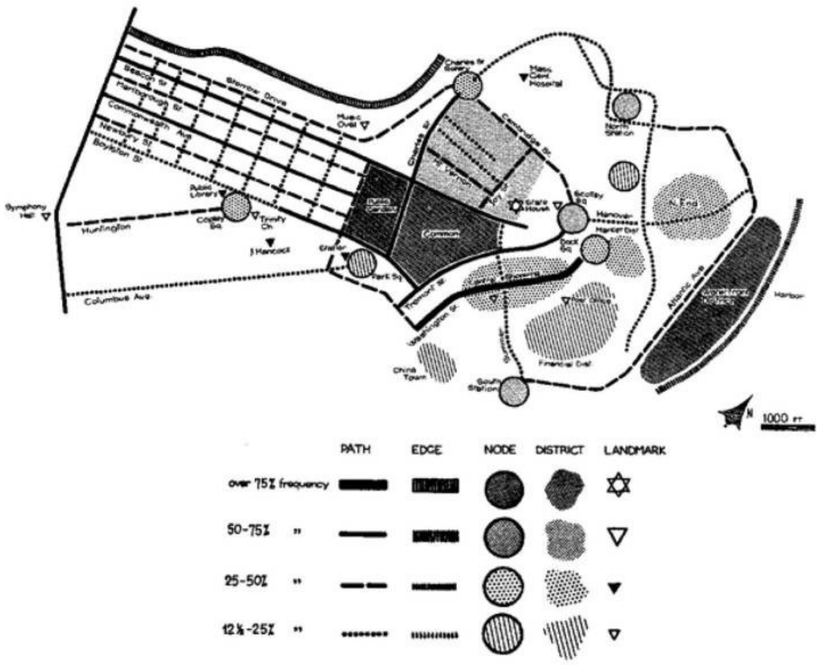
Mapping activities include drawing and conducting questionnaires to capture five elements that people perceive of their city: paths, edges, districts, nodes and landmarks (Lynch, 1960). All elements have distinctive features and can be analyzed on their own (Figure 2). Yet, the overall image of the city emerges from their interconnection.

As walking became a choice rather than a necessity, the act of walking turned into a perceptual instrument to understand, analyze and critically address urban environments and issues (Careri, 2002; Benjamin and Tiedemann, 1999; Valva, 2012; Foley et al., 2015). Similarly to Lynch's mapping techniques, approaches based on the experience of walking expose the students to the complexity of the urban environment while promoting curiosity, creativity and critical thinking (Oppezzo and Schwartz, 2014). They learn first hand that addressing the complexity of (un)sustainability is not only about understanding order but also disharmony and uncertainty (Kagan, 2011).

The act of walking can produce an experience that transforms students' perceptions of their daily environment (Masschelein, 2010, p. 46). Also, walking allows for collecting data (Kohler, 2014; Shortell and Brown, 2014) and is used in different fields. For instance, in the field ecology, line-transect sampling is used to analyze aggregations like ecological habitats, soil types and wildlife populations (Buckland et al., 2005). In urban ecology planning, walking is often used in combination with geographic information system. In ethnography, walking with research participants in a given place tells and shows their material, immaterial and social environments in personally, socially and culturally specific ways. It allows researchers to learn empathetically about a place from the experience of the people who inhabit it (Pink, 2007, p. 240). In technology governance studies, walking has been used to explore opportunities and risks of technical solution options to urban sustainability challenges (Foley et al., 2015).

In transect walks, students transect a section of the urban environment for several hours. Students are only given a point of departure and a point of arrival. They are free to travel from one to the other following the path that they find more interesting or feasible (Kohler, 2014). During the transects, students use sampling techniques and gather data and information about a complex and diverse urban system. By walking and collecting data, students experience different domains (i.e. society, environment, economy) and different scales (local to global) in which sustainability issues emerge (Clayton and Radcliffe, 1996; Crofton, 2000). Also, exploring the city on foot enables students to challenge their previous images and perceptions of the urban environment. Sharing the experience of the walk among the students allows for in-depth discussions of social, environmental, economic and cultural dimensions of urban sustainability (Ingold and Vergunst, 2008).

FIG. 36. *The Boston image as derived from sketch maps*



Note: This is one of Lynch's original mental maps of Boston (Lynch, 1960), which shows both the different elements (nodes, paths, etc.) of the city image and their interconnectedess

Figure 2 Lynch's mental maps

The Experience-Based Learning Framework

The experience-based learning framework engages students in a step-by-step learning experience. Instructors facilitate and help the students during most activities with a series of inputs and guidelines. Yet, students self-organize, sometimes individually, other times in small teams. Figure 3 shows that the framework has the shape of a spiral of repeated engagements that interweaves theoretical and methodological inputs, mapping and walking activities, as well as reflections and discussions (Bruner, 1960). Table I summarizes the activities in the framework focusing on the deliverables and outputs produced in the different steps of mapping and walking activities.

Part I of the experience-based learning framework captures and structures students' perceptions by using mental mapping methods. Part II unfolds into explorations of the urban environment using walking methods. The two parts are organized in four steps, respectively:

- Step 1 – Preparation: Instructors provide inputs on theoretical and methodological background of the activities.
- Step 2 – Data gathering and analysis: Students perform mapping and walking activities (data gathering), as well as organize, store and analyze the data.
- Step 3 – Interpretation and reflection: Students reflect on the data collected in light of sustainability. They apply sustainability principles in the assessment of (un)sustainability and situate their own social and cultural background in relation to sustainability in local contexts.
- Step 4 – Sharing students share their data and interpretations.

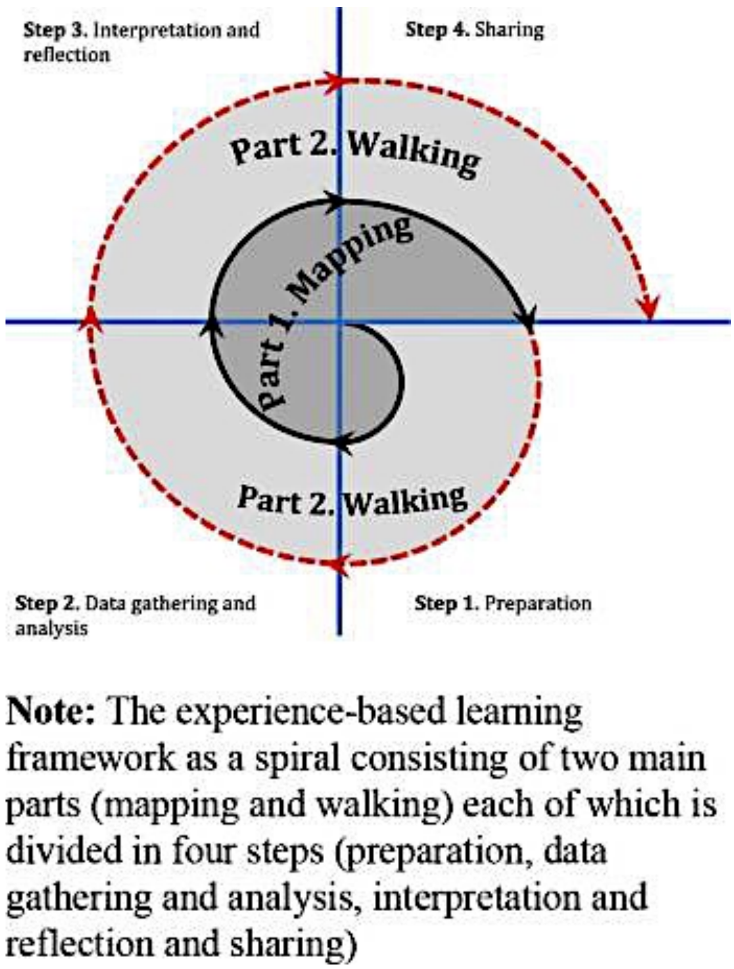


Figure 3 The experience-based learning framework

Part 1. Perceiving Sustainability. Mental Mapping

Step 1: preparation. Step 1 provides the students with theoretical and methodological foundations of visualization and mapping. Students become aware of their existing knowledge of the urban environment by using Lynch's methods:

Input: Instructors introduce basic ideas about mental mapping as visualizations of perceptions and experiences as well as Lynch's approach and elements (Lynch, 1960, p. 1ff, p. 46ff).

- Sketches and questionnaires: Without another geographic map for reference (e.g. Google maps), students draw a sketch of their urban environment, according to their habitual perceptions based on Lynch's guidelines. A short questionnaire complements their sketches with symbols, meanings and feelings attached to their image and its components.
- Class discussion: In class, students reflect on their individual sketches and compare them. Students capture common elements using Lynch's elements (i.e. nodes, paths, landmarks) and reflect on the reasons for differences in the sketches.

Step 2: data gathering and analysis. In Step 2, students learn basic principles about how to handle and analyze qualitative data, such as sketches and responses to questionnaires:

- Input: Instructors introduce basic procedures of data gathering and analysis in qualitative research and provide students with guidelines to gather and analyze new data.
- Data gathering: Each team selects and interviews students outside of class with the questionnaire of Step 1 and organize the responses. Optionally, instructors could also choose a different target group.
- Data analysis: With the help of the instructors, students code their data focusing on number of recurring places, feelings and meanings attached to those places and how they occur in both questionnaires and sketches. Students organize the outcomes in a spreadsheet.

Step 3: interpretation and reflection. In Step 3, students start learning how to assess the (un)sustainability of areas and communities by engaging sustainability concepts and principles. The central output of Part I is generated in this step in the form of a shared mental map (Table I):

(1) *Shared mental map*: In their teams, students look into the most recurring elements in the spreadsheet and apply Lynch's elements. Students look at how different places are connected to one another in people's experience of the urban environment. They finally visualize the information creatively into one single image.

Table 1 Main deliverables and outputs of mental mapping and walking activities

		Part I: mental mapping		Part II: walking		
No.	Steps	Substeps	Deliverables and outputs	Substeps	Deliverables and outputs	Learning objectives
1	Preparation	Sketches and questionnaires	Individual students produce sketches (mental maps) and description of their urban own environment	Methodological/ Theoretical input	N/A	Novice-level development of systems thinking, normative and collaborative competencies
		Class discussion	Students produce a short description of their individual sketches using Lynch's elements	Class discussion	Students produce a short piece about walking as a research method	
2	Data gathering and analysis	Data gathering	Teams produce a data base where they organize and store sketches and answers to the questionnaires they collected in the interviews	Data gathering	Teams produce a data base where they organize and store GPS data, visuals and field notes recording the walk; and answers to the evaluative questions	
		Data analysis	Teams produce a document with the results of the coding	Data analysis	Teams produce short written pieces about the walks that structure their impressions and ideas	
		Shared mental map	Central output of Part I. From the data collected, teams produce a visualization of the shared mental map of the city using the media they find more appropriate (Figure 4)	Narrative of the walk	Central output of Part II. From the data collected, teams produce a narrative of the walks using the media they find more appropriate (Figure 4)	
		Identifying/Assessing (un)sustainability	Teams produce short written pieces about sustainability issues identified in the mental maps by using different sustainability concepts (e.g. principles and dimensions)	Identifying/ Assessing/ Analyzing (un)sustainability	Teams produce short written pieces where they start assessing and analyzing the sustainability issues encountered in the walks. They use one set of sustainability principles, basic assessment methods and problem analysis	
No.	Steps	Substeps	Deliverables and outputs	Substeps	Deliverables and outputs	Learning objectives
3	Interpretation and reflection	Systems map	Teams produce a basic system map of sustainability problems encountered in the mental mapping activities	Systems map	Teams produce a basic systems diagrams of sustainability problems encountered in the walks	
		Situating perceptions	Teams produce a written piece where they reflect on how the perception of sustainability problems vary among different people; Individual students produce a short piece where they reflect on how their own socio-cultural background influences their perception of (un)sustainability	Situating new experiences	Teams produce a revised narrative including descriptions of how experiences of sustainability problems vary among different people; Individual students produce a short piece where they reflect on how their own socio-cultural background influences their experience of (un)sustainability	
4	Sharing	Presentation	Teams produce a presentation of their shared mental map from a sustainability perspective. Teams deliver the presentation in front of the class	Presentation	Teams produce a presentation of their walks from a sustain ability perspective. Teams deliver the presentation in front of the class	
		Class discussion	Individual students produce a final reflection piece where they discuss their learning process in the mapping activity	Class discussion	Individual students produce a final reflection piece where they discuss their learning process from the mapping activities to the walking activities	

(2) *Identifying and assessing (un)sustainability:*

- *Identifying sustainability issues*: With the help of the instructors, as well as based on specific criteria (e.g. harmfulness, urgency), student teams select a few sustainability issues and locate them on the mental maps, as far as possible. (see Section 4 for specific examples)

- *Becoming familiar with sustainability concepts and principles*: Students review relevant literature (Bell and Morse, 2008; Gibson, 2006; Seghezzo, 2009; Luederitz et al., 2013; Wu, 2014) and start applying sustainability principles to the issues identified. Exercises and assignments help them evaluate the sustainability issues they have selected in the mental maps and evaluate the (un)sustainability of areas and communities.

(3) Causal systems diagrams (optional): If instructors aim to develop systems thinking competence and if there is enough time, students could draw on the shared mental map to produce causal systems diagrams of sustainability issues. In these diagrams, students visualize and reflect on basic causal structures, as well as non-linear cause-effect structures, feedback-loops and cascading effects.

(4) Situating perceptions: Students reflect on how the cultural, social and economic background of the participants they interviewed might influence their image of the city. Students go back to their initial, individual sketches and reflect on how their own perception of the urban environment and of sustainability compares to other people's perceptions.

Step 4: sharing. In Step 4, students learn how to present, communicate and discuss results in relation to specific contexts, as well as communicate and listen actively to synthesize knowledge:

- *Presentations*: Students present the results of their mapping exercises to the other students. They elaborate on how social, disciplinary or cultural backgrounds influence people's image of the city.

- *Class discussion*: The material in the presentations is used for the discussion afterward. Here, instructors encourage the respectful communication of different perceptions, and active listening with openness and curiosity. Students discuss how both their image of the city and their perception of (un)sustainability are produced by specific local circumstances.

Part 2. Exploring Sustainability. Walking

Step 1: preparation. Step 1 familiarizes students with theoretical, historical and present foundations, sources and applications of walking methods:

- *Input*: Instructors introduce the theoretical and methodological background of transect walks. Also, they present and distribute the transects, i.e. the beginning and final points of the walks (see Figure 4 for examples of transect).
- *Walking targets*: Instructors can choose from different kinds of experience and data collection. For instance, walkers can focus on ecosystems services along their route and document those. Also, they can pay attention to the distribution of environmental benefits and burdens with a social justice focus. Another option is that students walk without any specific targets. In this case, they record subjective, surprising and interesting elements.

Step 2: data gathering and analysis. In Step 2, the students are paired up and walk the transects; they learn data handling and data processing of multiple sources. The central output of Part II is generated in this step in the form of a narrative of the walk (Table I):

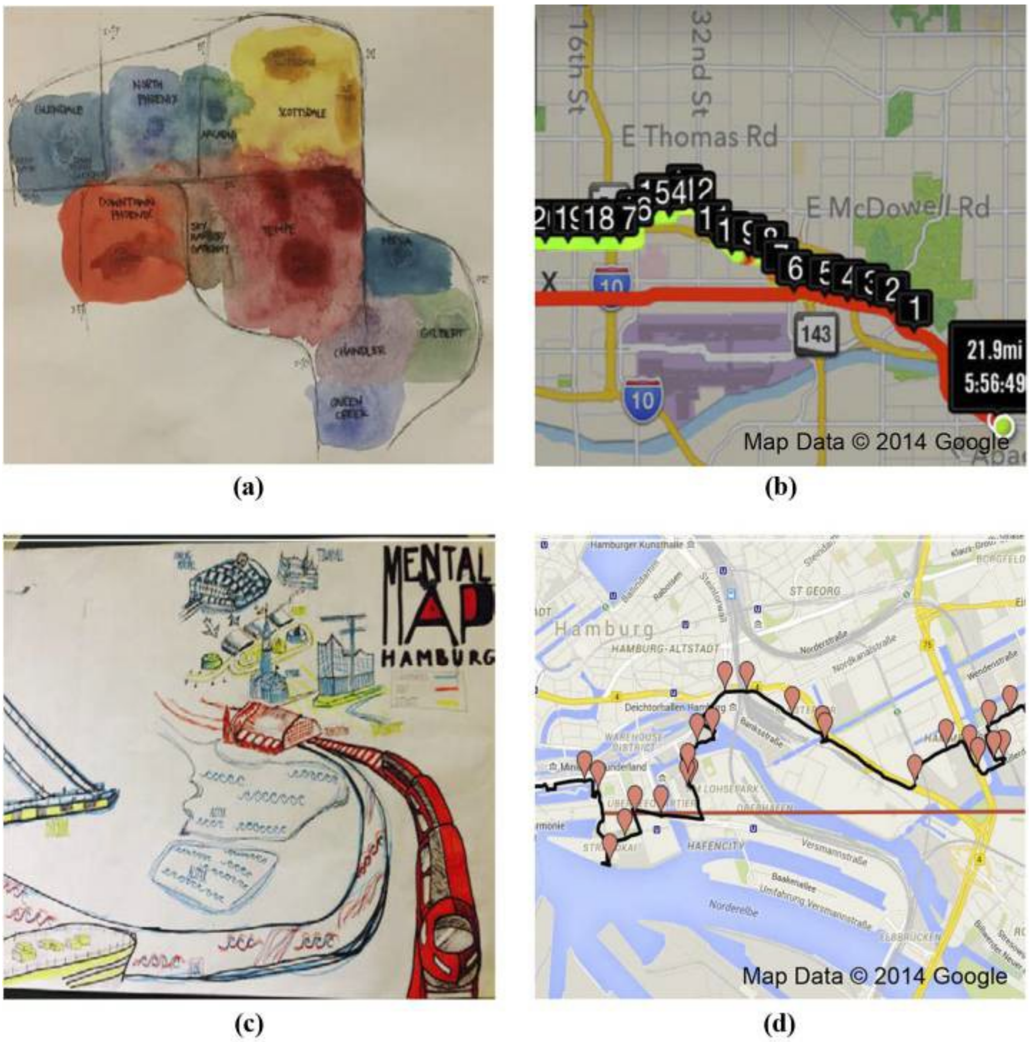
(1) Data gathering:

- *Recording* – Before the walks, students make decisions on how to document the walks. They agree on the media they would like to use (e.g. photos, videos, sound recording, notes), on how often and how they want to record (e.g. every 5 min, every 10 min; frontal picture, or panorama).
- *Evaluative questions* – During the walk, students supplement the recordings with a few evaluative, location-specific questions that focus their attention on the socio-environmental-economic quality (very poor to excellent) of the surroundings. Students write down their answer every 200-500 meters also recording the location.

(2) Data analysis:

- Organizing data – After the walks, students organize their field notes and recordings. They create a virtual version of their walks bringing together recordings, GPS logs and their answers to the question.
- Analyzing data – Using a template, students describe surprising elements and observations and organize their data through the lens of sustainability.

Step 3: interpretation and reflection. In Step 3, students learn how to deal with the gap between sustainability concepts and the concrete instances of (un)sustainability they have encountered during their walks. In this process, they learn how to make use of sustainability dimensions (cultural, social, ecological, economical, etc). and principles as well as of systems features (e.g. feedback loops and cascading effects) when assessing instances of (un)sustainability. They also learn how to conduct a basic problem analysis of sustainability issues. The central output of Part II is generated in this step in the form of a narrative of the walk (Table 1):



Note: The mental map A is about the Phoenix metropolitan area. It clearly shows the prominence of the highway systems as well as the blurry definition of features inside the main sub-districts which students referred to as an image of the urban sprawl. The mental map B is about the Hamburg metropolitan area. Here, the city image is structured with a decreasing presence of landmarks from front to back. The upper image C represents the transect walks that a group of students performed in the Phoenix metropolitan area, whereas the image D represents the planned transect (red) and the actual path (black) with landmarks that a group of students at Leuphana walked in the city of Hamburg

Figure 4 Examples of outputs from mental mapping and walking activities in The Global Classroom

(1) Narrative of the walk: In their teams, students look into the data collected and organized. As a team, they produce a narrative of their walk by using the media and form that they think is most appropriate.

(2) Identifying, assessing and analyzing (un)sustainability:

- *Identifying sustainability issues* – with the help of the instructors, as well as based on specific criteria (e.g. harmfulness, urgency), students select some sustainability issues that they encountered on their walks (see Section 4 for specific examples);
- *Assessment* – students make use of sustainability principles to assess the sustainability issues selected (Gibson, 2006). Students elaborate on the purpose (the objectives), the subject (what is being assessed), the criteria (what the subject is being assessed against), the procedure (how is the assessment being conducted) and the results of the assessment (what are the outcomes) (Wiek *et al.*, 2017); and
- *Problem analysis* – also, instructors give the students some guiding questions to help them analyze sustainability issues in local contexts. For instance, the questions are about factors and adverse effects that manifest in environment, society and economy; underlying drivers and causes (i.e. historically, geographically); and affected stakeholders.

(3) *Causal systems map (optional):* See description above (see Part 1 – Step 3). At this point, it would be also useful to have students reflect on the importance of systems thinking in sustainability problem-solving, for example, for anticipating future trajectories from a systems perspective and for identifying intervention points.

(4) *Situating new experiences:* Students situate their individual experiences in a structured reflection process. On a personal level, students think about their experience in relation to different areas of the city. They also reflect on how their perceptions changed before and after the walks, as well as how others people's cultural, social and economic backgrounds affect their perceptions and experience of the urban environment and its sustainability. These reflections lead also to an understanding on how the uneven distribution of sustainability issues in the city influences local experiences of (un)sustainability.

Step 4: sharing. In Step 4, students advance their professional skills of presentation, communication and discussion as well synthesizing knowledge to gain a better understanding of (un)sustainability:

- *Presentations*: Students select, organize and present the results from their walking activities. This creates a space that facilitates discussion and comparison among students who have walked in different areas and who have used different objectives in their walks.
- *Class discussion*: The discussion focuses on the changes of perceptions of sustainability the students have experienced from the mapping to the walking activities fosters the capacity to connect the students' different experiences to the complexity of urban sustainability issues while paying attention to disciplinary, social and cultural

differences. Instructors facilitate the discussion after the presentation encouraging respectful communication, active listening, openness and curiosity.

Application of The Framework in The Global Classroom

The experience-based learning framework was developed in "*The Global Classroom: Liberal Arts Education in the 21st Century*", a project between Leuphana University of Lüneburg in Germany and ASU in the USA funded by Stiftung Mercator (Wiek et al., 2013). The Curriculum Reform Manifesto inspired the learning objectives of the project (Elkana, 2012). Revolving around the question "Sustainable Cities: A contradiction in terms?", *The Global Classroom* offered over 70 students a research-based, interdisciplinary, team-based and international learning experience in sustainability (Wiek *et al.*, 2013). In this project, two cohorts of about 35 students each, one half in the USA and the other half in Germany, made use of the experience-based learning framework. The first cohort used the framework in Spring 2013, the second cohort in Spring 2014.

The Global Classroom has a modular structure that spans over three semesters (Wiek et al., 2013). In the first semester, the authors used the experience-based learning framework before introducing sustainability concepts, perspectives and frameworks to the students. This way, the experience-based learning framework offered an introduction to sustainability that preceded and complemented the conceptual and theoretical introduction to urban sustainability (Wiek et al., 2013). In the remaining two semesters of The Global Classroom curriculum, the students engaged in joint projects in small groups. The experiential and conceptual introductions became the basis for the further development of team projects in the following modules (Wiek et al., 2013).

The framework presented is the result of a formative assessment conducted in *The Global Classroom*. The formative assessment consisted in monitoring students learning, providing students with structured feedback at the end of the mapping and the walking activity and students' feedback after the activities were completed. In the feedback, instructors asked students, first, to assess the expectations that they had before performing the activities; second, to report what they thought they had learnt after the performance of the activity; and third, to suggest ways of improving the activities. The instructors were able to improve the framework from its first implementation in 2013 to the second round of implementation in 2014 and the final version of the framework that the authors have reported here.

The following sections describe how students started developing key competencies for sustainability. Beside this process of competency development that was the object of formative assessment, in the course of *The Global Classroom* project, the instructors also observed how students made use of insights from mapping and walking in their final projects in the second and third semester of the course. In the second and third semester of *The Global Classroom*, students often relied on their projects on what they had learnt, for instance, students relied on the lessons learnt about teamwork during the mapping and walking activities. With the guidance of the instructors, they further developed their collaborative and intercultural skills. Also, when it came to assessing sustainability issues, they addressed in their projects, students often referred to the way they had identified and started appraising sustainability issues both in the mapping and in the walking activities (Brundiers and Wiek, 2013). Also, feedback loop analysis as well as insights that local instances of (un)sustainability emerge from complex dynamics became common approaches for understanding cause– effect relations. Finally, students also made use of the mental mapping and walking as methods for their own research. In some projects, students asked stakeholders to draw mental maps of specific neighborhoods to capture different perceptions of the urban environment. In other projects, students performed transect walks of the urban areas they were investigating to get acquainted with sustainability issues.

Initial Development of Systems Thinking Competencies

This section presents observations about how students started developing basic systems thinking, normative and collaborative competencies through the activities of the framework. Students used the mental maps with their different elements (paths, nodes, etc). to visualize the urban environment as a complex unit composed of many interacting components (Clayton and Radcliffe, 1996). Figure 4 shows two examples of mental maps produced in Part I of the framework.

These two maps show that, by reflecting on the maps, students started articulating basic structures (i.e. built environment and urban layout) and functions (i.e. infrastructure services, recreational areas) of the urban environment both in Hamburg and in Phoenix. For instance, from the overall shape and features of the mental maps, students reflected on mobility and built infrastructure for public transport (Schiller et al., 2010). In the case of Phoenix, the maps revealed the role of the highway system as the main mobility option, whereas in Hamburg, the role of public transportation was more prominent (Figure 4). Also, students started thinking about sub-urbanism and the urban sprawl and how these phenomena manifest in the two different national and geographical areas of Hamburg and Phoenix (Figure 4).

Mobility and transportation issues became an entrance point to introduce the idea of feedback loops and non-linear cause–effect relations (Iwaniec et al., 2014). For instance, reflecting on the importance of the highway system in Phoenix triggered conversations about how mutually reinforcing factors – economic interests (i.e. the automobile industry), values (i.e. individualism) and technological developments – contributed to the current situation in sustainability terms.

Following up on the reflections from the mapping activities, reflections from the walks encouraged an understanding of urban systems as coupled social, ecological and economic domains (Ernstson et al., 2010). For instance, students directly experienced the socio-economic nature of boundaries, such as highways running in the middle of low-income neighborhoods. They also observed segregation, mostly in Phoenix (Ross, 2011), and gentrification patterns, mostly in Hamburg (Kirchberg and Kagan, 2013). Students observed how sustainability problems are unevenly distributed in cities and how different social groups are located in relation to sustainability issues in the urban environment (Dempsey et al., 2012). Relying on their field-notes and on the answers to the main question (see Step 2 in Part 2), students were able to identify challenges across the different domains and how those affect the quality of the overall urban system. Discussions revolved around the main drivers of (un)sustainable development. Here, also the ideas of feedback loops and non-linear cause–effect relations became more concrete and grounded.

Initial Development of Normative Competencies

In Step 2 of Parts I and II, students reflected on their own position in relation to social and spatial contexts, and how this may influence what they perceive in their city. This reflection introduced the importance of diversity of social groups in both Phoenix and Hamburg and tied back to observations of structural inequalities (Bullard, 1994; Agyeman, 2005). Adding this component to students' reflection on their different experiences provided opportunities for building capacity to think about and include justice as a sustainability perspective (Adams et al., 2007).

In the evaluation of the (un)sustainability emerging in the mapping activities, students learnt about how to apply generic principles to specific contexts and how to negotiate different principles. They also developed a critical awareness about underlying assumptions and applicability of those principles (Step 3 in Part 1). In the transect walks, students applied the prominent set of sustainability principles compiled by Gibson (2006). Students learnt about how to apply generic principles to specific contexts. For instance, in Hamburg and in Phoenix, students connected the presence, absence or quality of ecosystem services in different neighborhoods to equity issues (Gibson, 2006).

Initial Development of Collaborative Competencies

In sharing the results of the mapping and walking activities (Step 4), both at Leuphana and at ASU, students could not rely on previous knowledge of each other's local contexts. They had to add explanations about habits and lifestyles as well as basic information about infrastructures and urban form. Also, students prepared the material so as to allow for an effective intercultural communication. For instance, they had to make sure to translate measurement units from one system to the other or not to make use of slangs or acronyms because of language differences (also native vs non-native). In this way, they started developing diversity and intercultural competence.

Students conducted the mapping and walking activities in small teams (Steps 2-4). Working in changing team constellations required the students to hone their capacities to contribute to successful teamwork as members and leaders, to be professionally accountable and to use reflective and communicative capacities. For instance, in this process, students learnt how to hold effective team meetings making use of meeting minutes and distributing roles (e.g. time keeper and note taker). They also learnt how to distribute roles and responsibilities in the development of their projects (e.g. project manager, communication manager and technology manager). They were encouraged to switch their roles and responsibilities in the different activities so as to be able to experience the ones that would fit best their personalities and working styles. Building both communicative and collaborative capacities prepared students for the final projects in *The Global Classroom* where they engaged in transnational teams composed of both Leuphana and ASU students.

Discussion

After the development and first implementation of the experience-based learning framework in *The Global Classroom*, it is important to reflect on the opportunity and challenges that emerge when trying to provide a summative assessment of the framework with respect to learning objectives and when trying to adapt it to different educational contexts.

Towards A Summative Assessment of The Framework

In the spirit of the constructive alignment theory, future implementations of the framework should include a summative assessment (Sadler, 1989). The formative assessment provided feedback to the instructors in the development of the framework (Sadler, 1989). The summative assessment would aim to evaluate to what extent the activities in the framework actually lead to the achievement of learning objectives, i.e. the initial development of systems thinking, normative and collaborative competencies. The problem of how to summatively assess competency development has been discussed (Barth et al., 2007; Remington-Doucette and Musgrove, 2015). Singer-Brodowski (2015) asserts that, although existing case studies describe sustainability students' learning, a lack of systematic analyses about conditions for and processes of competency development in sustainability courses is still lacking.

Assessing the actual learning outcomes bears some challenges. First, deciding on indicators of students initial development of competencies is a difficult task, though one could rely on a recent operationalization by Wiek et al. (2015). Second, assessing whether this initial development can be attributed to the activities of the framework is challenging too. Yet, the authors are confident that existing assessment methods can support a summative assessment (Barth and Michelsen, 2013; Barth, 2009; Barth et al., 2007 Remington-Doucette and Musgrove, 2015; Remington-Doucette et al., 2013).

Remington-Doucette et al. (2013) and Remington-Doucette and Musgrove (2015) assessed the level of key competence among the students by having them analyze a case study at the beginning and at the end of the course. The case study was structured in the same way by describing a sustainability challenge, presenting a solution option and introducing key stakeholders. Students had to respond to a set of questions that aimed to capture the development of several key competencies (Remington-Doucette and Musgrove, 2015). Recently, Singer (2015) has proposed a qualitative approach to capturing competence development. This approach brings together:

- students' self-description, i.e. their subjective perception with regard to their own competency development; and
- reconstruction of learners' competent action in the relevant real-life situation with the goal to empirically reconstruct students' competency development.

In combining the two approaches, Singer makes use of several methods, such as interlinked surveys (group discussion, interviews and video recording) and most importantly action validation following up on students' real-world planning activity with reflections on their own learning. Both the action validation used by Singer (2015) and the case study approach used by Remington-Doucette et al. (2013) and Remington-Doucette and Musgrove (2015) provide starting points for the summative assessment of the experience-based learning framework.

Application of The Framework In Different Contexts

Although the experience-based learning framework was developed in a specific setting, here the authors suggest that instructors could use the framework in different higher education settings (e.g. large introductory classes and campus initiative) as well as in high-school educational programs and other project-based learning projects. This section presents three exemplary applications.

Instructors can adapt the framework to larger introductory classes in sustainability, where real-world experiences are more difficult to organize (Remington-Doucette et al., 2013). For this, instructors organize the activities in two different formats. Instructors can use Steps 1 and 2 of the framework in plenary sessions. Steps 3 and 4, which require a more active interaction of students and instructors, can be organized in smaller lab sessions with the help of teaching assistants previously trained in the use of the framework. Instructors can also use the framework in sustainability campus initiatives (Alshuwaikhat and Ismaila, 2008). The campus would represent the overall system in which students perform both mapping and walking activities. Following the different steps of the framework, students can capture sustainability issues on campus and start assessing them. The framework encourages students to research and develop new approaches and ideas about specific sustainability issues. Besides building a community of students who are engaged in ameliorating their campus, students can start engaging with appropriate faculty and staff to implement their ideas (Alshuwaikhat and Ismaila, 2008; Barr et al., 2014).

Instructors could also use a simplified version of the framework in educational programs that aim to introduce sustainability to high school students. The framework can help students understand complex, global issues by engaging with sustainability at a local level. The use of the framework can also serve to develop a community of engaged students as well as a sense of place both with respect to their school and to the surrounding community (Barr et al., 2014). Adopting the framework to this context requires to carefully organize the reflections and discussions limiting abstractions and making sure the students can continuously refer to their own personal experience.

As a third example, the framework could also help to facilitate shared understanding of sustainability issues and collaborations in other project-based learning formats such as transdisciplinary projects. In their initial phases, most transdisciplinary projects struggle with the elaboration of a shared research framework as well as with the creation of a collaborative research team (Lang et al., 2012). The experience-based learning framework could be used to facilitate both processes. The mapping exercises would let differences in perception among the different stakeholders emerge. Reflecting upon those could lead to a shared understanding of the local environment as well as of the sustainability issues that need attention (Clark et al., 2011). Following up on the mapping exercises, the experience of the walks – implemented by reflection and discussion moments – could help to further create a shared understanding of those issues. With its focus on collaboration, the framework could also facilitate communication and collaboration between professional academics, local communities and societal stakeholders (Lang et al., 2012).

Conclusions

In the context of the Global Classroom, the authors have created and implemented an experience-based learning framework that facilitates the first encounter of students with sustainability. The framework complements existing educational approaches in higher education for sustainability. Other programs and institutions may be able to use the experience-based learning framework as a complementary tool for the introduction of sustainability to students from different social, cultural and disciplinary backgrounds in international and intercultural settings. This article has presented how experiential, student-centered and bottom-up approaches can support the initial development of systems thinking, normative and collaborative competencies. The critical review of the implementation of the framework in the Global Classroom points out that the experience-based learning framework would benefit from a summative assessment as well as from further implementation in different educational settings. The step-wise organization of the framework presented in this article can inform and support further attempts to transfer experience-based learning activities in different educational contexts as well as in real-world transdisciplinary projects.

CHAPTER 5
Synthesis

Linking Representations for Sustainability

The purpose of this dissertation is to cultivate a better understanding of how representations and representational practices can be used in analyzing, envisioning, and engaging sustainability in order to develop a stronger basis for its application in methodological approaches as well as in mutual learning processes. In this chapter, I will demonstrate that functions and purposes that functions and purposes of representation and representational practice are already inherently included in knowledge processes. Within that context, they act as mediators, interpretative descriptions, communication tools, and experiments. In addition to the current use of representations, the case studies analyzed demonstrate that, in most cases, representational practice is carried out by individuals or groups of homogenous background; therefore, within learning applications, the use of representations tends to take place in a context that lacks an integrative, competence-oriented approach.

A number of major findings emerge that allow novel connections and applications of representations for sustainability: (i) Representations serve as tools for exploring and understanding global theories and concepts, while at the same time they focus on local context and realities which requires compatible (or even competing) representations. Competitiveness and comparability are useful to illustrate and explore complexity, as the urban metabolism models show; (ii) Understanding options within representational practice offers a way to change usage patterns such that they better represent knowledge types for problem-solving. For example, in visioning exercises, the final product of a desired future target state becomes a procedural product that may be changed and adapted according to the transformation's progress. It is also the case for the work in semi-immersive decision-visualization environments, where different practices and standards converge that affect how knowledge is represented. (iii) In all knowledge processes, co-production and participation connect to mutual learning that can be facilitated by representation and representational practice. Mutual learning with representational practice includes developing an understanding of and recognizing the local placement of sustainability problems and solutions. In participatory processes, representational practice can support the development for reflexive capacities.

Representations in Knowledge Processes

To Analyze

Analyzing past and current states of a society's relevant sustainability problems essentially revolves around finding a functional and pragmatic way to comprehensively describe complex cause-effect relationships and identify possible intervention points (Fiksel et al., 2013; Meadows, 1999). Increasingly, descriptive-analytical knowledge generation is coupled with the larger goal of implementing sustainability solutions, requiring the use of analysis tools to integrate a broader variety of aspects such as norms and values or perspectives from different actors (Jerneck et al., 2011; Miller et al., 2014). These analysis methods, in turn, are embedded within a larger transformational methodology in which pragmatism, cognitive distance, and conceptual open-mindedness between participating groups (as well as interdisciplinary ontologies and heuristics) converge.

Urban metabolism research provides a robust framework to frame such descriptive-analytical knowledge about the complex dynamics of cities and increasingly engages with a sustainability perspective. Focusing on contexts, products, and methods of urban metabolism research, John et al. (2019) uncovered distinct but partially overlapping topical clusters that provide substantial knowledge for the material basis of sustainability solutions without being fully connected with the field of sustainability research. Despite broad application areas and many years of expertise, the value of participatory processes for data collection and evaluation has not thoroughly pervaded the field of urban metabolism research. Subsequently, methods and results are not fully applicable at the science-society-policy interface. Advancing a sustainable urban metabolism means i) engaging in normative discussions about (un)sustainability from various positions, ii) capacity-building to understand the problem being addressed, and iii) linking the problem to a sustainable solution (John et al., 2019).

Urban metabolism research focuses on the functioning of a city "manifesting itself in flows and stocks of materials and energy" (Baccini and Brunner, 2012, p. 30). This approach builds a theoretical base by structuring and assessing all human activities in the form of metabolic processes, represented by indicator substances for a certain system and spatial scale. An urban metabolism therefore qualifies as a model, because it is "an interpretative description of a phenomenon that facilitates access to that phenomenon" (Bailer-Jones, 2008, p. 108). The models of urban metabolism have a representational value as mediators aiming to encompass highly aggregated flows (e.g., emergy). They are capable of providing a comprehensive view of the city as well as focusing on smaller-scale activities such as water management systems or food sourced nitrogen flows (c.f. John et al., 2019, Table 2).

In doing so, they abstract and simplify the complex cultural processes of the city that led, in part, to the shortcomings mentioned above; that is, they connect descriptive-analytical knowledge with sustainability. Simultaneously, the urban metabolism approach carries representational value as a metaphorical model, allowing the exploration of areas by "piecing together ideas based on analogies of better-analyzed empirical phenomena" (Bailer-Jones, 2008, p. 119). The term "metabolism" was coined from the understanding of metabolic processes of living organisms present in the fields of biology and ecology organisms (Fischer-Kowalski, 1998). This analogy was further developed to include the interpretation of human activities and inherent relationships, e.g., to clean, to reside, to transport, etc. (Baccini and Brunner, 2012; Bailer-Jones, 2008). Those fields that principally address integrative views of planning and management, policy, and decision-making combine data with discursive elements, effectively applying the metaphors of urban metabolism theory toward methodological innovation and including sustainability design or assessment criteria. By covering all the aforementioned features, urban metabolism serves as a perfect showcase for representations related to sustainability.

The value of the model as mediator lies not only in its ability to translate developed theories and to operationalize measures, but also in describing areas that do not yet have a robust empirical and theoretical foundation (Morrison and Morgan, 1999). Therefore, in complex sustainability problems where multiple theories converge with local realities, different types of models can support (i) conceptual framing to refine the problem and select appropriate methods, or (ii) formal systems thinking to uncover and validate relationships of the problem (Bergmann et al., 2010). The use of these models is paired with a strong exploration component and methodically implemented in the form of iterative integrations, which fosters enough agility that the models can be applied with diverse kinds of knowledge sources at the science-society-policy interface. This application is Morrison & Morgan's understanding of models as "autonomous agents" in the broader context of problem-solving (1999, p. 10) in which they allow models as representations to simplify, idealize, and show just a section of the whole system. In this situation, models function simultaneously as a means, a tool, and an object of research. Such an understanding makes models an important authority for the identification and framing, description, and interpretation of sustainability problems, especially for transdisciplinary research approaches (Bergmann et al., 2010). Looking at urban metabolism research with this augmented perspective for models shows that the tools (i.e., models to measure and explore) exist in abundance, but the available research designs still seem impractical from the standpoint of sustainability.

After having distinguished between different kinds of models acknowledged in urban metabolism research, the field also achieved a state where these models can coexist. The cluster distribution (John et al., 2019, Figure 1) displays this parallelism along the y-axis, where analyses at the city level (with highly aggregated flows and subsystems with distinct flows) contribute to the knowledge about the material basis of the city (see clusters “energy,” “ferrous,” “nutrition,” and “recovery”). Along the x-axis, clusters are overlapping with different perspectives and explanatory patterns, e.g. in decision-making and management practices (see clusters “footprinting,” “decisions,” “integrative”). These contrasting observations within one field can be explained with Mitchell’s (2004) “integrative pluralism” that accounts for the diversity of representations, either compatible or competitive, and which values their importance for insights in such a complex topic like cities. For example, along the y-axis, models provide compatible explanations about stocks and flows in the city along the varying scales of the system. Their insights are not mutually exclusive even though they ask similar questions about material and energy flows of the city. Along the x-axis, there are a number of competing models addressing similar questions about the same urban scale of city from varying perspectives. This competitiveness, based on a high number of case studies, is valuable in producing empirical evidence and explanations on the concrete level of complex systems; eventually, it helps us to understand the (historic) causal relationships of problems, and it influences the diversity of solutions (Mitchell, 2004). In the interdisciplinary field of urban metabolism, the integrative pluralism of models delivered a conceptual and methodological strength to make sense of the diverse research about complex urban system. Connecting sustainability and urban metabolism theory with new types of specific cases addressing the principles of equity and justice, or transformational practical outputs, should also be located under the account of pluralism.

To Envision

In sustainability research, envisioning is seen as a self-determined, empirically informed activity undertaken to shape the future toward a desired outcome (Wiek and Iwaniec, 2014). Hence, the visions themselves are supposed to have a proactive, motivational effect on the activities that lead to that new future. This understanding fundamentally differs from the historical view where the vision was provided by the expert, (i.e., the Delphic oracle of classical Greece, whose proclamations reflected immutable destiny). With regard to generating evidence-based target knowledge, however, visioning has systematically been merged with scientific practices and shaped through quality and design requirements (Wiek and Iwaniec, 2014; Wiek and Lang, 2016).

The study of urban visioning projects focuses foremost on procedural aspects, the surrounding conditions of visioning exercises and methods, and their influence on the sustainability in the vision itself. Within this context, it became clear that there are deficits in crafting a comprehensive sustainability vision that is systemic in focal spatial scale, embedded into the region, and balanced with regards to sustainability principles. Furthermore, visions (despite participation level and the diversity of actors involved) tend to relegate future responsibilities to the collective, institutional level, and tend to discount the contributions of individuals. This discrepancy compromises their quality of being shared and motivational. Counteracting such deficits requires that visioning exercises review certain generic method modules, such as preparatory sustainability understanding and the participatory component (John et al., 2015).

In order to rethink visioning activities, it is appropriate to conceptualize visions through representations. Visions can be considered a subset of images. Images are both internal mental representations and external pictures and visualizations; they have normative connotations, a mobilizing power, are capable of simplifying complex phenomena of the real world, and are culturally embedded (Beers et al., 2010). Very similar characteristics also describe visions, such as the idea of mobilizing change, serving as a beacon, and motivating innovative and purposeful actions. Often these two terms are implicitly treated with conceptual vagueness, and hence they are used interchangeably (Shipley, 2002). However, visions are clearly related to a future target state, and especially in the context of a sustainable future, they have a positive connotation, which is by definition not the case for images.

Visions, understood as representations, offer an effective and less demanding way to communicate and enhance understanding of the normativity and complexity of future sustainable states (Beers et al., 2010; Mößner, 2018). In visioning exercises this is demonstrated by the way the sustainable built environment is emphasized and illustrated (John et al., 2015). Participants are empowered to make clear connections from their current situation to their future by employing images that can store relatively large amounts of information. They may also rearrange them to focus on certain aspects and highlight particular elements in a comprehensible way. The tangibility that is achieved through visionary images interlinks participants' backgrounds with expert knowledge. For example, everybody is surrounded by the built environment and can contribute background knowledge to the discussion; this discussion is subsequently reviewed through using the principles of sustainability as a reference point. Tangibility is a key aspect in facilitating acts of comparing, forming relations, and working cognitively with visuals (Mößner, 2018). This means that visions are, first, a lens that explicates mental images and helps to relate abstract sustainability principles to personal perceptions and experiences of the built environment; second**,** visions serve to make mental images manifest, in their full complexity, at the urban scale. John et al. (2015) show that the complexity of, for example, a sustainable built environment and sustainable social and cultural processes are not equally well interpreted to the extent that the sustainable urban material basis and connection to its hinterland are not sufficiently covered in visions.

Visioning exercises can be seen as exploratory processes in which images are developed and applied to support participants as they reach insights about how to develop a sustainable future, that is, surrogate reasoning; such exercises can also be as well as where used as tools to unlock creativity, inspiration, and anticipation (Mößner, 2018; Suárez, 2008). Since visioning has developed into a method requiring broad and diverse participation by citizens and practitioners of diverse backgrounds, the quality of the final output has been discussed with regards to being comprehensive, systemic, and effective (Wiek and Iwaniec, 2014). Shipley (2002, p. 15) summarizes this critique, pointing out that the physical and social complexity aggregated into one shared, coherent, and uncontested vision is not implementable without larger trade-offs, which renders visions based on broad participation "either impossible or ineffective." Results about participation in John et al.'s study (2015), where small-sized expert communities representing a high diversity of actors yielded more coherent results than processes with large numbers of people, have been similarly regarded. These insights matter for the exploration of visioning exercises on several levels: first, having such quality criteria for final visions in place means that participants need to be provided with guidelines that limit, define, and enable relevant and intended inferences exploration, or surrogate reasoning (Suárez, 2008). Guidelines for sustainability visions, such as normative and construct qualities namely "systemic" and "sustainable," already exist (Wiek and Iwaniec, 2014). However, seeing visioning as an exploratory process with heterogeneous groups means that these guidelines need to be universally understood and are not exclusively for the researcher to apply and ensure after the fact. Ideally, as part of this process, participants internalize these guidelines and integrate them into their own background knowledge, thereby acquiring experiences to assess more complex concepts (such as regional resource connections with the hinterland, for example).

Exploration aiming for a single aggregated vision can be seen as directional understanding. For example, a group of people may use narratives and visuals to represent a sustainable city in 2050 as a target for a sustainable transformation (c.f. Giere, 2004). However, the various visioning methodologies and existing stepwise procedures suggest that these exercises are far richer than mere translations. If visioning exercises are understood as constant reconstructions through representational practices, the resulting stepwise procedural understanding becomes a source of improvisation and creativity (Bailer-Jones, 2008; Lynch and Woolgar, 1990). Latour (2000) extends this procedural discovery based on his observations in interdisciplinary research in the Amazon forest. He draws important insights that can be applied to visioning exercises as well, arguing for an intentional transformation during different stages of abstraction and construction that can be extended indefinitely. This is more congruent with envisioning a desired "moving" target that is not finite but adaptable, which changes over time because of actions undertaken upstream. In Latour's infinite chain of elements, as well as in Shipley's (2002) vision research, the evidence that was developed intentionally, e.g., along different social processes or about mental representations, keeps "circulating," or remains influential, even in a follow-up vision.

To Engage

Engaging is part of generating transformation knowledge and building sustainability solutions. Actionable knowledge develops "under real-world experimentation […] and continuous adaptations" (Wiek and Lang, 2016, p. 32) supported by the necessary evidence for a successful transformation of the problem. The challenge here is to bring the global level, e.g., universal theories, statistical data, and generalized concepts, together with the local level, i.e., small-scale, context-specific experimentation (Forrest and Wiek, 2014; Lang et al., 2017). This means considering a variety of models as "mediators" toward that end, as well as computer simulations as "quasi-experiments" that support the discovery of alternatives and potential development pathways (Bergmann et al., 2010; Lang et al., 2017). Computer-aided processes, semi-immersive decision-visualization environments provide such a local-to-global space for various transformative practices of exploration and experimentation.

Decision-visualization environments provide infrastructures in which "engaging" with transformation knowledge is not only accompanied by research, but also allows for planning, decision-making, and design. The core element of these environments is purpose-oriented visualization to catalyze communication and sense-making processes. Current practices of decision-visualization environments demonstrate the interdependence of visualizations, a facilitated process, and a user interface, while showing the overall potential of this combination for creating a transformative experience for its users. Despite that potential, the comprehensive design of these three elements is still in its infancy, particularly when it comes to facilitating individual or collaborative exploration processes with practitioners and integrating visualization into an inclusive narrative or storyline that mediates between mental models and the output-oriented purpose (a sustainable city development plan, for example) (John et al., submitted).

The decision-visualization environment can be considered an infrastructure that is dedicated to representations and representational practice that mediates between the scientific sources of particular problem constellations (e.g., data about climate adaptation potential), and the purpose of contextualizing and applying (e.g., resulting in a strategic urban planning decision) in a comprehensive way. Visualizations of different functions make up the most important representation within this space (John et al., submitted). Despite the prevalence of visualizations, it is the composite of (i) scientific exact representations with (ii) narratives that activates a series of cognitive processes and affects, and (iii) offers a space for new heuristics for exploration of patterns and information (Goodwin, 2009; Shaw et al., 2009; Vertesi, 2014) that makes the decision-visualization environment a unique artifact offering a practice of representation. Simulations, virtual/augmented reality, 3-D renderings, and other digital imagery emphasize the computer not as a revolutionary, but has developed into an indispensable, means for digital representational practice.

Since engaging the transformation knowledge emphasizes processes of knowledge generation, it is more useful to understand the representational practice in a decision-visualization environment as a whole, and not to focus on singular representations as outputs (i.e., specific types of images or graphs). The sequences or narratives of representations are very effective in that regard, because they are compiled in a distributed and associative manner (e.g., they display information as a mental map and interconnect it in a story with repetitive moments [Latour, 2014]). To foster associations and make connections between new information and experiences is part of natural "mental activities such as inferencing, category formation, and so forth," (Bransford et al., 2000, p. 127) and visualizations of such sequences support these mental activities by clarifying details and helping to compare and discover relationships, all in one location. Additionally, gesture and language commands, interactive touch displays, and user interfaces simplify live manipulation of visualizations (e.g., changing input data of line graphs and mapping data points on maps). Sequences are no longer a predefined convincing line of argument, but emerging decisions or hypotheses can immediately take on a certain shape and show causal relationships and co-occurrences. For example, a group of urban planners can map their collaborative decisions about urban greening into a 3-D model and instantly see the mediating effects on urban heat and groundwater management. They are then free to discuss the resulting legal, institutional, or other effects. Manipulations are part of a chain of changes with "circulating" references to interlinked consequences and concepts, and therefore they are very important in the representational practice for the sense-making process (Latour, 2000).

The representational practice with sequences of visualizations serves the knowledge generation, but it is also a communication tool between all participants, both researchers and practitioners (Lange, 2011; Mößner, 2018). However, the cumulative effects that visualizations can develop, the challenges they can pose before they are correctly decoded, and the computer as automated autonomous filter "choosing" the correct representation, should not be underestimated. These can lead to severe effects on the participants not trusting data and corresponding insights. A lack of transparency about how simulations are created can hinder the development of ownership about sustainable actions or prevent a certain group of people from engaging in debates (Kemp, 2014; Sheppard, 2015). Thus, the form and style of interaction, as well as empowerment and background knowledge determine how transformative the experience of the decision-visualization environment will be (Sedig and Morey, 2004). Publications with a focus on representations depart from interdisciplinary researchers that have a set of core competences that allow them to quickly adapt to new visuals while maintaining the necessary critical distance. Representations at the science-society-interface are, in most cases, reduced to “transmitting information to the interested public” (Mößner, 2018, p. 334). Engaging in transformation knowledge together with practitioners requires professional facilitation and is designed to accompany representational practices by providing the necessary support during encoding and decoding the visual information (Brundiers et al., 2013; Nerantzi et al., 2014; Rowe, 2005).

Table 4 Gaps and overview of synthesis organized after knowledge processes and learning

		Paper 1 To Analyze	Paper 2 To Envision	Paper 3 To Engage	Paper 4 To Learn
Gap		Knowledge processes to produce sustainability solutions requires interdisciplinary theories and methodologies that are able to integrate contested norms and values, and increase legitimacy and transparency to make solutions more salient and credible and thus actionable. Knowledge processes, such as to analyze, to envision, to engage, as well as the three generic knowledge types are mutually dependent. Currently, individual types of representations are rather applied and valued for their effectiveness in specific contexts of knowledge processes, while learning throughout the knowledge processes is considered a crosscutting approach utilizing selected types of and mechanisms. However, representations and representational practice have a broader set of characteristics and mechanisms that are able to universally mediate and organize between theories and real-world, between disciplines, and between different kinds of actors at the science-society interface.			
Characteristics and mechanisms of representations and representational practice	*Type* *Purpose* *Organizational Role* *Relationship* *Functional Role* *Process*	**Representation** Type/Purpose: model to operationalize measurement, application of laid-out "stocks and flows" theory to gather empirical evidence about cities; metaphorical model: innovation and experimentation by finding new connections through comparison and analogies of metabolism metaphor; Organizational Role: high diversity of parallel models with different idealized segments of the urban system, enhancing a comprehensive view and addressing the complexity of the urban system; shows interpretative flexibility about urban dynamics.	**Representation** Type/Purpose: Subset of images, mental images and external visualizations; purpose of communication of the final vision; purpose of exploration during the process. Images less demanding communication and sideway to normativity and complexity, while storing high amount of information particularly arranged, focused, or reduced;	**Representation** Type/Purpose: Facility as space for representation and practice; hosting all computerized representation and all purposes, mainly models, simulations, with purpose of exploration and experimentation; visualizations with purpose of communication between actors;	**Learning about:** Simplification, idealizations, reduction and focus, etc. is essential contributor to all knowledge processes and as such support learning about factual knowledge about sustainability (visual literacy).
		Practice Relationship/Functional Role: Highly systematic and formalized encoding and decoding through modelling in established methodological frameworks; high level of expertise is needed and excludes non-experts. Practice insufficiently covers a shared framing and interpretation. **Learning:** Factual knowledge (analysis) of the urban system; Mutual learning component is not facilitated	**Practice** Relationship/Functional Role: Multi-way relationship with many actors participating. Unrestricted use to unlock creativity, inspiration, and anticipation; Diversity of encoding/decoding expertise actively utilized and cultural embeddedness is deliberate. Process: Exploration of the future in process of constant reconstruction would allow for crafting a "moving" desired target state. **Learning:** Background knowledge is important to make right/intended inferences about sustainability and to provide tangible mental images to the discussion; Mutual learning for all actors at the science-society-interface necessary to draw from social complexity; Tangibility of images facilitates acts of comparing, relating, and cognitive work; Facilitation and moderation is required for effective representational practices.	**Practice** Relationship/Functional Role: Multi-way relationship including many actors and the computer as filter; encoding process utilizes narratives and storylines with sequences of visualization for high tangibility of content; decoding is not achievable without facilitation which enhances the background knowledge for correct usage and transparent reasoning Process: focus on easy, immediate manipulation of representations, interactive constant reconstruction in parallel processes simplified by representations the complexity of sustainability solutions and implications for cultural, institutional, administrational spheres. **Learning:** new set of background knowledge, to decipher the content, its production, and engage meaningfully into the digitalized, computer-aided process; increase transparency, saliency of the contents in order to provide access to debates about sustainability	**Learning through:** Exploration and experimentation are in all three knowledge processes the active mode of learning and representational practice. Important capacities (i.e. background knowledge) include how to design/manage a good representational practice (design for constant reconstruction, integrative pluralism), and develop critical comparing, referencing, reasoning to encode and decode representations given digitality, big data, code of ethics. **Learning with:** Advancing representational practices from individual to a collaborative and collective method (mutual learning); This develops skills/capacities/competencies for facilitating, managing dialogue, critical reflection, and build a part of the base of "background knowledge".

Representations in Learning Processes

Learning with regard to sustainability and transformation is not restricted to students in higher education; they are one group of many at the science-society-policy interface whose core competencies and capacity building require advancing in order to analyze, envision and engage with sustainability problem solving (Wiek et al., 2011). Learning about sustainability in a participatory setting at this interface, or "mutual learning," becomes repeatedly apparent in the studies discussed above. However, there are three major areas of learning, namely *about, through,* and *with*. The first area is the factual side of recognizing complex sustainability problems and solutions by attributing meaning and relevance through engaging in a dialogue and co-production between local contextualized practical knowledge, global potentials and challenges, and scientific concepts (Hirsch Hadorn et al., 2008b, p. 25; John et al., 2015). For example, this takes place in a model with discrete event simulation in order to enhance problem and strategy awareness about urban water management for decision-makers (Huang et al., 2007). The second consists of finding modes and methods for informal and formal activities of exchange and exploration to elicit new knowledge and innovations (Polk and Knutsson, 2008). This takes place, for example, through specific initiatives of experimentation to understand the barriers and necessary changes of political dynamics of resource flows (Hodson et al., 2012). Third is the critical reciprocal and reflexive process that takes place in a collaborative environment embedded into participatory settings**.** Within this process, an individual makes use of their interpersonal skills and reflective capacities to articulate, negotiate, and navigate their own backgrounds with regard to the belief and value systems of others (Lotz-Sisitka et al., 2015; Wittmayer and Schäpke, 2014). For example, this occurs in urban visioning through multi-level organization of teams where they provide a mix of skills while ensuring a functional checks-and-balances (John et al., 2015; VisionPDX, 2007).

The experience-based learning framework is an integrative learning activity that translates aspects of analyzing, envisioning and engaging into learning targets involving systems thinking, normative thinking, and collaborative competences development. The framework focuses here on the context of higher education, but its activities are drawn from a wider range of research practices, such as field ecology, anthropology, and social sciences, and thus is not limited per se to the target group of students (Felson et al., 2013; Kohler, 2012; Lynch, 1960). Mapping and walking activities capture perceptions and information about the complex urban environment through drawings, photography, and geospatial visualization. In reflective activities, the individual and group perspectives are compared and critically assessed against generic sustainability criteria. The framework draws on an active mode of enabling students to understand larger conceptual underpinnings as well as their real world manifestation (Caniglia et al., 2016).

Mapping, like walking activities, principally makes use of different kinds of representations. A paper-pencil representation brings the student in direct contact with the medium. A camera lens, photographs, and videos make them understand how reality can be cropped and focused. The digital designing of a sequence and storyline of several representations functions along similar lines (Suárez, 2008). All these representations serve as mediators between concepts of sustainability and a target of the real world (urban) system. For example, generations of urban planning students have employed models (marquettes**)** to study zoning, microclimate, and wind streams. From such models, students acquire knowledge about systems, feedback loops, and other basic phenomena and conditions for urban design. For sustainability problems and solutions, it is equally important to find representations, similar to those found in an experience-based learning framework, that mediate uncertainty and diverse (possibly contentious) perspectives in highly contextualized cases. Bringing these into curricula with a set of activities will support *learning about* sustainability, while teaching students to visualize data ethically and responsibly (Evagorou et al., 2015; Mößner, 2018).

However, applying these representations in a learning process emphasizes that the chosen representational practice is as relevant as producing a correct, realistic representation of the urban system. Engaging in representational practice requires literacy in reasoning, the possibility to explore develops background knowledge and reflexive capacities that are necessary in order for students to use and build their own representational capacities. This corresponds with the idea of *learning through*, which is not about “reproducing supposedly correct answers, [but] to may or may not find meaningful answers through […] research,” (John et al., 2017, p. 71). The experience-based learning framework provides steps in both walking and mapping activities to learn by collecting, analyzing, and sharing individual and collectively produced knowledge (Caniglia et al., 2016). In particular, walking activities point toward the vast array of images and software tools at one’s disposal to manipulate data by cleaning it up or by color processing (Kemp, 2014; Mößner, 2018). As Mößner (2018) states, the responsible and accurate application of data (as well as interpretation) can be subsumed under a “visual literacy” that requires training, materials, and curricula (Evagorou et al., 2015). However, in a knowledge society, visual literacy is interdependent with data and digital literacy; all three types of literacy are predicated upon software skills, a critical distance vis-à-vis the technology, and a reflexive capacity about the data and its context, and all three are crucial to effective participation in both virtual and real environments.

Representational practice with a focus on social and epistemic process can support mutual learning and *learning with* and from others. The role of the collective and collaborative learning aspect has not yet been prioritized with representation literature; they have been exclusively considered for the explanatory functional role and intra-collective communication (Mößner, 2018). For problem-solving, all knowledge processes presented above require a mutual learning component at the science-society-policy interface that has not yet been consistently implemented, similarly to the area of urban metabolism. However, the implemented tools are not fully taken advantage of, either in practice (to foster mutual learning) or for the development of theories on effective collective representational practice.

In its efforts to develop intercultural communication skills as well as normative competencies, the experience-based learning framework demonstrates how well mediating characteristics and negotiation activities build critical reflection skills in students (as compared to their peers). These include non-violent communication skills, which may be simple but are also a step toward the development of greater skills that help participants from all societal spheres to recognize, articulate, and negotiate values and perspectives in larger participatory processes.

In Sum: Interlinking Representations

Using representations and representational practice as a lens for looking into the knowledge processes of *to analyze, to envision,* and *to engage* is a first step toward assessing what these practices can contribute to methodological approaches and mutual learning processes toward the development of sustainability solutions. Major links discovered during the synthesis are indicated in Figure 3, and Table 4 provides an overview of the synthesis.

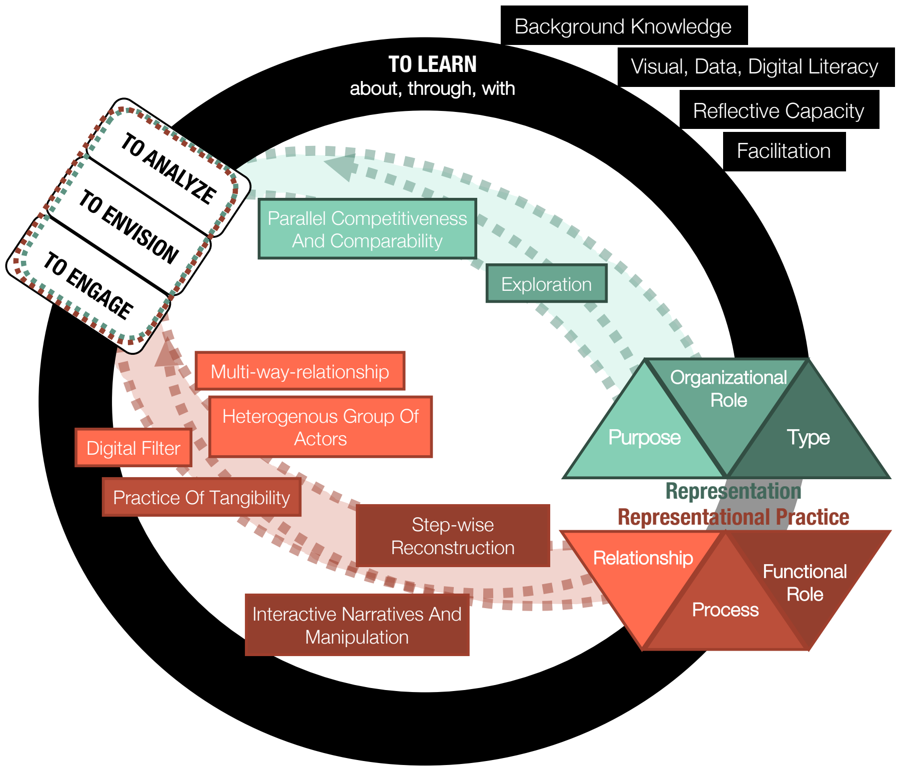


Figure 3 Conceptual frame with three knowledge processes to analyze, to envision, and to engage; interconnected through learning; specified characteristics and mechanisms of representations (green) and representational practice (red) considered as tools to enhance all three knowledge processes; resulting in specific implications (black) for learning.

The three studies are a first inquiry into the given possibilities and current examples of representations. This first step reveals important functions and mechanisms as well as a diversity of representations that contribute to knowledge generation. Models, metaphorical models, images, and simulations all belong to this family of representations, and all of them possess a strong visual component. Within the three knowledge processes, they take on a critical mediating role and support the understanding of sustainability and actions.

The previous section points to elements of representational practice. Although they haven't yet been applied in this context, each of them has the potential to fit across all knowledge processes. Exploration has played an important role in different practices. The ability to formally, conceptually, or creatively use exploration seems to be an essential vehicle in all three applications to uncover new connections, innovate, and communicate. Similarly shared is that powerful mediation in representational practice has a mode of constantly stepwise comparing and constructing, subsequently moving towards the target; this position is a procedural, inferential, constructivist understanding, and opposite to a mechanistic view. Despite that, different knowledge processes specify this with distinct additional practices: (i) a practice of parallel competitiveness and comparability to (un)cover evidence and relationships, (ii) a practice of tangibility to allow for comparison and references to deviate from the known towards the unknown, and (iii) interactive narratives and manipulation to make consequences transparent. These three should not be seen as exclusively bound to one specific knowledge process, but rather as a universal source to modify current representational practices in general.

If all three knowledge types are linked by mutual dependencies and serve overall the same purpose of problem-solving, one might point out that the corresponding representational practices should be similarly designed and understood in order to deliver compatible results. This would imply that either one representation or the above-mentioned mechanisms apply throughout the knowledge processes. The urban metabolism models, for example, show particular shortcomings in that regard. This unification carries important insights for transfer and scaling of methods and results; however, sustainability problem-solving and strategy building is not a linear process. To address their complexity and adaptivity, it is the mechanism of competitiveness that allows a group (coming from highly diverse perspectives) to analyze, envision, and engage with competing representations that might deliver more robust solutions. Applying the idea of such integrative pluralism, which mediates and makes both mechanisms explicit, should occur both in order to solve a specific problem and also to move from a global, theoretical level to the more concrete level of an individual case study.

For all the simplification, dense information, and connotations that representations are able to encode, an effective and successful mediation increases with the kind and level of background knowledge. Managing consciously different aspects of background knowledge also means managing the diversity of backgrounds present in larger processes. First, "background" includes both the methodological skills (to design a purposeful representational practice) as well as the experience to participate in such a method; it relates to visual literacy (to build ethically responsible representations, as well as understand their origins and production); and it relates to factual knowledge about sustainability, justice, etc. Second, background knowledge captures a set of competencies that help in sense-making of new knowledge gained during representational practice, and which matter greatly to create successful mutual learning in a participatory environment. This includes interpersonal and collaborative competencies that allow for i) effective collective, inclusive dialogue and negotiations and ii) the reflective capacities to articulate and understand one's individual perspectives in reference to those of others. Aligned, they form the *learning through* and *learning within* practices, and they are present in both dedicated educational experiences and the science-society-policy interface.

An increasing diversity of representations and backgrounds (in the form of skills and experiences) requires committed facilitation that supports the representation in the mediating tasks. In participatory processes, it is not often possible to be able to rely on a coherent homogenous level of background and core competencies. Therefore, representational practice needs to extend its procedural view to include empowerment. Facilitation and moderation in a knowledge and information society are not carried out only by trained experts, but, increasingly, by audio-video material, self-guided gaming, or language and gesture movements integrated in user interfaces that guide and restrict the range of actions (and limit the user's margin of error). The role of the computer includes software, applications, technology, and has expanded beyond the production of representations (e.g., computerized simulations, geo-spatial mapping, virtual reality). The computer was introduced as a tool of representational practice decades ago, but has not been sufficiently acknowledged as an individual autonomous factor in human-computer-content interactions, despite the standardization of artificial intelligence and neural networks, even in home appliances. The inclusion of the computer into mediation processes inevitably reduces transparency and attachment (e.g., origins of data points and data processing functions). Consequently, while visual literacy alone is an incomplete description of the background knowledge that today's representational practices require, it correlates positively with data literacy and digital literacy.

CHAPTER 6
Conclusion

Contributions to Sustainability Science

Representational practices have the primary function to organize scientific knowledge as they mediate between theory and the object of interest. Therefore, this dissertation has argued that representational practices carry the potential to enhance current methodologies to better capture new conditions, characteristics, and modes of research which are purposefully oriented toward sustainability actions and solutions. To achieve this goal, this dissertation departed from the fundamental concept of representation and representational practice as mediators between theory and the world (Hacking, 1983). Drawing on this account about their role as a tool in the generation of knowledge and sense-making in (natural and social) sciences, the pluralistic appearances and application modes exhibit essential mechanisms and functions that contribute to the purpose of achieving sustainability through three interrelated knowledge processes which exemplify how we make use of representations to explore (un)sustainability: namely *analysis,* e.g., using models to describe the material basis of the sustainable city and utilize methods and participation at the science-society-policy interface; *envisioning,* e.g., to craft a desired and innovative image of a sustainable urban community; and *engaging*, e.g., to employ learning processes that help us to articulate and negotiate contrasting values.

Representations: A Tool in Knowledge Processes

In this dissertation, I have argued that representations and representational practices are no longer a four-way relationship or a translation activity of the researcher who uses a representation to represent a particular object of interest to draw conclusions about the same (Giere, 2004). Instead, I have shown that representations and representational practices for sustainability make room for multi-way relationships that embrace pluralism in the following respects:

> The first is the highly diverse, parallel, and compatible application of representations. These are applied to the knowledge about systems, targets, or transformations in a way that uncovers multiple perspectives and the complexities of the same without falsifying each others' evidence. An example of this is the diverse field of urban material models, which has built a rich understanding of different urban system scales.
>
> Second is the representational practice that leads to the object of interest, e.g., a comprehensive problem identification (or urban vision) gains importance when

actively integrated into methods that move away from mere translation to cultivate a stepwise procedural understanding. An example of this appears in visioning exercises, where a stepwise reconstruction of images helps to make the future more tangible, to disentangle the complexity of social processes within the city, and to craft an adaptive image of the future.

The third is the expanded stance of a digital process and representations that acknowledges the computer as an additional component influencing both production and interpretation. An example of this is the decision-visualization environment where the computer acts as a filter that allows direct manipulation and interaction, but that also decreases transparency through its autonomous functioning.

Fourth is a heterogeneous collective or cooperative group that provides the necessary shares and stakes in the form of perspectives, values, and knowledge. This collective replaces the exclusive, individual researcher as the leading actor in this activity. An example of this is community visioning, whereby large participatory settings are necessary to adequately represent the intended target of a desired future sustainable city.

These four components provide an interpretation for mechanisms and characteristics of representations and representational practice from a sustainability stance and as such build a shared foundation of their application as tools across different knowledge processes.

Representational Literacy

As I pointed out in this dissertation, representation and representational practices are strongly interwoven with three streams: learning factual knowledge about sustainability, learning processes influenced by background knowledge, and learning in reference to others. As part of a multi-way relationship, the learning takes over functions that have important implications for how we effectively utilize representations in knowledge processes. In this sense, learning is an integrative process with representations for the purpose of generating different knowledge types. This understanding leverages situations in which mutual learning at the science-society-policy interface can take place in a way that blends perspectives and background into a meaningful process, such as visioning exercises highlight. Connecting both learning and representations draws on people's natural ability to employ representations and is worthy of further investigation.

Hacking (1983) describes representational practice as an inherent human activity and as a practice that subsequently leads to evaluation, assessment, and reflection of its contents. The term "literacy" has also been used to describe learned skills such as "environmental" or "transformative" literacy (Schneidewind, 2013; Scholz, 2011). In these contexts, the term captures the appropriate understanding and application of environmental information and information about societal changes toward the goals of sustainable development. Accordingly, representational literacy would address the ability to understand and apply representations and their practices to the broader sustainability context. Salient aspects would include:

(i) the ability to design and conduct a representational practice, considering methodical functions of exploration or explanations and the efficient organization of narratives and sequences.

(ii) a visual skill to build purposeful, ethically responsible representations that encompass data and digital literacy as a means for their production and manipulation.

(iii) interpersonal and collaborative competencies to manage, negotiate, and mediate kinds of perspectives and backgrounds and to support transparent, democratic facilitation techniques for mutual learning and co-production of knowledge at the science-society-policy interface.

(iv) a reflective capacity that fosters effective and correct inferences from representations about content, factual knowledge, and the skills to decode and encode mental images, values, and concerns.

One interesting characteristic of such representational literacy is its capacity in comparison to other existing concepts. These include key competencies, which are a compound of "knowledge, skills, and attitudes" necessary for problem-solving (Wiek et al., 2011, p. 204); practical capacities as enablers to "initialize, facilitate, implement, or contribute" to transformations (Keeler et al., 2018, p. 2); and the aforementioned topical literacies. In the future, a representational literacy for sustainability might be operationalized as learning outcomes integrated into curriculum activities, such as in project-based learning (Brundiers et al., 2010; Caniglia et al., 2017a).

Achieving Sustainability – Moving Forward

The three processes *to analyze, to envision, and to engage* are characteristic knowledge processes that contribute to achieving sustainability, and within these three sub-purposes, representations and representational practice play an essential methodological role for sense-making and knowledge generation. How can we effectively make use of representations and representational practices in the research process so as to contribute to achieving sustainability?

Effective representations are those which allow for exploration between theory and the object of interest. Exploration with representations aims at a practical way of approaching the three knowledge types: to decode complex and large amounts of information into artifacts that can be manipulated, changed, and adapted. New forms of augmented and virtual reality fabricate almost-physical objects that simulate and create tangibility, expanding on the formerly predominant use of representations as images, visualizations, and models. For engaging with knowledge about solution strategies, such new forms will play a significant role in decision-visualization environments and may also spark new practices. For transdisciplinary research modes in which representational practices are already considered to be integration methods, this dissertation shows that the explorational focus can guide research at the science-society-policy interface beyond the current focus on problem framing and interpretation (Bergmann et al., 2010). While representations have already been recognized for their ability to mediate between theory and practice, this thesis demonstrates that one feature of representations (exploring manipulation and tangibility) has the power to move beyond mediation into action.

On a more conceptual note, other insights of my thesis aim toward diversity and pluralism: Representations are both competitive and compatible, and the theory delivers a comprehensive discussion about how different analysis levels can fit together and results can be generalized from this. Mitchel's (2004) work on integrative pluralism sets an analytical milestone with regard to the understanding of complex systems' understanding, and Hacking (1983) draws from historical anecdotes particularly insightful for discussions in sustainability. In particular, he addresses how to generalize case-based knowledge into large-scale models and vice versa to inform local action, leading to the specifics of mutual dependencies between knowledge types and how can they be leveraged for solutions (Lang et al., 2017).

Representations and representational practices have been a fundamental path toward sense-making of knowledge in research as well as in the sociocultural realm. Continuing to develop these methodological advantages in integrative learning as part of achieving sustainability also means contributing to the analogies and metaphors that help us bridge between theoretical knowledge and objects of interest for action in the real world. The digitalization of representations and representational practice has become even more central for exploring, experimenting, and communicating aspects about the empirical world and requires further methodological research and evaluation.

Appendix

References and Supplementary

References

Introduction, Background, Synthesis, Conclusion

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Paper 1: Toward Sustainable Urban Metabolisms. From System Understanding to System Transformation

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Appendix

Paper 1 Supplementary Material

Data Preparation

The research design consists of eight steps (see Table): the first three dedicated to data preparation, step four and five comprising the multivariate analysis and steps six through eight structuring the literature review (see Table 1). The statistical analysis was conducted with R 2.15 (R Core Team, 2012).

Tab 1 Eight main steps of the research design, steps 1-3 data preparation; steps 4 and 5 detrended correspondence analysis, steps 6-8 literature review.

#	Steps	Prodecdure	Results
1	Data Gathering	Database search on Scopus and Google Scholar using defined search strings.	Bibliographical information of 486 potentially relevant publications (duplicates excluded).
2	Data Cleaning	Cleaning of publications based on: only English language, only articles (no books, conference proceedings, grey literature), cited at least once per year	A total of 264 potentially relevant articles identified
3	Data Scoping	Screening of abstracts for relevance guided by the criteria urban area, urban metabolism sustainability, sustainable development; Download of all papers classified as potentially relevant	Download of 221 potentially relevant publications excluding 14 papers with no institutional full-text access.
4	Clustering	Abundant unique keywords, detrended correspondence analysis, agglomerative hierarchical cluster analysis	Unique keywords N= 1900 8 Cluster
5	Cluster Descriptions	Indicator word typography	Results in the sections below
6	Paper classification	Screening of database of relevant publications for relevant case studies only	N= 152 of relevant case studies
7	Paper review	Analysis of papers classified as case studies that serve the study focus using 5 defined review categories in the analytical framework.	Coherent dataset of case study papers with coded information for 5 review categories and 13 variables
8	Statistical analysis	Analysis of all relevant data points using R 2.15	Results in the section below

Although this study is not considered exhaustive, it covers a substantial part of literature related to the research question available on the databases of Scopus and Google Scholar. The search string „sustaina* AND urban metabolism OR (resource, flow, ecology) resulted in 486 scientific publications, identified as relevant from title, abstract, and keywords. The abrupt decrease in the number of published papers marks the stop in data collection for the analysis. In the data cleaning step: (i) book chapters, conference papers, grey publications or reports were not included; furthermore, articles were only included if they were (ii) fully written in English language and (iii) well-cited. We considered well-cited articles with at least an average of one citation per year allowing us to focus on publications for analysis deemed relevant and influential by their research fields and communities. In the scoping step we reviewed title, abstract, and keywords excluding publications with a secondary focus or buzz wording of central concepts of sustainability, sustainable development, urban area, or urban metabolism. 221 publications were downloaded and included in the next steps of the analysis (4 and 5; 6-8), which are described in the following sections.

Details About Systematic Review

The systematic qualitative content analysis of the 152 papers was conducted using an analytical framework to obtain coded categorical data (Auer-Srnka and Koeszegi, 2007). An additional description was implemented to aid identification of the specific situation and information on the location, e.g. introduction section, method sections, etc. Subsequently, a descriptive statistical analysis was conducted to obtain information about relations and co-occurrences between categorized data points.

Details About Multivariate Statistical Analysis

First, we produced a list of abundant unique keywords within the full text publications, appearing in more than 1% or the papers. This resulted in 8300 words of which we removed all without any conceptual information, e.g. adjectives, pronouns, articles, numbers and abbreviations, authors, affiliations, and all those with varying context specific connotations and multiple meanings, e.g. goal as goal of the publication vs. societal goal. We reduced the amount to the topical specific vocabulary to around 1900 words, presenting the "landscape" of sustainable urban metabolism publications, which we used to identify principle gradients in the "landscape" of sustainable urban metabolism publications. In a detrended correspondence analysis of these words we down weighed rare words to identify gradients of the vocabulary used in different papers. Second, we performed an agglomerative hierarchical cluster analysis based on Euclidian distances using Ward's method. Here we took into account all relative abundances of conceptual keywords, and started by clustering single elements (i.e. publications) into aggregates of two elements, and continued until one cluster remained, in order to minimize within-group variance and maximize differences between groups. An "indicator species analysis" which is abundantly applied in ecology (Dufrene and Legendre, 1997) was then used to characterize each research cluster by significant indicator words.

Auer-Srnka, K. J., & Koeszegi, S. (2007). From Words to Numbers: How to Transform Qualitative Data into Meaningful Quantitative Results. *Schmalenbach Business Review*, *59*(January).

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R Core Team. (2012). A Language and Environment for Statistical Computing. R. Vienna, Austria: Foundation for Statistical Computing.

Supplementary Material 2 – Full List Of Publications

Method	Reference
Clustering and Review	Agudelo-Vera, Claudia M.; Leduc, Wouter R.W.A.; Mels, Adriaan R.; Rijnaarts, Huub H.M. (2012): Harvesting urban resources towards more resilient cities. In: Resources, Conservation and Recycling 64, S. 3–12. DOI: 10.1016/j.resconrec.2012.01.014.
Clustering and Review	Agudelo-Vera, Claudia Marcela; Mels, Adriaan; Keesman, Karel; Rijnaarts, Huub (2012): The Urban Harvest Approach as an Aid for Sustainable Urban Resource Planning. In: Journal of Industrial Ecology 16 (6), S. 839–850. DOI: 10.1111/j.1530-9290.2012.00561.x.
Clustering and Review	Alfonso Piña, W. H., & Pardo Martínez, C. I. (2014). Urban material flow analysis: An approach for Bogotá, Colombia. *Ecological Indicators* , *42* , 32–42. http://doi.org/10.1016/j.ecolind.2013.10.035
Clustering	Amano, K., & Ebihara, M. (2005). Eco-intensity analysis as sustainability indicators related to energy and material flow. *Management of Environmental Quality: An International Journal* , *16* (2), 160–166. doi:10.1108/14777830510583173
Clustering	Andrews, Clinton J. (2008): Energy Conversion Goes Local. Implications for Planners. In: Journal of the American Planning Association 74 (2), S. 231–254. DOI: 10.1080/01944360801993531.
Clustering	Angelo, Hillary; Wachsmuth, David (2015): Urbanizing Urban Political Ecology. A Critique of Methodological Cityism. In: Int J Urban Regional 39 (1), S. 16–27. DOI: 10.1111/1468-2427.12105.
Clustering and Review	Arboleda, MartÃ-n (2015): The biopolitical production of the city. Urban political ecology in the age of immaterial labour. In: Environ. Plann. D 33 (1), S. 35–51. DOI: 10.1068/d13188p.
Clustering and Review	Arvesen, A., Liu, J., & Hertwich, E. G. (2010). Energy Cost of Living and Associated Pollution for Beijing Residents. *Journal of Industrial Ecology* , *14* (6), 890–901. http://doi.org/10.1111/j.1530-9290.2010.00265.x
Clustering and Review	Bai, H., Zeng, S., Dong, X., & Chen, J. (2013). Substance flow analysis for an urban drainage system of a representative hypothetical city in China. *Frontiers of Environmental Science and Engineering* , *7* (5), 746–755. doi:10.1007/s11783-013-0551-y
Clustering and Review	Balogh, Stephen; Hall, Charles A. S.; Gamils, Drew V.; Popov, Alexander M.; Rose, Ryan T. (2014): Examining the historical and present energy metabolism of a Rust Belt City. Syracuse, NY 1840–2005. In: Urban Ecosyst. DOI: 10.1007/s11252-013-0342-z.
Clustering and Review	Barles, S. (2007). Feeding the city: Food consumption and flow of nitrogen, Paris, 1801-1914. *Science of the Total Environment* , *375* (1-3), 48–58. doi:10.1016/j.scitotenv.2006.12.003
Clustering and Review	Barles, S. (2007). Urban metabolism and river systems: an historical perspective – Paris and the Seine, 1790–1970. *Hydrology and Earth System Sciences Discussions* , *4* (3), 1845–1878. doi:10.5194/hessd-4-1845-2007
Clustering and Review	Barles, S. (2009). Urban metabolism of Paris and its region. *Journal of Industrial Ecology* , *13* (6), 898–913. doi:10.1111/j.1530-9290.2009.00169.x
Clustering	Barles, S. (2010). Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues. *Journal of Environmental Planning and Management* , *53* (4), 439–455. doi:10.1080/09640561003703772
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Supplementary Material 3 – Coding Scheme

#	Category	Criteria	Operationalization	Code
1	General	Publication year		text
		Country of case study		text
		City of case study		text
2	Research Approach and Design	Approach	problem-oriented research solution-oriented research	ordinal
		Design	disciplinary or interdisciplinary transdisciplinary or participatory actors or their activities considered	ordinal
		Method	Flow, Spatial , Scenario, Qualitative	ordinal
3	Boundaries	Spatial scale	building neighborhood city region	ordinal
		Time scale	historical development (>-5yrs since pub) present (-5yrs>pub>+10 yrs) future (pub >+10yrs)	ordinal
4	Knowledge Types	Systems knowledge	complex systems (indirect cause-effects) resilience social-ecological systems other system framework	yes/no
		Target knowledge	existing sustainability definition	text
			Sustainable Principles, Design Crtieria, Assessment justice and fairness	ordinal
			Sustainable Development Goals 11	ordinal
		Transformational knowledge	outlook for practical solution stepping stone, pilot projects (testing strategies) concrete strategies for downstream	ordinal

Supplementary Material 4 – List Of Unique Keywords

A	B	C	C	D	E	F	G	I	J	M	O	P	R	S	S	T
abiotic	bacteria	compute	cables	dairy	earth	fabric	gallons	illegal	joule	mechanical	occupancy	planetary	radiation	safe	suffer	trophic
acceptance	balance	computer	cadmium	damage	ecolmodel	facilities	garbage	image	joules	mechanism	occupation	planner	railway	safety	sufficiency	tropical
access	balances	conaccount	calculate	dams	ecological	facility	garden	images	journey	mechanisms	ocean	planners	railways	sale	sufficient	truck
accessibility	bank	concept	calculation	debate	ecologically	factor	gardening	immigration	jurisdiction	media	offers	plans	rain	sales	sugar	trucks
account	banks	concepts	calibrated	debris	ecologies	factories	gardens	impact	justice	medical	office	plant	rainfall	salt	suggestions	turnover
accumulate	barrier	conceptual	calibration	decarbonization	ecologist	factory	gas	implementation	**K**	medicine	official	planting	rainwater	sand	sulfur	typologies
accumulation	barriers	concern	campaign	decay	ecologists	faeces	gaseous	implicit	kerosene	meeting	officials	plants	rebuilding	sanitary	sulphur	typology
acidification	baseline	concerns	campaigns	decentralized	ecology	faeth	gases	import	kilogram	meetings	offset	plastic	recharge	sanitation	sun	**U**
acquisition	basin	concomitant	canal	decision	economic	fair	gasoline	imports	kilograms	megacities	oil	plastics	reclamation	satellite	sunlight	unequal
action	basins	concrete	canopy	decisionmaking	economical	families	gender	improvement	kilometer	melbourne	oke	platform	recommend	savings	supplementary	uneven
active	batteries	condition	capabilities	decisions	economically	family	generating	improvements	kilometers	member	openness	policies	recommendations	scales	supplemented	unified
actor	bed	conditions	capability	decline	economics	farm	generation	incentive	kinetic	members	optimisation	policy	reconstruction	scaling	suppliers	uniform
actors	behavior	conference	capacities	declines	economies	farmers	generations	incentives	kitchen	men	optimization	policymakers	records	scarce	supplies	unintended
adapt	behavioral	confidence	capacity	decomposition	economist	farming	geographers	incineration	knowledge	mental	optimize	political	recreation	scarcity	supply	unsustainable
adaptation	behaviors	conflict	capita	decoupling	economists	farmland	geographic	incinerator	**L**	mercury	optimum	politically	recyclable	scenario	surface	untreated
adaptive	behaviour	conflicts	capital	decrease	economy	farms	geographical	incinerators	labor	message	order	politicians	recyclables	scenarios	surfaces	upstream
adjustment	benchmark	congestion	capitalism	deficiencies	ecopolis	fashion	geography	income	laboratory	metabolic	orders	politics	recycle	sea	surplus	uptake
adjustments	benchmarking	congress	capitalist	deficit	ecosystem	fate	geological	incomes	labour	metabolism	ore	pollutant	recycled	seafood	surrounded	urban
administration	benchmarks	connection	car	definition	ecosystems	feature	geology	index	lake	metabolisms	ores	pollutants	recycling	seas	surrounding	urbanisation
administrations	benefit	connections	carbon	definitions	edible	features	geomorphology	indexes	lakes	metal	organic	pollution	reduce	sector	surroundings	urbanism
administrative	benefits	connectivity	cardboard	degradation	education	federal	geophysical	indicator	land	metallic	organics	pool	reduction	sectoral	survey	urbanization
advances	beverages	consensus	carrier	degree	educational	federation	geopolitical	indicators	landfill	metals	organisation	pools	reductions	sectors	surveys	urbanized
advancing	bio	conservation	carriers	demand	effectiveness	feed	geopotential	indices	landfills	metaphor	organisations	poor	refinement	secure	survival	urbanizing
advantage	biochemical	conservative	cars	demands	efficiencies	fees	ghg	indigenous	landscape	meteorological	organism	populated	refining	security	survive	urgency
advantages	biodegradable	consistency	cascading	democracy	efficiency	feet	ghgs	indoor	landscapes	meter	organisms	population	regeneration	sediment	sustain	urine
advice	biodiversity	consolidation	catchment	democratic	efficient	ferrous	gis	industrial	laundry	methane	organization	populations	regenerative	sediments	sustainability	user
advisory	biofuels	constant	catchments	demographic	effluent	fertility	glass	industrialized	law	method	organizational	port	regime	sequestration	sustainable	users
advocate	biogas	constituent	categories	demographics	effluents	fertilization	global	industries	lawns	methodological	organizations	portfolio	regimes	service	sustainably	utilisation
aerial	biogeochemical	constituents	categorized	demography	electric	fertilizer	globalization	industry	laws	methodologies	organize	poultry	region	services	sustained	utilities
affairs	biogeochemistry	constraint	category	demolition	electrical	fertilizers	globe	inefficiencies	lay	methodology	origin	poverty	regional	settlement	sustaining	utility
affluence	biological	constraints	causal	demonstrate	electricity	fiber	goods	inefficiency	layer	methods	originate	power	regions	settlements	sustains	utilization
affluent	biologically	construction	cause	demonstrates	electronic	field	govern	inefficient	layers	metric	origins	powered	regression	sewage	symbiosis	**V**
affordability	biology	constructions	causes	demonstration	electronics	fields	governance	inequalities	layout	metrics	outcome	powerful	regulate	sewer	symbiotic	valuation
agencies	biomass	consultants	cell	dense	emergy	figs	government	inequality	leachate	metro	outcomes	powers	regulation	sewerage	symbolic	value
agency	biophysical	consultation	cells	densities	emission	figure	governmental	infiltration	leaching	metropolis	outdoor	practice	regulations	sewers	synergies	vegetable
agenda	bioscience	consulting	cellular	density	emissions	figures	governments	inflow	leaders	metropolitan	outer	practitioners	regulatory	shifts	synthesis	vegetables
agendas	biosphere	consume	cement	depletion	emit	filter	gradient	inflows	leadership	migration	outflow	pragmatic	rehabilitation	ships	synthesized	vegetation
agent	biotic	consumer	census	deposition	empirical	finance	gradients	informal	leads	mine	outflows	precipitation	relationship	shopping	synthetic	vehicle
agents	blueprint	consumers	center	deposits	employees	financial	grain	informatics	leaf	mined	output	predict	relationships	short	system	vehicles
agglomeration	board	consumption	central	desert	employment	financially	graphical	information	leakage	mineral	outputs	predicted	release	shortage	systematic	village
aggregation	bodies	consumptions	centralized	design	empower	financing	graphically	infrastructure	legacy	minerals	outside	predicting	renewable	shortages	systemic	villages
agricultural	body	container	centre	designed	encyclopedia	fine	grass	infrastructures	legal	mines	outward	prediction	renewables	shortcomings	systems	vintage
agriculture	boiler	containers	centres	designers	energetic	fire	gravity	inhabitant	legislation	mining	overflow	predictions	renewal	shrinking	**T**	virtual
air	boom	contaminant	centuries	desire	energetics	firms	greenhouse	inhabitants	legislative	ministry	owner	prefecture	renewed	simulate	tank	visibility
airborne	border	contaminants	century	destroyed	energies	fiscal	greening	initiative	leisure	mission	owners	preference	renovation	simulation	tanks	visible
airport	borders	contamination	cereals	destruction	energy	fish	grey	initiatives	lessons	mitigate	ownership	preferences	repair	simulations	tax	vision
algorithm	boundaries	contested	certification	detached	engagement	fisheries	grid	inland	letters	mitigation	oxidation	prentice	replace	sink	taxes	visions
allocating	boundary	context	chain	detect	engine	fishery	grids	innovation	license	mix	oxide	preservation	replacement	sinks	team	visual
allocation	box	contexts	chains	deteriorating	engineer	fishing	gross	innovations	life	mixture	oxides	press	representations	site	teams	visualization
alteration	boxes	continental	challenge	deterioration	engineering	flat	ground	innovative	lifecycle	mobile	oxygen	pressure	representative	sites	technical	vital
alterations	branch	contract	challenges	develop	engines	fleet	grounds	inorganic	lifespan	mobility	ozone	pressures	representatives	skills	technique	vitality
aluminium	branches	contribution	challenging	developers	entering	flood	groundwater	input	lifestyle	mode	**P**	prevalence	reservoir	sludge	techniques	volatile
aluminum	breakdown	control	change	development	enterprise	flooding	group	inputs	lifestyles	model	package	prevention	reservoirs	slum	technological	vulnerability
ambiente	brick	controls	channel	developments	enterprises	floods	groups	inspection	lifetime	modeling	packaging	price	reshaping	social	technologies	vulnerable
amenity	bricks	convenience	channels	device	entity	floor	grove	installation	lifetimes	modell	panel	prices	residence	societal	technology	**W**
ammonia	bridge	convenient	characteristic	devices	entropy	flow	grow	installations	light	models	paradigm	pricing	residences	societies	temperature	warming
anaerobic	bridges	conventional	characteristics	dialogue	environment	flowing	grows	institution	lighting	modern	paradigms	proactive	resident	society	temperatures	washing
analogy	brundtland	convergence	charge	diamond	environmental	flows	growth	institutional	likelihood	modernity	paradox	produce	residential	socio	temporal	waste
analyse	budget	conversion	chemical	diesel	environments	fluctuations	guidance	institutions	lime	modernization	parameter	producer	residents	socioecological	temporary	wasteful
analyses	budgets	cook	chemicals	diet	equally	flush	guide	instrument	limestone	modes	parameters	producers	residuals	socioeconomic	tendencies	wastewater
analysis	buffer	cool	chemistry	dietary	equation	flushing	guidelines	instruments	limit	modification	park	produces	residue	sociological	tendency	water
animal	building	cooling	chemosphere	diets	equations	flux	**H**	insufficient	limitation	modifications	parks	product	residues	sociology	theory	watering
animals	buildings	cooper	choice	difference	equilibrium	fluxes	habitat	insulation	limitations	modify	parliament	production	resilience	software	thermal	waters
annum	built	cooperation	choices	diffusion	equipment	food	habitats	insurance	linkage	modifying	participants	productive	resilient	soil	thermodynamic	watershed
anthropogenic	bulk	coordinate	circle	digestion	equitable	foods	habits	intake	linkages	module	participate	productivity	resistance	soils	thermodynamics	watersheds

anthroposphere
anticipate
antipode
apartment
apartments
appliances
applicability
approach
aquatic
aquifer
aquifers
arable
architects
architectural
architecture
area
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arena
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composite
composition
compositions
compost
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compound
compounds
compromise
computation
coordination
copper
corporate
corporation
correlate
correlation
correlations
correspond
correspondence
cost
costs
cotton
council
councils
counter
counties
countries
country
countryside
county
coupled
cradle
creative
creativity
credit
crises
crisis
criteria
criterion
criticism
criticisms
critique
crop
cropland
crops
crude
cultivated
cultivation
cultural
culture
cultures
currency
customers
cyborg
cycle
cycles
cyclical
cycling
circuit
circular
circulation
circulations
circumstances
cities
citizen
citizens
city
civil
civilization
claims
class
classes
classification
classified
clay
clean
climate
climates
climatic
closure
clothing
club
cluster
clusters
coal
coarse
coast
coastal
cohesion
coke
coking
collaboration
collaborative
collection
collective
collectors
colonial
combination
combustible
combustion
comfort
commerce
commercial
commission
commissioned
commitment
committee
commodities
commodity
digital
dimension
dimensions
dioxide
directive
dirty
disaster
discarded
discharge
discharges
disciplinary
discipline
disciplines
discourse
discovery
discussion
disease
diseases
disparities
disparity
dispersion
disposal
dispose
dissipated
dissipation
dissolved
distance
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district
districts
diversity
domain
domestic
downscaling
downstream
downtown
drain
drainage
drinking
drive
driver
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drought
dry
duration
dust
dwellers
dwelling
dwellings
dynamic
dynamics
equity
erosion
establishment
estate
estuary
ethical
ethics
eutrophication
evaporation
event
events
evolution
evolutionary
exceed
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excessive
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exploitation
exploration
explorations
export
exported
exporting
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externalities
extraction
foot
footprint
footprinting
footprints
forecast
forecasting
forecasts
forest
forestry
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fossil
foundation
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fraction
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framework
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freight
fresh
freshwater
fringe
fruit
fruits
fuel
fuels
function
functionality
fund
funding
funds
furniture
future
futures
handbook
harmful
harmonious
harmonized
harmony
harvest
harvesting
hazard
hazardous
hazards
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heat
heating
help
helpful
helps
heritage
heterogeneity
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heterotrophic
hierarchies
hierarchy
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hinterland
hinterlands
historic
historical
history
holistic
home
homogeneous
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hospital
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housing
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humans
hunter
hybrid
hydraulic
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hydrogen
hydrologic
hydrological
hydrology
hydropower
hygiene
integrated
integrating
integration
integrative
intellectual
intelligence
intensification
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interdependence
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interrelated
intersection
intertwined
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intervention
interventions
interview
interviews
inventories
inventory
investing
investment
investments
involvement
irrigated
irrigation
isolation
liquid
liters
livability
livelihood
livelihoods
livestock
loads
local
localized
locally
locations
logistic
logistics
longterm
loop
loops
loss
lpg
M
machine
machinery
machines
macro
macroeconomic
mainland
mainstream
maintain
maintenance
majority
man
manage
management
managers
managing
manufacture
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map
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maps
marine
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mathematical
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matrices
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neighboring
neighbourhood
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ngos
nitrogen
node
nodes
noise
nonlinear
normalization
normalized
normative
nuclear
numerical
nutrient
nutrients
nutrition
participation
participatory
particle
particles
parties
partner
partners
partnership
passenger
passive
path
pathogens
paths
pathway
pathways
pattern
patterns
paved
pavement
pavements
pay
payment
pays
peak
penetration
penguin
people
perception
perceptions
performance
performances
periphery
periurban
permission
permit
permits
person
persons
perspective
perspectives
pesticides
pet
petroleum
pharmaceutical
philosophy
phosphate
phosphorus
photosynthesis
photovoltaic
php
physical
physically
physics
physiological
pipe
pipeline
pipelines
pipes
place
placed
places
plan
planet
products
professional
professionals
profit
progress
progressive
project
projection
projections
projects
proliferation
promotion
propagation
properties
property
prospects
prosperity
prosperous
protection
protocol
prototype
providers
province
provinces
provincial
provision
public
publicly
pump
pumping
purification
resolution
resource
resources
respiration
responsibility
responsible
restaurants
restoration
restrictions
retail
retain
revenue
revenues
rice
right
rights
risks
river
rivers
road
roads
roadways
roof
roofs
room
root
roots
route
routes
routine
rubber
rubbish
rule
rules
runoff
rural
solar
solid
solids
solution
solutions
source
sources
spatial
spatio
species
specification
specifications
speed
sport
sports
sprawl
sprawling
spread
staff
stakeholder
stakeholders
states
steam
steel
stock
stocks
stone
storage
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stories
storm
stormwater
strategic
strategies
strategy
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streams
street
streets
stress
stresses
student
students
study
studying
style
styles
subsidies
substance
substances
substitute
substituting
substitution
subsystem
subsystems
subtracted
subtracting
suburban
suburbs
success
successful
threat
threats
threshold
thresholds
timber
time
timeframe
times
timing
tires
toilet
toilets
tonne
tonnes
tool
tools
topography
tourism
town
towns
toxic
toxicity
trace
track
tracks
trade
tradeoffs
trading
tradition
traditional
traffic
training
trajectories
trajectory
transaction
transactions
transboundary
transfer
transfers
transform
transformation
transformations
transformities
transformity
transforms
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transition
transitions
transmission
transnational
transparency
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transportation
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tree
trees
trend
trigger
trips
waterways
welfare
well
wellbeing
wetland
wetlands
wildlife
window
windows
withdrawal
women
wood
work
worked
workers
workshop
workshops
world
worlds
worldwide
Y
yellow
yield
yields
Z
zone
zones
zoning

Paper 2 Supplementary Material

Appendix A

Document analysis and codification process

The document analysis and codification processes are preparatory steps toward the analysis with rough set analysis (RSA). They aim to transfer the basis of knowledge about the study cases into the suitable data format for RSA with ROSE 2 software. Both processes are aligned along the multi-attribute analytical-evaluative framework which was developed deductively and consequently determines already the necessary information. The document analysis was conducted with 82 case documents that were easy accessible. Among those were workshop materials, final vision reports, project websites, city council protocols, official statistics, newspaper and scientific articles. The knowledge obtained through document analysis is being mapped into the information table using ordinal values on the scale {1, 2} or {1, 2, 3} codifying the qualitative data with help of the codification matrix.

Codification of conditional attributes (cccs)

For conditional attributes the information was extracted directly out of the existing documents. Predefined attributes and their codes were already very distinct without room for interpretation and led to be either applicable or not. In cases of ABG, YK, and CMO the available documents did not sufficiently provide information about participation. In these cases project representatives were contacted and inquired.

Codification of sustainability and resilience attributes (srcs)

Document analysis of vision documents and discretization of information for sustainability and resilience criteria (SRCs) was more elaborate due to broad variations of formats and descriptions of the final vision reports. As described in method section of this paper, the sustainability and resilience criteria of the framework are synthesized from literature. The final SRCs one through seven in the framework used for as decision attributes for RSA are a summary of a total of 19 sub-criteria. All these sub-criteria are described by a set of three to six keywords which identify sustain- able strategies and practices within the area. This entire system is deductively built from literature. The keywords function as necessary prerequisites to be fulfilled to reach a full account of the criterion equaling the code 3 = important, or the code 2 = marginal, or code = 1 not an issue. The scoring board shows the distribution of points for each code.

Appendix B – Scoring Board Of Srcs Keywords

Scale	SRC	#	Criteria	Answer Keywords	Maximum points per subcriterion	Case #1 Gothenburg 2050	Case #2 Ahrensburg 2030	Case #3 Saskatoon 2060	Case #4 Portland 2030	Case #5 Dublin 2020	Case#6 Ingolstadt 2020	Case#7 Canmore 2030	Case#8 York 2051	Case #9 Sydney 2030	Total	Total Possible
			Built form processes	**Urban form**		**21**	**14**	**25**	**28**	**29**	**22**	**11**	**26**	**25**	**Total SRC 1**	
		1	**Land use and built form**	Networks of green corridors		1	1	1	2	1	2	1	2	2		
				Mixture of land use		0	0	2	1	2	0	0	2	2		
				Intensive use of urban land		0	0	2	0	2	2	1	0	2		
					6	**1**	**1**	**5**	**3**	**5**	**4**	**2**	**4**	**6**	31	**54**
		2	**Density**	Retrofitting existing dristricts		2	0	2	2	0	2	0	2	2		
				Relatively high density		0	2	2	2	2	0	2	0	1		
				Pattern of growth		1	0	2	2	2	2	2	2	2		
					6	**3**	**2**	**6**	**6**	**4**	**4**	**4**	**4**	**5**	38	**54**
		3	**Accessibility and transport infrastructure**	Shops and services		2	2	2	2	2	1	0	2	2		
				Street connectivity		2	0	1	0	0	0	0	2	1		
				Social Benefits and Urban form		0	0	0	1	2	2	0	0	0		
				Land use and transportation		0	0	0	0	0	0	0	0	0		
				Means of sustainable transport		2	2	1	2	2	2	0	2	2		
	SRC1			Traffic Management/ Transportation planning		2	2	2	2	2	2	1	2	2		
				Communication technology		1	0	0	0	2	0	0	2	0		
					10	**9**	**6**	**6**	**7**	**10**	**7**	**1**	**10**	**7**	63	**90**
		4	**Housing characteristics**	Green building principles		2	0	2	2	2	1	0	2	2		
				Flexible design/Mixed use		2	1	2	1	2	0	0	2	0		
				Housing and community development / Shelter needs		0	2	0	1	2	2	2	2	2		
				Affordable homes		0	2	2	2	2	2	2	2	2		
					8	**4**	**5**	**6**	**6**	**8**	**5**	**4**	**8**	**6**	52	**72**
		5	**Energy**	Renewable energy		2	0	2	2	2	2	0		0		
				Energy efficiency / Reduction of energy consumption		2	0	0	2	0	0	0	0	0		
				Energy management		0	0	0	2	0	0	0	0	1		
					6	**4**	**0**	**2**	**6**	**2**	**2**	**0**	**0**	**1**	17	**54**
			Ecological Processes	**Local-to Regional Ecosystem Services**		**12**	**2**	**5**	**10**	**0**	**5**	**0**	**13**	**4**	**TOTAL SRC 2**	
		6	**Air filtering**	Local air quality		0	2	1	1	0	1	0	2	0		
				Zero CO2 Emissions		2	0	0	0	0	0	0	1	2		
					4	**2**	**2**	**1**	**1**	**0**	**1**	**0**	**3**	**2**	12	**36**
		7	**Water**	Water quality/sanitation		2	0	0	2	0	2	0	2	0		
				RRR/Efficiency Water		2	0	2	2	0	2	0	2	2		
				Sustainable water/grey water systems/technical		2	0	0	1	0	0	0	2	0		
	SRC2				**6**	**6**	**0**	**2**	**5**	**0**	**4**	**0**	**6**	**2**	25	**54**
		8	**Soil**	Soil quality		0	0	2	0	0	2	0	0	0		
		9	**Climate**	Micro-Climate Regulation		0	0	0	0	0	0	0	2	0		
		10	**Food**	Urban agriculture		2	0	2	2	0	0	0	2	0		
				Local Sustainable food		2	0	0	2	0	0	0	2	0		
					4	**4**	**0**	**2**	**4**	**0**	**0**	**0**	**4**	**0**	14	**36**
			Sustainable Production, Consumption, Economy			**11**	**0**	**6**	**15**	**9**	**5**	**5**	**12**	**10**	**TOTAL SRC 3**	
		11	**Consumption/ Production**	Local Sustainable materials/ Sustainable building materials		2	0	1	2	0	0	0	0	1		
				Short supply chains / food supply		2	0	0	2	0	0	0	2	0		
				Waste reduce, reuse recycling, Zero Waste		2	0	2	2	2	2	0	2	2		
				Carbon neutral lifestyle		2	0	0	2	0	0	0	2	0		

SRC3			Behavioural changes		0	0	0	0	0	0	0	0	0		
			Organizational environmental assessments		0	0	0	0	1	2	1	1	0		
				12	**8**	**0**	**3**	**8**	**3**	**4**	**1**	**7**	**3**	37	**108**
	12	**Local economy**	Local ownership		0	0	0	1	0	0	1	0	2		
			Community self-reliance		1	0	0	2	2	0	2	2	2		
			High social performance		1	0	2	2	2	0	1	2	2		
			Income/ Poverty		0	0	1	2	2	0	0	0	0		
			Local entrepreneurship, employment		1	0	0	0	0	1	0	1	1		
				8	**3**	**0**	**3**	**7**	**6**	**1**	**4**	**5**	**7**	36	**72**
		Social and Cultural Processes			4	8	10	15	14	10	8	10	7	**TOTAL SRC 4**	
	13	**Health**	Reducing health risks		1	1	0	1	0	2	0	1	0		
			Happiness, well-being		0	0	2	2	2	1	1	1	0		
				4	**1**	**1**	**2**	**3**	**2**	**3**	**1**	**2**	**0**	15	**36**
SRC 4	14	**Culture**	Community spaces		1	2	2	2	2	2	2	2	2		
			Cultural hertiage identity		0	1	2	2	2	1	2	2	2		
			Sense of place / Local identity		0	2	2	2	2	1	2	1	2		
				6	**1**	**5**	**6**	**6**	**6**	**4**	**6**	**5**	**6**	45	**54**
	15	**Education**	Educational Institutions		0	1	1	2	2	2	0	1	0		
			Research		0	1	0	2	2	0	0	0	0		
			Knowledge Production		2	0	1	2	2	1	1	2	1		
				6	**2**	**2**	**2**	**6**	**6**	**3**	**1**	**3**	**1**	26	**54**
		Governance and Resilience in cities			**2**	**3**	**5**	**6**	**13**	**7**	**8**	**14**	**14**	**TOTAL SRC 5**	
	16	**Governance**	Public services, Distribution, Inclusion		2	1	2	2	2	2	2	2	2		
			Public safety		0	0	1	2	2	2	0	2	0		
			Community participation		0	1	1	2	2	1	2	2	2		
SRC 5			Urban governance / Governing		0	0	0	0	2	2	0	2	2		
			Planning		0	0	1	0	1	0	2	2	2		
			Assessment		0	1	0	0	2	0	2	2	2		
				12	**2**	**3**	**5**	**6**	**11**	**7**	**8**	**12**	**10**	64	**108**
	17	**Local to regional ecosystem services**	Co-Management		0	0	0	0	2	0	0	0	2		
			Adaptive governance		0	0	0	0	0	0	0	2	2		
				4	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**2**	**4**	8	**36**
		Resilience of cities			**8**	**0**	**0**	**4**	**0**	**2**	**2**	**2**	**1**	**TOTAL SRC 6**	
	18	**Integration of human settlement**	Human settlement in reciprocal relationship with dynamic landscapes + regional ecosystems (Climate/Topography) Adaption and integration of		2	0	0	0	0	2	2	0	0	6	
			Climate change mitigation and adaption, atmospheric change		2	0	0	2	0	0	0	2	0	6	
			Urban Metabolism		2	0	0	0	0	0	0	0	1	3	
			Global boundaries perspectives		2	0	0	2	0	0	0	0	0	4	
				8	**8**	**0**	**0**	**4**	**0**	**2**	**2**	**2**	**1**	**19**	**72**
					6	**0**	**2**	**4**	**2**	**2**	**4**	**6**	**2**	**TOTAL SRC 7**	
	19	**Networks across scales**	Social networks + processes across spatial, temporal scales		2	0	0	0	2	0	2	2	0	8	
SRC 7			Cultural networks + processes across spatial, temporal scales		0	0	0	0	0	0	0	0	0	0	
			Ecologcial networks + processes across spatial, temporal scales		2	0	2	2	0	0	2	2	0	10	
			Technical networks + processes across spatial, temporal scales		2	0	0	2	0	2	0	2	2	10	
				8	**6**	**0**	**2**	**4**	**2**	**2**	**4**	**6**	**2**	**28**	**72**

Appendix C – Legend For Spectrum Of Scoring Srcs

Criteria	Abbr.	not an issue	marginal	important
(SRC) Sustainability/Resilience				
Built Form Processes (urban form, transportation, energy)	SRC 1	0-12	13-24	25-36
Ecosystem Services (preservation local-to-regional ecosystem services)	SRC 2	0-6	7-12	13-18
Sustainable Consumption, Production, Economy	SRC 3	0-8	9-12	15-22
Social and Cultural Processes (Education, Culture, Health)	SRC 4	0-5	6-10	11-16
Governance	SRC 5	0-5	6-10	11-16
System of City (Integration of human settlement)	SRC 6	0-3	4-5	6-8
Spatial Networks and Relationships with hinterland	SRC 7	0-3	4-5	6-8

Appendix D - Universe Of International Urban Visions Used For Purposeful Sampling

#	Cases	Sources
	Germany	
1	München	http://www.innovations-report.de/html/berichte/studien/nachhaltige_staedte_modell_zukunft_155141.html http://sustainablecities.dk/en/city-projects/cases/theresienhohe-a-new-dense-and-green-neighbourhood-in-munich
2	Titisee-Neustadt	http://www.titisee-neustadt.de/servlet/PB/menu/1163708_l1/index.html
3	Ingolstadt	http://www.faape.org/visionen-fuer-ingolstadt-leitbild.pdf http://www2.ingolstadt.de/media/custom/465_2218_1.PDF?1291636420 http://www.ingolstadt.de/buergertag/entwicklung_und_ziele.htm
4	Dellbrück	http://www.stadt-delbrueck.de/buergerservice/downloads/Zukunftswerkstatt_Delbrueck.pdf
5	Tennenbronn	http://www.schramberg.de/ceasy/modules/cms/main.php5?cPageId=598
6	Braunschweig	http://www.zgb.de/barrierefrei/content/regionalplanung/stadt2030_projekt.shtml
7	Gießen	http://www.stadt2030.giessen.de/frame.htm
8	Ahrensburg	http://www.zukunftswerkstatt-ahrensburg.de/
9	Ludwigsburg	http://www.ludwigsburg.de/servlet/PB/menu/1248437_l1/index.html
10	Augsburg	http://www.augsburg.de/fileadmin/www/dat/04um/a_agenda/handlungsprogramm/Augsburg_Nachhaltigkeitbericht_2010.pdf http://www.augsburg.de/index.php?id=115
11	Dortmund	http://www.dortmund-project.de/de/home/
12	Leipzig	http://www.leipzig.de/de/buerger/stadtentw/konzept/
13	Heidelberg	http://www.heidelberg.de/servlet/PB/show/1161051_l2/12_pdf_STEP_2015_engl_mit_Lesezeichen_s.pdf
	Great Britian/Ireland	
14	Bristol Bay Region	http://www.bristolbayvision.org/vision/
15	Cardiff	http://www.cardiffproudcapital.co.uk/content.asp?nav=164&parent_directory_id=2
16	Liverpool	http://www.liv.ac.uk/civdes/Centenary/Future_City_Region.htm
17	Birmingham	http://www.bebirmingham.org.uk/page.php?id=21&mid=7 http://bigcityplan.birmingham.gov.uk/
18	Leeds	http://www.leeds.gov.uk/Council_Publications/vision_for_leeds.aspx
19	Belfast	Belfast City Centre: Vision for the Future ISBN 0337083096
20	Dublin	http://www.dublincity.ie/Planning/DublinCityDevelopmentPlan/Documents/Dev_Plan_-_Vol_1_-_Written_Statement.pdf http://dublincitydevelopmentplan.ie/vision.php http://www.dubchamber.ie/Uploads/2020%20Vision.pdf
21	Kilkenny Irland	http://www.kilkennycity.ie/eng/Services/Planning/Development%20Plans%202008-2014/Kilkenny_City_Environs_Development_Plan_2008-2014.html
22	Waterford	http://www.waterfordcity.ie/documents/development-plan/DevelopmentPlanAsIssued2.pdf
23	Cork	http://www.corkcity.ie/newdevelopmentplan/plan.pdf
24	St.Helena	http://www.sainthelena.gov.sh/data/files/downloads/st_helena_sdp.pdf
25	Chesham	http://www.buckscc.gov.uk/assets/content/bcc/docs/business/Chesham_Community_Vision.pdf
26	Galway	http://www.galwaycity.ie/AllServices/Planning/DevelopmentPlanandPolicySection/GalwayCityDevelopmentPlan20112017/
	Canada	
43	Vancouver	http://www.imaginecalgary.ca/project.php http://www.imaginechicago.org/who.html http://www.calgary.ca/PDA/LUPP/Documents/Publications/mdp-municipal-development-plan.pdf
44	Calgary	http://www.imaginecalgary.ca/project.php
45	Lawrence Township	http://www.sustainablelawrence.org/
46	Town of Olds	http://www.olds.ca/communty/strtegy3.pdf
47	Canmore	http://www.canmore.ca/Municipal-Sustainability/Civic-Leadership/Mining-the-Future-A-Vision-for-Canmore.html
48	Halifax	http://www.halifax.ca/VisionHRM/index.html http://www.halifax.ca/recreation/YouthEngagementToolKit.html
49	Strathcona County, Alberta	http://www.strathcona.ab.ca/local_government/sustainability.aspx
50	Williams Lake, BC	http://williamslake.ca/files/4/Imagine%20Our%20Future%20ICSP%20Framework%20-%20Final.pdf
51	Town of Caledon, Ontario	http://www.town.caledon.on.ca/contentc/townhall/departments/planningdevelopment/EPO_2009_Enviro_Action_Report.pdf
52	Whistler, BC	http://www.whistler2020.ca/whistler/site/genericPage.acds?context=1967914&instanceid=1967915
53	York	http://www.york.ca/Departments/Planning+and+Development/Long+Range+Planning/Vision+2026/default+Vision+2026.htm
54	Edmonton	http://www.edmonton.ca/city_government/documents/MDP_Bylaw_15100.pdf
55	West Milford	http://www.sustainablewestmilford.org/
56	Hamilton Wentworths	http://www.unesco.org/most/usa4.htm
57	Saint John, NB	http://www.saintjohn.ca/vision2015-index.cfm
58	Dawson Creek, BC	http://www.planningforpeople.ca/what_we_are_doing/sustainability_plan/vision.asp
59	Rossland, BC	http://cfdcmall.com/cms/index.php?id=338
	USA	
60	Burlington, Vermont	http://burlingtonlegacyproject.org/
61	Tucson	http://www.sustainabletucson.org/ http://cms3.tucsonaz.gov/livable
62	Atlanta	Helling, Amy. 1998.Collaborative Visioning: Proceed With Caution!: Results From Evaluating Atlantas Vision 2020 Project. Journal of the American Planning Association 64 (3) (September 30): 335-349.
63	Ahwahnee	http://www.lgc.org/ahwahnee/principles.html
64	San Francisco	http://www.sustainable-city.org/
65	Asheville	http://www.ashevillenc.gov/docs/sustainability/AVLSust.Plan.pdf
66	Phoenix	http://phoenix.gov/greenphoenix/sustainability/index.html
67	Aspen	http://www.aspencommunityvision.com/page_1
68	Maryvale	Steel, K., Ahrentzen, S., Fonseca, E. (2010). Maryvale on the Move – Planning and Charrette Documents. Herberger Institute's School of Architecture and Landscape Architecture, Stardust Center for Affordable Homes and the Family, Arizona State University.

Sweden

27	Jönköping	http://www.jonkoping.se/download/18.28b5389012698e197d380002125/PHU+eng.pdf
28	Göteborg	http://www.waterfrontcommunitiesproject.org/downloads/coolsea_goteborg.pdf http://www.goteborg2050.se/

Switzerland

29	Basel	http://www.novatlantis.ch/fileadmin/downloads/partnerregionen/Flyer_PR_Basel_tot_e.pdf

Italy

30	Morbegno	http://www.morbegno2020.it/images/stories/doc/libretto_2020.pdf

Australia

31	Melbourne	http://www.futuremelbourne.com.au/info/facts/cityplan
32	Brisbane	http://www.brisbane.qld.gov.au/2010%20Library/2009%20PDF%20and%20Docs/6.Facilities%20and%20Recreation/6.13%20Facilities%20recreation%20plans%20%20projects/Mt%20Coot-tha/facilities_and%20recreation_our_shared_vision_mt_coottha_2030_draft.pdf
33	Sydney	http://www.cityofsydney.nsw.gov.au/2030/documents/strategy/00_A_CITY_VISION.pdf https://s3.amazonaws.com/media.cityofsydney/2030/documents/Consultation-overview.pdf http://www.sgsep.com.au/system/files/About%20Sustainable%20Sydney%202030%20project%20_web_.pdf
34	Blue Mountains, Katoomba	http://www.sustainablebluemountains.net.au/our-city-vision/city-vision-publications/
35	Maroochy	http://www.maroochy2025.net/
36	Vincent	http://www.vincentvision2024.com.au
37	Hume	http://www.hume.vic.gov.au/About_Us/Our_City/Our_Vision_Mission
38	Western State Sustainability Strategy Australia	http://www.dec.wa.gov.au/content/view/3523/2066/

New Zealand

39	Auckland	http://www.aucklandcity.govt.nz/council/documents/bright/docs/final.pdf
40	Clevedon	http://www.towards2060.org.nz/assets/Outputs/Final_Reports/Clevedon-Community-Report-on-Design-the-Future-Workshop.pdf
41	Christchurch	http://www.ccc.govt.nz/homeliving/sustainableliving/sustainabilitychristchurch/sustainablechristchurch.aspx http://www.greaterchristchurch.org.nz/
42	Wellington	http://www.wellington.govt.nz/plans/annualplan/ltccp/vol1.html

69	City of Lake Oswego	http://welovelakeoswego.com/wp-content/uploads/2011/01/Inspiring-Spaces-Places-Background-Goal-2-14_-01.03.121.pdf
70	Beaverton	http://www.beavertonoregon.gov/DocumentView.aspx?DID=22 http://www.beavertoncivicplan.com/about/
71	Saskatoon	http://www.saskatoonspeaks.com/saskatoon-speaks-community-vision/
72	Portland	http://www.portlandonline.com/bds/index.cfm?a=195005&c=46936 http://www.portlandonline.com/portlandplan/
73	City of Cartersville Georgia	http://www.cityofcartersville.org/DocumentCenter/Home/View/169
74	Chicago	http://www.chicagometropolis2020.org/DevelopmentTransportation-Overview.html http://www.imaginechicago.org/who.html
75	Deland	http://www.deland.org/Pages/DeLandFL_Planning/DeLand2050/Report%20Only.pdf
76	New York	http://www.beyondoilnyc.org/
77	Central Texas	http://envisioncentraltexas.org/makingvisionreal.php
78	North Texas	http://www.visionnorthtexas.org/regional_summit/North_Texas_2050.pdf
79	Hillsboro, OR	http://www.hillsboro2020.org/Default.asp?Page=52
80	Washington DC	http://www.inclusivecity.org
81	Bend, OR	http://www.bend2030.org/
82	California Dreaming	http://iftf.me/public/IFTF_SR-1313_CaliforniaDreaming.pdf
83	Southern California	http://www.scced.org/
84	Chesapeake Communitites	http://www.chesapeakecommunities.org/
85	Sustainable Arizona	http://www.sustainablearizona.org/
86	San Mateo County	http://www.sustainablesanmateo.org/
87	Colorado	http://sustainablecolorado.org/
88	Hawaii	http://www.hawaii2050.org/images/uploads/Hawaii2050_Plan_FINAL.pdf

South Africa

89	Durban	http://www.imaginedurban.org/index.php/Imagine-Durban-Imagining-tomorrow-today.html
90	Johannesburg	http://usj.sagepub.com/content/43/2/337.short

India

91	Hyderabad (Indien)	http://www.ourmch.com/cdp/chapters%201.pdf

Asien

91	Singapur	http://app.mewr.gov.sg/web/Contents/Contents.aspx?ContId=1342
92	Tokyo	http://unpan1.un.org/intradoc/groups/public/documents/apcity/unpan003024.pdf

Paper 3 Supplementary Material

Supplementary Material 1

DVE catalogue

First, the web search of websites, grey and peer reviewed publications was conducted to catalogue existing facilities and institutions; We stepwise extended the search words in German, English and Spanish. Second, we distributed an online survey to all DVEs in our database. The return rate was 26 %. Third, we conducted semi-guided expert interviews and two site visits to complement the dataset (see below). Overall, we found 34 DVEs up and running as well as discontinued. They are located in the United States, Canada, China, Mexico, Germany, Italy, and Sweden. For data protection reasons we anonymized information. Original data is available from the corresponding author on reasonable request.

In the following table, we summarize the information categories, the source and how we obtained the information. We were able to fill around 50% of information through web search.

Table 1 Catalogue category and source

Category	Information source
Name Institution/ Organization	Web search
Location (Institution, City, Country)	Web search
Contact Information	Web search
Signature Projects	Web search
Infrastructure/ Visualization/ Computational tools	Web search
Process (facilitation, moderation, engagement aorund the interface)	Web search
Purpose (Decision Making, Capacity Builiding, research driven, modeling, information...)	Web search
Products or solutions	Web search
Sustainability related	Web search
Operations start date	Web search
What is the name of your Decision Theater or similar environment?	Survey
To what institution does your Decision Theater belong to?	Survey
Since when has your Decision Theater been in operation?	Survey
On average, how many events does your Decision Theater host per year?	Survey
What was the overall budget for establishing your Decision Theater (incl. design, construction, equipment, etc.)?	Survey
What is the overall annual budget for your Decision Theater (incl. salaries, electricity, rent, etc.)?	Survey
What is the overall annual budget for your Decision Theater (incl. salaries, electricity, rent, etc.)? [Comment]	Survey
Could you please briefly describe the facility and equipment of your Decision Theater? (Number of rooms, technology features such as	Survey

screens, audio, projectors and other visualization tools, computational capacities, etc.)	
Could you please briefly name any specific software or computational tools that were developed for and/or have been used frequently in your Decision Theater?	Survey
What are the primary purposes your Decision Theater is used for? [Research] [University education] [Capacity building in professionals and the public] [Information dissemination] [Decision support] [Other]	Survey
What are the primary topics that are being addressed in your Decision Theater? (Climate change, public transit, energy, immigration, entrepreneurship, etc.)	Survey
Who are external participants you work most frequently with? [Government Agencies] [Non-Governmental Organizations] [Businesses] [The Public] [Other]	Survey
Could you please briefly describe the way you engage with these participants in your Decision Theater?	Survey
Could you please name the three projects most representative for the work in your Decision Theater?	Survey
Could you please provide any links to pictures videos, manuals, articles, etc. that provide relevant information on your Decision Theater?	Survey

Expert interview

Following up on the background search, we conducted semi-guided expert interviews following Kaiser (2014). Expert were considered (i) principal investigators (professors) with research projects in the DVE, (ii) directors or other leading positions of DVE, (iii) staff involved in the preparation or actual event. We chose seven experts from the DVE that answered our survey and of which we already gathered most of the data from other sources, in order to create a comprehensive picture and engage in an informed conversation.

Kaiser, R. (2014). Qualitative Experteninterviews: Konzeptionelle Grundlagen und praktische Durchführung. Springer. https://doi.org/10.1007/978-3-658-02479-6

Interview questionnaire

The questionnaire divides into three columns, the dimension of analysis, a set of questions that pertain to that dimension, and the actual interview question. This basic set of questions was then informed by the background research per each DVE and respectively individualized.

Table 2 Basic set of interview questions

Dimension of Analysis	Set of Questions	Interview questions
General introductory information	Introduction and role of the person interviewed	Would you please introduce yourself, and say some words about your background and your work in the DVE?
	Cases and topics treated in the DVE (Case already selected during sampling)	Which case would you like to focus on as exemplar in this interview and for what reason to you chose this one?

	Outputs/outcomes of the cases	What kind of outputs and outcomes did you produce with your case in the DVE?
	Description Success /effective/performance of the case, self-assessment of the case	How would you describe success and effectiveness of cases and projects treated in the DVEs? On a scale of 1 to 10 , how successful and effective was the case you refer to?
Purposes of use	Different goals and purposes	We understand that the DVEs can be utilized for very different purposes. Could you describe the purpose and goal of this case at hand?
	Involvement of different kinds of actors, participation	Can you describe the types of actors that are involved in the processes and participated in your case?
Visualizations	Different kinds of visualizations	What are the kinds of visuals and visualization of your data that you utilized in the named case?
	Series of subsequent visualizations	Do you apply a series of visuals and if yes what is the logic behind the series of images?
	Adaptation of visuals to target audience (and recipients background)	In what ways did you consider the adaptability or relatability of the visuals to the audience/recipients in the room?
Infrastructure	Interface equipment (hardware and software, room setup)	What are the specifics of your interface equipment for that respective case? Is this interface and set-up different from case to case?
	Input data and models	What is the model and what are the data sources that you use in that case?
	Visualization equipment	What kind of software and equipment did you use to produce and display the visuals in your DVE?
	Training, tech staff, other personnel, organization to get the infrastructure to use	Could you briefly describe whom (in terms of roles and expertise) do you need to get a case running in the DVE? Have you considered a training of staff or manuals to use your DVE?
Facilitation processes	Description of the process utilized in the DVE	Could you describe what the main subsequent facilitation/moderation/ interactive elements in your participatory setting are?
	Kinds of interaction around the visual(s)	What kind of specific interactions did you have around the visuals or how did you integrate the visuals into the process together with the participants?
	Feedback visuals, process and interface	How do you feed the data generated around the visuals and in the facilitated process with actors back into the model and in the interface

Transfer and Scaling	Transfers to other topics, with other type of purposes, or actors (past, present or future)	How do you evaluate options to transfer this specific set-up of visuals and engagement with actors, as well as hardware and software to other contexts, cases and topics or purposes? or Have you tried already?
Obstacles, challenges, and advantages of DVEs	Challenges in the general use of the DVE and specifically with visualization	What are the areas (technically, process-wise, infrastructure related) with the most challenges and why?
	Advantages in the general use of the DVE and specifically with visualization	What are the advantages of the usage and work in a DVE that you would you like to point out?
Future developments	Future development of DVEs in infrastructure/interface and application area	How do you envision the future development of DVEs for different application areas (such as research, or planning) with practitioners, regarding the infrastructure and interface, and specifically with regards to visualizations?

Interview results

The results of the interview were coded with MaxQDA software using an inductive approach in order to capture different terminology from interdisciplinary fields. A stepwise grouping and aggregation of the codes allowed for an overall comparison and the development of individual profiles per category. The table in the main text summarizes per each category, criteria that were built with respective attributes. “1” and “0” indicates for each DVE the applicability of the attribute.

Pool of DVEs

Institution	DVE	Location	Source
Arizona State University	ASU Decision Theater	Arizona, USA	http://www.dt.asu.edu/
Portland State University	Data Visualization Studio	Oregon, USA	https://www.pdx.edu/sustainability/data-visualization-studio
University of British Columbia	BC Hydro Decision Environment Theatre	Vancouver, Canada	http://cirs.ubc.ca/building/building-overview/research-learning-infrastructure/
University of British Columbia/Forest	Landscape Immersion Laboratory	Vancouver, Canada	https://www.researchgate.net/figure/248843024_fig2_Fig-2-The-Immersion-Lab-at-the-Forest-Sciences-Centre-University-of-British-Columbia

Science Center			
Universidad Nacional Autónoma de México	Anfiteatro de Decisiones LANCIS	México DF, México	http://lancis.ecologia.unam.mx/anfiteatro/
University of Alaska Fairbanks	Decision Theater North	Alaska, USA	http://www.dtn.alaska.edu/
Linköping University campus Norrköping	Visualization Center C	Linköping, Sweden	http://visualiseringscenter.se/en
University of Wisconsin-Madison	The Geoscience Visualization Center	Wisconsin, USA	http://www.geology.wisc.edu/facilities/viz_lab/ http://geoscience.wisc.edu/geoscience/people/faculty/harold-tobin/?id=627
UC Davis	Center for Visualization	California, USA	Center for Visualization: http://vis.ucdavis.edu/
Instituto Tecnologico de Monterrey (Centro del Agua para Americal Latina y el Caribe)	Nucleo Estrategico de decisiones (NED) (Strategic Decisions Nucleus)	Monterrey, México	http://www.centrodelagua.org/ned.aspx
Newcastle University	Decision Theater	United Kingdom	http://www.ncl.ac.uk/sciencecentral/urban/decision-theatre/
University of Vermont	Decision Theater	Vermont, USA	http://www.uvm.edu/~transctr/facilities/facilities_decisiontheater.html
Smart City Italia	Decision Theater	Torino, Milan, Genoa, Italy	http://www.smartcityitalia.net/projects/decision-theatre/
Huazhong University of Science and Technology	Visdec Electronic Decision Theater	Wuhan, China	https://www.christiedigital.com/en-us/news-room/press-releases/Chinese-University-Pioneers-Theater-Sized-Advanced-Visualization

North Carolina State University	The Hunt Library Teaching and Visualization Lab	North Carolina, USA	https://www.lib.ncsu.edu/spaces/teaching-and-visualization-lab
Harbin Institute of Technology	Decision Theater	Harbin, Heilongjiang, China	http://som.hit.edu.cn/html/tjdsq.html
Rochester Institute of Technology	Decision Theater	New York, USA	https://www.rit.edu/gis/research/facilities/instructional-areas
Desert Research Institute	Decision Theater	Nevada, USA	https://www.dri.edu/applied-innovation-center/research-areas-and-emerging-platforms/engineering-design-virtual-environments
Oregon State University	Graphics & Image Technologies Laboratory	Oregon, USA	http://eecs.oregonstate.edu/research/research-facilities
The Collider (Non-profit)	Technology Theater	Ashville NC, USA	https://thecollider.org/book-an-event/
The McCain Institute for International Leadership	Decision Theatre	Washington DC, USA	https://www.mccaininstitute.org/initiatives/decision-theater/
Laboratorio Binacional para la Gestion Inteligente de la Sustentabilidad Energetica y la Formacion Tecnologica	Teatro de Decisiones (Decision Theater)	Mexico City, Monterrey, Guadalajara, Mexico	http://energialab.com/
Our Lady of the Lake University	Business Decision Theater	Texas, USA	https://www.bizjournals.com/sanantonio/stories/2006/05/29/story8.html

Barcelona	Media TIC Incubator	Spain	https://de.wikiarquitectura.com/geb%C3%A4ude/media-tic/; http://www.22barcelona.com/content/view/41/427/lang,en/
TU Deft	INSYGHTLab	Netherlands	https://www.tudelft.nl/en/eemcs/research/facilities/insyghtlab/
UC San Diego	Studio Ten 300, Broadcast Studio	California, USA	http://ucpa.ucsd.edu/services/studio/
University of Illinois Chicago	Advanced Visualization Laboratory	Chicago, Illinois, USA	http://avl.ncsa.illinois.edu/category/current-projects
University of Illinois Chicago	Electronic Visualization Laboratory	Chicago, Illinois, USA	https://www.evl.uic.edu/list.php?id=2
University of Hawai'i	Laboratory for Advanced Visualization and Application	Hawaii, USA	http://lava.manoa.hawaii.edu
Helmholtz Zentrum für Umweltforschung	Visualization Center TESSIN VISLab (Vislab)	Leipzig, Germany	http://www.ufz.de/index.php?en=37716
Deutsches Forschungszentrum für Künstliche Intelligenz GmbH	Visualisierungszentrum/ Intel Visual Computing Institute	Germany	http://www.intel-vci.uni-saarland.de/ https://viscenter.dfki.de/ https://www.dfki.de/web
Technische Hochschule Nürnberg	3D-Visualisierungszentrum	Nuremberg, Germany	https://www.th-nuernberg.de/de/einrichtungen-gesamt/in-institute/institut-fuer-chemie-material-und-produktentwicklung/ohm-cmp/3d-visualisierungszentrum/
Swiss Federal Institute of	IWF - Innovation Center Virtual Reality	Zurich, Switzerland	https://www.icvr.ethz.ch/ https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/7375/eth-29681-02.pdf

Technology Zurich			
UCI Applied Innovation	The Beach	Californ a	http://innovation.uci.edu/the-cove/

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