Systems approaches to sustainability

Innovation and social-ecological-technological systems

Brooke Wilkerson

Thesis for the degree of Philosophiae Doctor (PhD)
University of Bergen, Norway
2023

UNIVERSITY OF BERGEN

Systems approaches to sustainability

Innovation and social-ecological-technological systems

Brooke Wilkerson

Thesis for the degree of Philosophiae Doctor (PhD)
at the University of Bergen

Date of defense: 19.12.2023

Year: 2023
Title: Systems approaches to sustainability

Name: Brooke Wilkerson
Print: Skipnes Kommunikasjon / University of Bergen

Scientific environment

This research has been conducted at the System Dynamics research group in the Department of Geography, and at the Center for Climate and Energy Transformation at the Faculty of Social Sciences, University of Bergen, Norway. Portions of the research were conducted as part of the New Water Ways research project with funding from the Norwegian research council (270742).

Acknowledgements

It’s a rare privilege to be given the opportunity to thank others so publicly and permanently. While the PhD is often celebrated as an individual triumph, the truth is that I would not be writing this page, in preparation for hitting the “send” button on the thesis submission website in just a few short hours, without the help, support, humor, critique, and company of many others. A PhD is not a solo achievement, and I’m lucky to have had so many kind and insightful people joining me on this journey.

First, I thank my supervisor and friend, Birgit Kopainsky, for sage advice, lightning quick comments on drafts, practical and empathetic perspectives, and enduring the occasional 10 km run. You share the gift of your time and wisdom so effortlessly and help others discover joy in research. I’m grateful for your mentorship and your friendship.

The Center for Climate and Energy Transformation and all the CETlers have built an incredible interdisciplinary community full of curiosity and enthusiasm. Thank you all for challenging discussions and questions, for serious and silly conversations, and for creating an inclusive and welcoming workplace that I’m happy to come to every single day.

The system dynamics research group has provided an excellent network for collaboration and shared learning. I thank especially my fellow “Crunchers,” Anaely Aguiar and Lars-Kristian Trellevik, for support in the final year of the PhD. You both are excellent sounding boards, and I hope our collaborations can continue on into the future.

The Alternet summer school has been a vital part of my intellectual and personal community for many years. I’m grateful to my fellow convenors, tutors, speakers, and numerous students, who have enlightened and challenged me and who have moved me to think critically about how my work – personal and professional – can help shape a

changing world. Thank you all for seeing the best in me and helping me see the best in everyone around me. You all will always have a special place in my heart.

I'd like to acknowledge the support and inspiration I gleaned from involvement in additional communities, including Get Ready, Get SETS: GI!; the sustainability reading group at UiB; Arqus European University Alliance; and the New Water Ways research project. Through these networks and communities, I have had the opportunity to research and write collaboratively with many people. To my mind, there's no work more joyful than bringing ideas to fruition together, and I'm grateful to my coauthors, all of whom have made me a better thinker and a better writer.

And lastly, I thank my family, Shale and Kai, for putting up with long days and late nights and enduring the occasional lecture on arrows and variables. Shale, you've been through this process yourself, and you still thought it was a good idea. Thank you for your love and support. And Kai, some people say that they can't imagine doing a PhD while having a kid. Well, I can't imagine doing a PhD without one. Thank you for making sure that I jumped on the trampoline, played badminton, and read Dog Man after long days in front of a computer. Your lessons in wooden sword fighting will no doubt prepare me well for the thesis defense. I love you both infinity times infinity.

Abstract in English

Sustainability is increasingly integrated into innovation and planning processes, yet the term is often incompletely or implicitly conceptualized and operationalized in those contexts. Operationalizing sustainability requires consideration of actions across sectors and across spatial and temporal dimensions. Sustainability is also inherently relational and systemic, and understanding interactions between individual components and the system as a whole is key to operationalizing the term. Approaching sustainability from a relational and dynamic perspective demands consideration of feedback and change over time. This points to the suitability of systems methods for understanding and operationalizing this term.

This thesis addresses the broad research question: How can systems approaches help understand and inform transitions towards sustainability? Within this scope, sustainability is conceptualized and operationalized in several ways. First, key facets of sustainability are identified that can support definition of innovation problems. Second, systems mapping methods are implemented in sustainability-oriented innovation processes to better highlight sustainability aspects. Third, system dynamics modeling is applied to an urban policy implementation case to illustrate interactions and synergies between stormwater management policies.

The primary conclusion of this thesis is that system methods have the potential to improve problem definitions for innovation and planning processes and to foster shared learning about complex sustainability issues. In particular, the methods developed in this thesis support more nuanced and complex thinking about sustainability and are perceived as useful by various types of practitioners. In addition, understanding urban policy innovations from a systems perspective can help identify potential goal conflicts and help optimize implementation. Though defining and operationalizing sustainability remains a challenge, efforts to further develop the concept and its application can still provide valuable guidance. As sustainability challenges continue to grow, the demand for such guidance will only become more urgent.

Sammendrag på norsk

Bærekraft integreres i økende grad i innovasjons- og planleggingsprosesser, men begrepet blir ofte ufullstendig eller implisitt konseptualisert og operasjonalisert. Å operasjonalisere bærekraft krever vurdering av handlinger på tvers av dimensjoner som rom, tid, og sektorer. Bærekraft er i seg selv et relasjonelt og systemisk begrep, og det er derfor avgjørende å ha en forståelse av samspillet mellom individuelle komponenter og systemet som helhet. Å tilnærme seg bærekraft fra et relasjonelt og dynamisk perspektiv krever dermed evaluering av tilbakekoblinger og endringer over tid. Dette peker på at systemmetoder er egnet for å forstå og operasjonalisere begrepet om bærekraft.

Denne avhandlingen tar opp det overordnede forskningsspørsmålet: Hvordan kan systemtilnærminger bidra til å forstå og informere overganger mot bærekraft? Innenfor denne rammen blir bærekraft konseptualisert og operasjonalisert på flere måter. For det første identifiseres sentrale aspekter ved bærekraft som kan understøtte en definisjon av innovasjonsproblemer. For det andre implementeres systemkartleggingsmetoder i bærekraftsorienterte innovasjonsprosesser for å bedre belyse ulike bærekraftsaspekter. For det tredje brukes systemdynamisk modellering og simulering for å forstå implementering av urban politikk, og for å illustrere samspill og synergier mellom ulike grep for håndtering av overvann.

Hovedkonklusjonen i denne avhandlingen er at systemmetoder har potensiale til å forbedre problemdefinisjoner for innovasjons- og planleggingsprosesser, og til å fremme felles læring og forståelse av komplekse bærekraftsproblemer. Spesielt støtter metodene utviklet i denne avhandlingen en mer nyansert og kompleks tenkning om bærekraft som oppfattes som nyttig av ulike typer praktikere.

I tillegg kan et systemperspektiv og systemforståelse av urbane politiske innovasjoner bidra til å identifisere potensielle målkonflikter, samt optimalisere implementering. Å definere og operasjonalisere bærekraft er fortsatt en utfordring, men bidrag til

videreutvikling av begrepet og dets anvendelse gir verdifull veiledning og retning. Ettersom bærekraftsutfordringene fortsetter å vokse, vil behovet for slik veiledning bare bli mer presserende.

Contents

List of articles

0. **Wilkerson**, B., A. Aguiar, C. Gkini, I. Czermainski de Oliveira, L.-K. Lunde Trellevik, and B. Kopainsky. 2020. Reflections on adapting group model building scripts into online workshops. System Dynamics Review 36:358-372. (research note; Wilkerson 30%)

1. **Wilkerson**, B., In review. Advancing sustainability-oriented innovation practice with quality criteria for problem definitions. Heliyon.

2. **Wilkerson**, B., and L.-K. L. Trellevik. 2021. Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches. Thinking Skills and Creativity. (Wilkerson 50%)

3. **Wilkerson**, B., E. Romanenko, and D. N. Barton. 2022. Modeling reverse auction-based subsidies and stormwater fee policies for Low Impact Development (LID) adoption: a system dynamics analysis. Sustainable Cities and Society. (Wilkerson 55%)

Reprints were made with permission from System Dynamics Review, Thinking Skills and Creativity, and Sustainable Cities and Society.

“Those of us who have talked about sustainability for a long time have stopped defining it. We sometimes say that it’s like jazz, or quality, or democracy — you don’t know it by defining it, you know it by experiencing it, by grooving with it, by living it — or perhaps by mourning its absence.” (Meadows, 1995)

“The nature of systems is a continuing perception and deception, a continuing re-viewing of the world, of the whole system, and of its components. The essence of the systems approach, therefore, is confusion as well as enlightenment. The two are inseparable aspects of human living.” (Churchman, 1968, p. 231)

1. Introduction

Sustainability is a broad and normative concept, with shifting and evolving definitions that have grown out of a desire to ensure that both current and future generations can meet their own needs without compromising planetary life support systems (Brundtland, 1987; Nagatsu et al., 2020; Shahadu, 2016). In an applied context, sustainability has implicit characteristics that require explicit consideration in innovation and planning settings. This thesis strives to structure sustainability's relevant characteristics and operationalize the concept for these complex contexts. I use systems methods to explore and understand diverse settings in which the concept of sustainability is applied, and I develop tools that can support a coherent application of sustainability by practitioners.

In particular, I identify and address three major research gaps. First, there is a conceptual gap for how sustainability is defined and understood in relation to innovations, including policy innovations. Second, a methodological gap is found in the lack of tools and practices that support defining sustainability problems. Third, there is an implementation gap defined by the challenges of implementing policies with sustainability aims, which can involve complex feedbacks, tradeoffs, and goal conflicts that are poorly understood. Together, these gaps track sustainability from an ambiguous concept to its practical application (figure 1). In sum, I argue for a reflexive and systemic approach to sustainability that accounts for social, ecological, and technological interactions.

Figure 1, Illustration of how articles in the thesis relate to different modes of sustainability. Roman numerals refer to the article number on previous page.

In the following sections of this introduction, I present salient characteristics of sustainability for the contexts addressed in this thesis (section 1.1), explain the relevance of the innovation and urban contexts for sustainability questions (section 1.2), and briefly present the systems approaches used to address sustainability (section 1.3).

1.1 Sustainability characteristics

The way sustainability is conceptualized has implications for its practical applications in real-life situations. As a lens, sustainability directs attention to particular aspects of complex problems. In framing the research in this thesis, and applying sustainability to innovation and planning contexts, there are several aspects of sustainability that are particularly salient.

Working towards sustainability requires consideration of multidimensional targets, including environmental, social, and economic impacts (Buhl et al., 2019; Videira, Antunes, Santos, & Lopes, 2010). As sustainability is inherently multidimensional, operationalizing sustainability requires careful attention to actions and impacts across sectors and an appreciation of interrelations and interdependencies across spatial and temporal scales, including future generations (Gibson, 2006; Hjorth & Bagheri, 2006;

Videira et al., 2010). This also leads to an understanding of sustainability as a process-oriented concept. Working towards sustainability requires a negotiation of relationships among shifting targets, goals, ambitions, and real-world conditions that will vary over time. This “relational unfolding” means that approaching or maintaining sustainability requires constant adjustment across its interrelations and interdependencies, even as one moves closer to a normative sustainable future (West, Haider, Stålhammar, & Woroniecki, 2020).

Sustainability is a system property, rather than a property of elements in the system (Gaziulusoy, 2015; Lanhoso & Coelho, 2021). This has implications for individuals embedded in a society and the many interlinkages and feedbacks among individuals and communities. Sustainability at the individual level depends on and is inextricably linked with sustainability at the societal level (Ruggerio, 2021). In addition, the consequences of working towards or achieving sustainability may be different at the individual versus the societal level, raising questions of social justice and equity (Bennett, Blythe, Cisneros-Montemayor, Singh, & Sumaila, 2019). Individuals may need to change their lifestyles and livelihoods in ways that are difficult or uncomfortable in order to move towards sustainability at the societal level. Changes that may be experienced as negative at the individual level may have emergent positive impacts at the societal level. This has implications for which tools are appropriate for working with sustainability and points to the imperative of considering both individuals and society in an explicitly systems perspective (Bennett et al., 2019). This systems quality has implications for what level(s) of society actions should target and where impacts can expect to be felt.

As a normative concept, sustainability is animated by visions of what a desirable future could look like in addition to more fixed attributes (Schlaile et al., 2017). The term is context and people dependent and imbued by worldviews. From this perspective, sustainability will always be contested, but that does not mean that it’s meaningless (Ramsey, 2015). Rather, the normative aspect of sustainability should be considered an integral element that tethers the definition of the term to a specific use and context.

Lastly, sustainability cannot be predicted; it can only be identified in retrospect (Costanza & Patten, 1995). Only when we look back on how a system has behaved can we assess that system’s sustainability as an emergent quality. While we are surrounded by obvious examples of what “unsustainable” looks like, finding examples of sustainable systems can be more difficult. This can make it challenging to operationalize the concept, and to describe a desirable future (in an innovation process or in a scenario) when we have few examples on which to base our visions.

These characteristics of sustainability as a concept need to be considered when applying sustainability to specific contexts. Summarizing across these characteristics, as outlined in Wilkerson (unpublished manuscript), one should consider that sustainability is:

- **Dynamic across sectoral, spatial, and temporal scales:**

As an inherently dynamic concept, operationalizing sustainability requires a comprehensive consideration of actions and impacts across sectors (such as environment, society, and economy) and a recognition of interrelations and interdependency across spatial and temporal scales, including future generations (Gibson, 2006; Hjorth & Bagheri, 2006; Videira et al., 2010). Actions towards sustainability should be robust to nonlinear dynamics and a range of potential conditions.

- **Relational and systemic:**

Sustainability is a relational property that arises from dynamic system interactions (Shahadu, 2016). Only when the system as a whole is sustainable can the individual components of the system be considered sustainable (Gaziulusoy, 2015). Stakeholders are central actors situated in specific contexts who influence and are influenced by community and environment relations, and knowledge is always positioned and partial (Leach, Stirling, & Scoones, 2010).

- **Emergent:**

Overlaying relational and dynamic understandings highlights the emergent aspects of sustainability as a complex system. The emergent qualities of systems mean that the consequences of working towards or achieving sustainability may be different at the individual versus the societal level, raising questions of relational interlinkages and just transformations (Bennett et al., 2019; Jerneck et al., 2011). Unfolding relationships among people and places reveal emergent dynamics that demand reflexive and iterative approaches (Gaziulusoy & Brezet, 2015). Sustainability is a deeply normative concept, with descriptions of a desired state that are embedded in and emerge from social interactions and worldviews (Schlaile et al., 2017).

1.2 Contexts

The characteristics of sustainability as a concept have implications for how we envision and plan for the future. Working towards sustainability will require innovations in how we live, work, and relate to each other and the world around us. Designing appropriate innovations requires a deeper engagement with sustainability's characteristics and an understanding of the potential near- and long-term impact of those innovations from a comprehensive and dynamic perspective. This thesis explores, applies, and operationalizes this understanding of sustainability in two different contexts, using systems approaches.

First, innovation processes are increasingly incorporating sustainability as a goal. Participants in sustainability-oriented innovation (SOI) processes often struggle with defining the innovation problem with adequate consideration of sustainability's characteristics. Though innovation can be broadly defined as "new ways of thinking and new ways of doing" (van den Hove, McGlade, Mottet, & Depledge, 2012), typical innovation processes are focused on individual products or services. These innovations result in only minor improvements in sustainability terms (Gaziulusoy & Brezet, 2015), yet SOI will often require solutions that move beyond incremental adjustments on a product or technology level (Buhl et al., 2019). In this thesis I examine innovation processes and integrate system methods into problem definition activities to better capture important attributes of sustainability that can be overlooked.

Second, in complex urban environments, planning and implementing policies for sustainability can have unintended consequences, goal conflicts, or lack optimization. Cities are highly interconnected, complex, adaptive systems (McPhearson, Haase, Kabisch, & Gren, 2016). Climate projections for Europe foresee an increase in precipitation extremes (Nikulin, Kjellstro, Hansson, Strandberg, & Ullerstig, 2011), and concentrations of people in urban areas can increase vulnerability to climate disasters and extreme events. Ongoing densification in cities also increases the amount of hard, impermeable surfaces in the city, increasing the challenges of adapting to a changing climate, such as managing stormwater. I use quantitative and qualitative systems approaches to understand policy implementation and tradeoffs in cities as social-ecological-technological systems (SETS).

Together, these two contexts take sustainability from conceptualization, to methods for application, and on to implementation. My work in the innovation context focuses on improving understandings and definitions of sustainability issues. Within this context, I’ve engaged with both the private sector and education sector. A central challenge is how to enable and support comprehensive and coherent definitions of sustainability issues. My work with urban planning and stormwater management moves beyond problem definition to focus on implementation of sustainability policies. This work focuses on policy implementation and on anticipating policy tradeoffs. Collectively, these contexts and applications provide a broader picture of how sustainability could be operationalized to realize desirable outcomes and traces aspects of sustainability from conceptualization to operationalization and implementation.

1.3 Systems thinking approaches

These contexts are considered using systems approaches. Beneath the broad umbrella of systems thinking and systems approaches are a number of quantitative and qualitative approaches which can generate different levels of insights (Barbrook-Johnson & Penn, 2022; Cabrera, Cabrera, & Midgley, 2021). Regardless of the specific systems method used, systems approaches generally include an understanding of a system as a bounded and interconnected set of elements set in relation to each other (see for example (Bertalanffy, 1968; Meadows, 2008). Systems thinking, *sensu lato*, can help address the intertwined drivers and relationships that characterize sustainability issues (Seto et al., 2012). A systems thinking approach typically includes a focus on feedback and awareness that a system’s structure creates its behavior. It provides a transdisciplinary perspective in which no single sector is more important than another (McPhearson, Haase, et al., 2016).

Systems thinking has experienced a “Cambrian explosion” of methods in recent years (Cabrera et al., 2021), and there is often confusion among overlapping methods, terminology, and names. For example, what I call “systems mapping” in this thesis is considered a single approach (more or less equivalent to causal loop diagraming or group model building) by some, while others consider “systems mapping” to be a broader term that encompasses a suite of different quantitative and qualitative systems methodologies (Barbrook-Johnson & Penn, 2022).

In the context of this thesis, I use both systems mapping and group model building to describe a method of guiding participants through a process of generating a shared map and understanding of a complex system. My intention with using the term “systems mapping” (as opposed to causal loop diagraming, participatory system dynamics, or group model building, which are all terms used at times for similar methodologies) is not to seed confusion but rather to appeal to non-experts who may otherwise be unfamiliar with systems methodologies and who may be confused or intimidated by the more technical wording in other names. Thus, when writing about methodology to a systems modeling audience in the *System Dynamics Review*, I use the name “group model building” (Wilkerson et al., 2020), while when writing about new approaches for sustainability-oriented innovation to a general audience in *Thinking Skills and Creativity*, I use the name “systems mapping” (Wilkerson & Trellevik, 2021).

I make use of two systems methods in this thesis. Systems mapping can enable knowledge co-production and enlarge or reframe stakeholders’ perspectives. This method is used primarily in the innovation context. Quantitative system dynamics modeling can help identify tipping points and optimize policy implementation. This method is applied to understanding urban sustainability policies. In this thesis I include applications of both of these methods to address operationalization and implementation of sustainability across contexts. How these methods fit within the “family tree” of systems thinking methods is discussed in section 2.5.

2. Literature review

In this section, I outline the primary fields of scholarship that I draw on in this thesis, including sustainability science approaches to sustainability, sustainability-oriented innovation, social-ecological-technological systems, blue-green infrastructure, and systems methods.

2.1 Operationalizing sustainability

Pursuing a definition of sustainability can be like entering a thicket of endlessly forking paths. Definitions diverge, overlap, evolve, and blink out. It's not surprising, then, that many researchers simply hop over defining this well-used term and take a stance similar to US supreme court justice Potter Stewart's definition of "hard core pornography": "I know it when I see it" (1964). It can be easier to say what's not sustainable than to define what is sustainable. Yet sustainability *does* have meaning, and the concept is employed in countless contexts that shape the decisions we make, delineate the problems we focus on, and define policy directions.

As a normative term, sustainability is imbued by how we approach the world and the breadth and depth of our ambitions for the future. We cannot "define our way to clarity" (Ramsey, 2015). Rather, it is through acts of engaging with and performing sustainability that the term becomes tangible. The term can only be meaningful in relation to its context (Ramsey, 2015), and sustainability can only truly be recognized in retrospect (Costanza & Patten, 1995). At the same time, businesses and organizations require guidelines and measurable objectives if they are to make progress towards a desirable, sustainable future (White, 2013).

This is a central tension for operationalizing sustainability: on the one hand, there is an endless demand for measures and indicators for operationalizing sustainability. On the other hand, as we employ the term in social context and practice, appropriate measures and indicators – indeed, even who and what sustainability is for – will inevitably change. The term cannot be defined "from above" (Ramsey, 2015). This thesis operates within this central tension – between the desire to provide usable, concrete guidance for working with and towards sustainability and the recognition that any such guidance, if it is to be useful, depends deeply on context and is almost certainly ephemeral.

In situating this tension, it's worth exploring some of the definitions of sustainability and the dimensions along which various incarnations of the term can be placed. While we cannot "define our way to clarity," we can examine definitions to understand what they say about how sustainability has been operationalized in various points in time and contexts. In general, the concept of sustainability has changed over time and across disciplines and applications, becoming both broader and more diffuse. Faber et al.'s (2005) analysis provide a useful entry point for considering how sustainability has been conceptualized and what implications that can have for how the concept is employed. Presented here in an abbreviated form, the authors identify two continua, which I will illustrate using two different definitions of sustainability. The first is the definition of sustainable development presented in the UN 1987 report Our Common Future (also known as the Brundtland report). In that document, sustainable development should "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). The second definition comes from the field sustainability science. Shahadu (2016) describes sustainability as "the goal of keeping the productive capacity of life support systems in harmony with the demands placed on them, at all times." These definitions are chosen for their familiar yet contrasting framing of the concept.

The first continuum defined by Faber et al. considers the goal orientation for the change towards sustainability (figure 2). One end of the axis is the "absolute perspective," that is, embedding an idealized end state in the definition. The other end is the "relative perspective," in which sustainability is defined relative to the current situation. The Brundtland (1987) definition's emphasis on "future generations" as its reference point puts it on the absolute end of the continuum. In contrast, Shahadu's (2016) focus on harmony "at all times" situates sustainability as a concept that is always relative to the current situation.

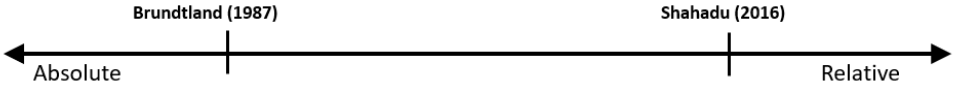


Figure 2, Goal orientation continuum based on Faber et al. (2005), which ranges from an absolute, idealized end state to a relative goal in reference to current conditions.

The second continuum in Faber et al.'s framework considers the relationship between the object of sustainability and its environment (figure 3). Along this continuum, the relationship can be considered static or dynamic. In a static relationship, the object is dynamic but its environment isn't (though it may have resource limits). From this perspective, the Brundtland (1987) definition can also be considered static, as it assumes that underlying social and environmental structures remain constant (Faber, Jorna, & Van Engelen, 2005). At the dynamic end of the axis, both the artifact and its environment are subject to both exogenous and endogenous forces that require continuous adaptation in order to be sustainable. Thus sustainable is no longer conceived as an achievable goal but as continuous process of improvement that requires constant effort (Faber et al., 2005). Shahadu's (2016) definition, with its emphasis on an active process towards harmony, can be considered dynamic.

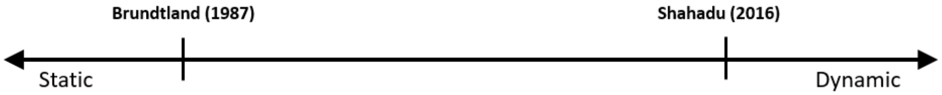


Figure 3, Continuum based on Faber et al. 2005 that illustrates the relationship between the object of sustainability and its environment. The continuum ranges from static (sustainability as a goal) to dynamic (sustainability as a process).

Over time, definitions of sustainability have tended to migrate from absolute to relative, and from static to dynamic, reflecting a broader and more relational vision of sustainability (Faber et al., 2005). The sustainability science literature, in particular, reflects these shifts, and explicitly relational and dynamic approaches to social-ecological systems are standard (Clark & Harley, 2019; Schlüter et al., 2022). It should be noted, however, that one of the challenges of working with sustainability and its definitions is not just how the term has evolved over time but also how easily the term attracts modifiers. Sustainable development, sustainability science, corporate sustainability, and social sustainability – to name a few – will naturally define sustainability within its own modified context. Thus noting that one conceptualization is more relative, or more dynamic, than another is not a judgement against the quality of that conceptualization but rather an acknowledgement of where the term is situated and used.

A complementary framing can be extrapolated from Helfgott's (2018) work on resilience, and supported from various sources that have worked on sustainability. Interrogating definitions of sustainability with questions such as "of what" (what is being sustained) and "for whom" (for whom is it being sustained) can expose the framing of the term (Table 1). Sustainability "of what" is a question raised by Costanza and Patten (1995) and by Faber et al. (2005). Sustainability "for whom" is a question found in work by Ruggerio (2021) (who addresses geographic area) and Gunder (2006) (who questions who benefits from sustainability measures). An additional question, "to what end," is not part of Helfgott's framing of resilience, but is especially important when considering sustainability. Sustainability is normative and defined, in part, by our articulated ambitions, so answering "to what end" is integral to understanding the normative dimension of a sustainability definition. "To what end" is a question raised by Schlaile et al. (2017), who ask, "what future do we want?" in an innovation context, and Schneider et al. (2019), who encourage sustainability science researchers to engage in sustainability visions. Together, answers to these questions can help reveal the framing of sustainability that is used and how it is being operationalized in a specific context. In Table 1, I present these framing questions, with examples for how they could be answered, and a revisiting of the Brundtland (1987) and Shahadu (2016) definitions of sustainability.

Table 1, Questions for framing and operationalizing sustainability.

Sustainability questions	**Description**	**Example answers**	**Brundtland (1987)**	**Shahadu (2016)**
Of what	What do we want to sustain? What is the focal object for the definition?	Innovation product; Environmental resources; Society	Development	Life support systems
For whom	Who are the primary beneficiaries if actions towards sustainability are taken?	Current and/or future generations; Non-human beings; Geographically or politically limited areas	Future generations	Present generations
To what end	What is the vision/goal? What is the desirable future that can be achieved if actions towards sustainability are taken?	Resource self-sufficiency; human wellbeing; human dignity	Meeting human needs	Harmony between capacity and demand

Sustainability is a concept in flux. As understandings of system interactions becomes more nuanced, understandings of sustainability become broader (expanding boundaries and time frames), and it can become more difficult to capture essential elements that comprise sustainability. Sustainability cannot be reduced to a succinct and universal definition, as the "systems are too complex, the constituencies too varied, and the applications are too diverse" (White, 2013). Yet, in order to be usable and relevant to specific contexts and decision making, there is a need to identify and "re-gather" these elements to create a coherent understanding of sustainability, even as this understanding is temporary and will be replaced by new understandings. The characteristics listed in section 1.1 are an example of salient aspects of sustainability for specific contexts, in this case innovation and planning. Identifying key elements of sustainability for specific uses and contexts can make this often nebulous concept more practicable and constructive. Doing so is not merely an exercise in conceptual clarity but defines a worldview of what we prioritize and how we interact with the world (Ramsey, 2015).

2.2 Sustainability-oriented innovation

One context in which how sustainability is operationalized plays an important role is sustainability-oriented innovation (SOI). SOI is often distinguished from other types of innovation processes by its characteristics such as accounting for a long time horizon, setting a given problem in a larger context, and considering multidimensional targets (Buhl et al., 2019), yet those aspects are not always explicit. In many SOI processes, sustainability is not directly operationalized, and problem statements or descriptions are often absent or vague (Buhl et al., 2019). Yet how sustainability is understood in a SOI process, and therefore how the innovation problem is defined, has a significant impact on the scope of innovation process and the ambitions of the resulting innovation.

In the innovation context, sustainability's often implied and assumed qualities can make room for a broad variety of understandings and expectations (Nagatsu et al., 2020). In a positive sense, the open-ended nature of sustainability can accommodate diverse responses to complex challenges (Savaget, Geissdoerfer, Kharrazi, & Evans, 2019). Yet in a negative view, sustainability can be described as a concept that “lacks consensus and direction” (Faber et al., 2005; Hjorth & Bagheri, 2006). A more serious threat is that sustainability’s ambiguous and drifting qualities as a concept can be exploited to create a pacifying “win-win” discourse that hides real, essential tradeoffs (Ben-Eli, 2018; Savaget et al., 2019). This can be especially troubling in innovation arenas, where poorly-conceived sustainability “solutions” can have deleterious side effects.

Where one’s definition of sustainable falls along Faber et al.’s (2005) continua has implications for the scale and scope of the innovation process and its resulting innovation. For example, an innovation process grounded in an absolute, static perspective may be more likely to result in innovations in the form of products or services that may underestimate their broader impacts on society. An innovation process that takes an explicitly relative and dynamic view of sustainability will naturally take societal perspectives and shifting environmental conditions into account, creating the space for transformative innovations at the system level (Clark & Harley, 2019). More relational and dynamic conceptualizations of sustainability require more complex responses to address sustainability issues. Innovation aimed at sustainability should have a systems and societal scope that accounts for multidimensional targets (Buhl et al., 2019).

In addition, parallels to this transition in how sustainability is defined can also be seen in how SOI practices have progressed. As discussed by Adams et al. (2016), and expanded on by Ceschin and Gaziulusoy (2019), SOI best practices have evolved from a narrow technical- and product-centric focus towards a focus on system level changes (Ceschin & Gaziulusoy, 2019). This change can be mapped along two dimensions (figure 4). First, the insular/systemic axis describes a progression from innovations which address a firm's internal issues toward a focus on making changes to the wider socio-technical (or socio-technical-ecological) systems. This axis describes the scope of the innovation. Second, the technology/people axis ranges from a techno-centric and incremental view of innovation to human-centric perspectives in which user practices and behavior play a fundamental role in SOI (Ceschin & Gaziulusoy, 2019). They further envision moving beyond human-centric to earth-centric as a necessary expansion towards sustainability transformations. Ceschin and Gaziulusoy (2019) describe the potential positive impact for sustainability as increasing the further out one is along these axes.

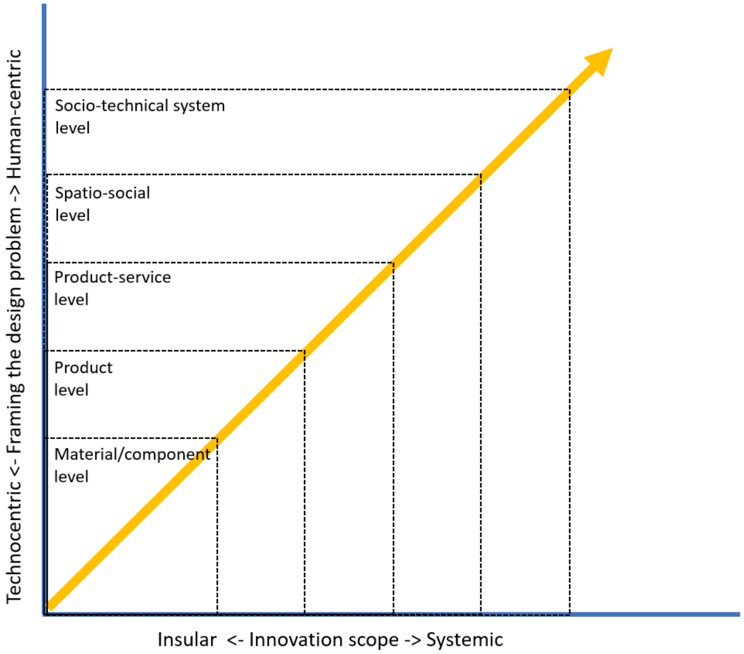


Figure 4, SOI levels, simplified based on Ceschin and Gaziulusoy (2019). The yellow arrow indicates increasing potential for a positive impact for sustainability.

Progressing along the axes in figure 4 depends not only on how sustainability is operationalized but also on how the innovation problem is defined. Defining the scope of the problem sets the boundaries for where innovative solutions can be developed. A problem defined too narrowly can restrict the room for available solutions and could lead to innovations that are too limited to have a meaningful contribution towards sustainability (Hoolohan & Browne, 2020). Yet, as outlined in Wilkerson and Trellevik (2021), problem definition is an often overlooked phase in SOI, and current SOI processes are usually characterized by absent or vague problem statements (Buhl et al., 2019).

Further, traditional approaches to innovation, such as design thinking methodologies, tend to target individual users and their needs when defining the problem. This focus, though valuable, can exclude the broader, cross-sectoral and systems perspectives needed to adequately define a sustainability-related problem. A key research question for SOI is how innovation methodologies such as design thinking can engage in reconfiguring social, political, and material systems in support of sustainability aims (Hoolohan & Browne, 2020). Systems approaches, including systems mapping, can help address this need (Wilkerson & Trellevik, 2021).

2.3 Social-ecological-technological systems (SETS)

Cities are complex systems with dynamics among social, built, and environmental sectors that are often poorly understood and difficult to capture and quantify (Bettencourt, Lobo, Helbing, Kühnert, & West, 2007). In the context of transitions towards sustainability, this incomplete understanding of urban dynamics can lead to poorly implemented policies or counterintuitive outcomes. Complex system interdependencies can lead to many possible urban transition pathways with very different sustainability outcomes (Webb et al., 2018). Advancing urban systems science requires new approaches that can provide insight and guidance on how to make our cities more sustainable, resilient, equitable, and livable (McPhearson, Haase, et al., 2016).

Successfully planning for and managing of urban areas requires an understanding of how the diverse components of a city interact to create patterns and processes that influence urban system dynamics (McPhearson, Haase, et al., 2016; McPhearson, Pickett, et al., 2016). Driving forces in urban areas include socioeconomic, political, technological, natural, and cultural dynamics (Haase and Schwarz 2007). Relationships in urban areas are complex, intertwined, and dynamic, and feedback loops, nonlinearities, and emergent phenomena are the norm (Seto et al., 2012).

Social-ecological systems (SES) are well-established conceptual frameworks for exploring and understanding complex human-nature interactions. Human and natural systems are tightly interwoven with multiple dependencies and feedback effects. In an urban context, these complex interactions are mediated by human-built infrastructure, such as roads, buildings, and sewer systems (McPhearson, Haase, et al., 2016). Most SES perspectives view technological systems as a subset of social systems, yet in an urban context, technological systems and their attendant infrastructure have long lifespans that exert strong path dependencies and lock-ins that can constrain policy options (Markolf et al., 2018).

In contrast, from an engineering perspective, technological systems can take precedence over social and ecological systems, and traditional infrastructure planning approaches can treat social and ecological domains as external design conditions rather than embedded system characteristics (Kim et al., 2022). While social, ecological, and technological systems can often be decoupled in planning and management, in reality they are tightly intertwined. Infrastructure systems are typically relatively inflexible, rigid, and long-lasting (obdurate), and they can exert significant influence and agency relative to social and ecological systems (Markolf et al., 2018). Broadening a SES approach to explicitly consider technological interactions helps contextualize the role of infrastructure in shaping interdependencies in complex urban systems. Social, ecological, and technological spheres are increasingly interconnected and interdependent in an urban context (Markolf et al., 2018).

Social-ecological-technological systems (SETS) merge these two perspectives through acknowledging the strong influence of infrastructure within the complex interactions among social and ecological systems (fig. 5). SETS can be defined as "interacting natural and human systems in which the technological component represents the increasingly complex realm of interaction between the human and natural systems" (Cosens et al., 2021). Accounting for the emergent and interconnected nature of SETS allows for a fuller exploration and development of the solution space for infrastructure in changing environments and extreme events (Markolf et al., 2018). The SETS perspective helps reveal the complex causality of infrastructure opportunities, constraints, and failures (Markolf et al., 2018).

Urban green infrastructure, in particular green stormwater management, is a realm in which these complex interactions are particularly pronounced. By highlighting technical aspects as a third component (instead of placing them under social systems) the SETS framework adds focus to the lock-in and path dependencies that are integral characteristics of technological systems. These characteristics are especially important for urban stormwater management, where long-lived infrastructure can reduce adaptive capacity and exert a large influence on innovation potential and policymaking. The role of urban infrastructure can be decisive for how human-nature interactions unfold and how vulnerabilities and interdependencies are created and experienced. Identifying S, E, and T aspects of research framings or policy interventions can help illuminate how that work is situated in the urban context and where the ambitions for impact are targeted.

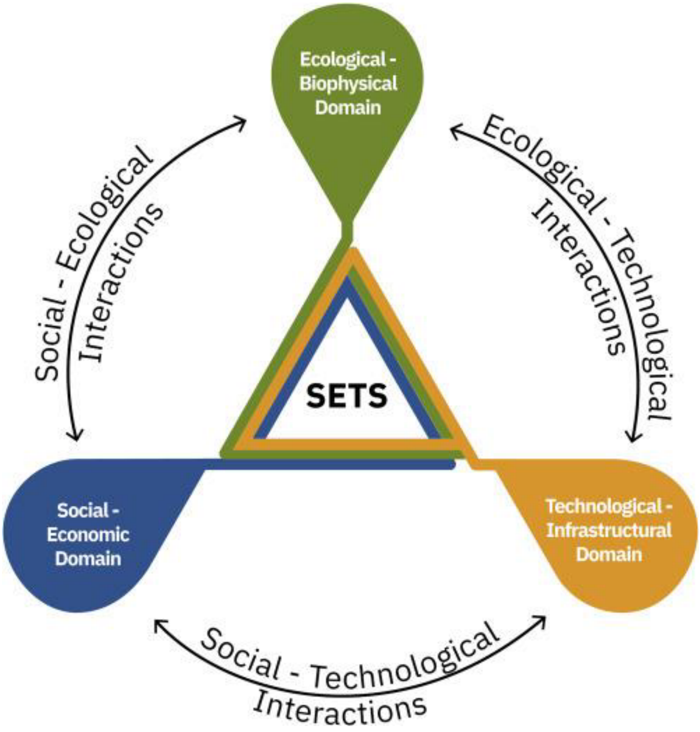


Figure 5, Conceptual diagram of social-ecological-technological systems, taken from (McPhearson et al., 2022).

While SETS framings acknowledge the inherent systemic complexity of these interacting realms, there are few SETS studies that take an explicitly systems approach to understanding SETS (though see (Markolf et al., 2018)). Systems thinking and awareness of corresponding structures and dynamics are a particularly underdeveloped aspect of urban planning and analysis, especially in cross-cutting issues such as water and ecosystem management (Wolfram, 2019). In many cities, there's a widespread deficit in dealing with both complex problems and sustainability (Wolfram, 2019). There is a need for new approaches for understanding SETS.

The SETS framework is able to bring together and conceptualize different topics and processes, but it does not provide defined analytical or methodological approaches (Branny et al., 2022). The framework operates at the conceptual level. As recent literature has coalesced around the concept, SETS have been increasingly defined as "entangled" or "intertwined" with "dynamic interrelationships" and "dynamics and emergent outcomes that are increasingly beyond our grasp" (Chester et al., 2023; McPhearson et al., 2021). These articles point to the complex couplings and interdependencies among domains and suggest that SETS can be a starting point for holistic system approaches for addressing sustainability challenges (McPhearson et al., 2021).

Transforming urban areas towards sustainability will require radical departures from traditional "siloed" management perspectives (McPhearson et al., 2021), and paradigms of infrastructure control should yield to more nuanced and novel decision-making approaches (Chester et al., 2023). Yet in my view, proposed approaches emerging from these perspectives are ambitious in scope, unclear in their timeframe, and indirect in their impacts on policy. It is unclear if and how these entangled perspectives can actually shape and inform policy and society. While there is academic value in highlighting the real complexities of urban systems, there is also a danger, I would argue, that decisionmakers can be paralyzed by this multi-layered and entangled framing. New methods are needed to understand urban systems in the context of normative goals such as sustainability and resilience and to identify potential tradeoffs that can limit progress towards those goals (McPhearson, Haase, et al., 2016), and they need to be relevant to target user groups. As the conceptualization of SETS becomes more settled, the emerging next steps are to decompose aspects of SETS entanglements into actionable problems, and to implement the SETS framework in the context of tangible policy measures.

2.4 Urban low-impact development as an example of SETS

As cities adapt to climate change, changes in urban green space can affect multiple aspects of society. Establishing or upgrading low-impact development (LID) or blue-green infrastructure (BGI) is an increasingly common approach to address climate change and urbanization impacts through managing stormwater infiltration and buffering against flood events while providing other benefits in urban areas (McPhearson, Haase, et al., 2016). In many regions, these "nature-based solutions" are seen as a necessary component of climate change adaptation (Kabisch et al., 2016). Integrating BGI into planning is seen as a policy innovation especially well-suited for urban areas, as these areas are characterized by strong, dynamic interplay of ecological and social systems (Hansen & Pauleit, 2014).

BGI, such as rain gardens that allow surface water to collect and slowly infiltrate soil, can have the added benefit of serving as attractive green spaces and park areas. Integrating BGI into the fabric of urban areas is often viewed as a win-win situation that reduces pressure on stormwater systems while providing spaces for recreation. Families in urban areas are especially dependent on access to green areas for recreation. BGI can also provide a number of other societal benefits in the urban context, including climate regulation, noise reduction, pollinator habitat, and water purification (Gómez-Baggethun & Barton, 2013). However, aspects of urban greening and sustainable design in service of reducing climate vulnerability may affect aspects of social sustainability such as housing prices and affordability (Cavicchia, 2021).

Setting clear policies and expectations for establishing LID in new building projects is relatively straightforward, but in an urban environment, most areas are characterized by a patchwork of small, built properties managed by diverse owners. For example, Oslo, Norway, has implemented a "blue-green factor" regulation for setting minimum requirements for LID in new building projects (Oslo kommune, 2018), but lacks tools for incentivizing adoption of LID on existing built properties. Integrating any new infrastructure -- even green infrastructure -- into established urban areas can be costly and disruptive (Schifman et al., 2017). As small-scale infrastructure, LID requires widespread adoption in order to have a meaningful impact in stormwater management systems. Increasing adoption of LID requires innovations in policies and an understanding of how various policies interact with each other.

Though cities are commonly understood as complex systems, dynamic approaches to understanding urban complexity are relatively uncommon. In particular, dynamic modeling is poorly integrated with urban analyses (Haase & Schwarz, 2009). Integrated dynamic models that capture both feedbacks and emergent behavior are especially relevant to urban systems but have been little used (Kolosz et al., 2018; Webb et al., 2018). This gap is especially apparent when innovative and ambitious policies can have unanticipated consequences. For example, improvements in urban greenspace can lead to gentrification and displacement (Anguelovski et al., 2022), and cost-sharing programs for BGI on private property can favor already wealthy landowners (Brent, Cook, &

Lassiter, 2022). Closing this gap is critical to understanding policy implications and anticipating tradeoffs in transitions to sustainable futures.

2.5 Systems methods

Approaching sustainability from a relational and dynamic perspective demands consideration of feedback and change over time, and systems methods are therefore a natural fit for further engaging with and operationalizing the concept. As this thesis engages with a range of systems methods, it’s worth tracing how these methods relate to and inform each other. Systems methods, sometimes also called systems thinking, is comprised of an expanding number of quantitative and qualitative approaches. Though systems thinking is poorly defined in the literature, it’s broadly understood as an approach to complexity that emphasizes feedback and an awareness that a system’s structure creates its behavior. Cabrera et al. (2021) outline three “waves” of systems thinking that trace the evolution of the field. Unlike a Kuhnian paradigm shift (Kuhn, 1970), waves represent a shift in focus rather than an abrupt revolution, and they can coexist more-or-less compatibly in the vast ocean of systems thinking practices. The waves do not replace each other; rather, each wave represents its own state of the art. Importantly, methodologies that are the product of earlier waves continue to evolve and mature even as new waves emerge.

2.5.1 The first wave (1950s)

Though antecedents to systems thinking can be found as far back as ancient Taoist texts, the first “modern” wave of systems thinking emerged in the 1950s. It relies primarily on quantitative modeling, and is characterized by expert analysis and a pursuit of objectivity, often with a focus on optimizing a system (Cabrera et al., 2021; Jackson, 1994; Midgley, 2001). Originating in engineering and operations research, systems were seen as primarily physical, and a computational metaphor undergirded most approaches to understanding systems (Cabrera et al., 2021). It was in this wave of “hard systems thinking” that system dynamics modeling was born (Forrester, 1961; Midgley, 2001).

This first wave was revolutionary in its critique of the predominantly reductionist practice of science at the time, which tended to focus on decomposing complexity and simple, linear causalities (Cabrera et al., 2021). Yet, this wave of systems thinking maintained one critical assumption of the dominant practice of science of the time: objectivity (Cabrera et al., 2021). The implicit assumption of the first wave is that a practitioner or modeler (as a sole decisionmaker) could achieve an objective, and perhaps omniscient, understanding of a system through mathematical modeling (Jackson, 1994). This wave is still in practice today in system dynamics modeling, systems engineering, and systems analysis, and these methodologies continue to be expanded and refined.

2.5.2 The second wave (late 1970s)

The second wave of systems thinking is characterized by qualitative modeling and participatory practice. Sometimes called “soft systems thinking,” it grew in response to the perceived limitations of “hard systems thinking” (Cabrera et al., 2021). The second wave emphasized accounting for human and non-technical aspects of systems and exploring multiple and subjective perspectives (Cabrera et al., 2021). This resulted in multiple new methodologies, including soft systems methodologies, interactive planning, and Churchman’s systems approach (Cabrera et al., 2021; Churchman, 1968). Importantly, the idea of a system transformed from a physical object and computational metaphor to a “useful conceptual device” for interpreting complex situations (Cabrera et al., 2021). Within the system dynamics community, group model building, in which stakeholders (typically system managers or decision makers) are for the first time involved in modeling, emerges.

The second wave explicitly takes reality as mediated through our perceptions and interpretations (Midgley, 2001). A systems practitioner is no longer objective but is, instead, a participant-observer. Instead of optimization, practitioners' focus shifted toward discovery and adaptation of complex adaptive systems (Jackson, 1994). Stakeholders' perceptions and values, in addition to the practitioners', mediate the construction and interpretation of the system (Cabrera et al., 2021). This dramatic shift in the practitioners' role made room for qualitative methodologies and led to a change in emphasis from systems existing in the real world to perspectives on actions having systemic impacts and methodologies as systemic processes of inquiry (Cabrera et al., 2021).

Rather than being external and knowable, reality is constructed through participatory dialogue, shared understanding, and exploration of assumptions (Cabrera et al., 2021). The second wave represented, therefore, an epistemological rupture with the first wave of system thinking, and, for a time, it fragmented the systems research community as researchers turned their focus inward to developments within their own systems specialties and paradigms (Jackson, 1994).

2.5.3 The third wave (late 1980s)

The third wave of systems thinking emerged from the insight that the first and second waves could represent complementary approaches that did not need to be mutually exclusive (Cabrera et al., 2021). This new wave (sometimes called "critical systems thinking") emphasized mixed methods drawn from both preceding waves to create a more flexible and responsive systems practice and expand the “tool kit” in order to meet the needs of multiple contexts (Jackson, 1994). The third wave also drew from critical social theory, understanding of power relations, and critiques of boundary judgements and distinction making in systemic inquiry (Cabrera et al., 2021). Subjectivity became central in systems methodologies. In contrast to the idea of creating one single, objective model of a problem, aims shifted towards generating a systemic learning process in which participants came to appreciate more fully each other’s worldviews (Jackson, 1994).

Methodologies that engage deeply with stakeholders, such as community-based system dynamics (CBSD), grew out of the broader group model building discourse and were born in this wave (P. S. Hovmand, 2014). CBSD aims to empower diverse communities in systems thinking and action and to build community capacity to understand and change systems that perpetuate inequity (Gullett et al., 2022). Thus, CBSD typically incorporates multiple methods, with an explicit focus on stakeholder power relations and empowerment.

The ”big tent” of the third wave made room for multiple approaches and welcomed methodological diversity (and their attending manifold philosophical underpinnings) (Cabrera et al., 2021; Jackson, 1994). While this wave remains dominant, recent critiques have emerged. Most prominently, the plurality of approaches is critiqued for lacking a strong core narrative of what systems thinking is or fundamentally consists of, slowing the field’s further maturation (Cabrera et al., 2021). This lack of core identity can also result in an ultimate fragmentation of the field, as researchers and practitioners are forced to define “system thinking” in the context of their own work and, over time, meanings drift apart and become incommensurable. Indeed, in reviewing systems thinking literature, I find few modern authors who are willing to define systems thinking, and even Donella Meadows manages to eloquently describe many components of systems thinking in her classic "Thinking in Systems" without actually defining the term (Meadows, 2008). Thus, the third wave is perceived as both a flourishing of and a threat to the field of systems thinking.

Though these three waves all are included under systems thinking, they differ fundamentally in several key aspects, including the role of science and scientists in society, the objectivity of knowledge, and the value of non-technical/non-expert knowledge. As a result, it can be difficult to define systems thinking as a coherent methodology. The waves represent not only an evolution in methodologies but also an evolution in worldviews. This is not to say that one methodological worldview should be favored over another – the third wave is not superior to the first wave – but rather that one must reflexively consider the worldview that one is adopting in choosing a specific methodology and consider whether that worldview is suited to the problem being addressed.

The choice of systems methodology has implications for working with sustainability as well. Different systems methods will foreground different conceptualizations of and aspects of sustainability. The normative aspects of sustainability will be more easily visible in a critical systems thinking approach, while aspects such as resource management and relationships between policy actions and sustainability targets may be clearer in a hard systems thinking approach. Emergent aspects of sustainability may be easier to capture in a stakeholder-driven critical systems thinking approach, but those same emergent elements may be more easily measured with a hard systems thinking methodology.

3. Research gaps

The literature review of key concepts points to several important research gaps to address.

A **conceptual** gap: Sustainability is often incompletely (and implicitly) conceptualized in innovation and planning processes. In particular, sustainability's emergent and dynamic qualities are often under-considered (Gaziulusoy & Brezet, 2015; Schlaile et al., 2017). In an innovation context, stakeholders can struggle with defining the innovation problem adequately to achieve deeper and more durable sustainability-oriented innovations (Buhl et al., 2019). Studies of urban sustainability are often insufficiently grounded in social, ecological, and technological context, limiting understanding of complex relationships and how path dependencies can shape interactions (Keeler et al., 2019; Markolf et al., 2018; McPhearson et al., 2022).

A **methodological** gap: People need tools that allow them to understand and engage with sustainability and apply the concept to illuminate and define problems. Stakeholders attempting to effect change towards sustainability often lack tools that support them in taking a systemic perspective on their role and contribution in a larger system (Buhl et al., 2019). Developing and providing tools that support systemic approaches to sustainability questions is key to empowering stakeholders working with complex sustainability issues (Videira, Antunes, & Santos, 2017). In a policy context, cities are commonly understood as complex systems, yet system approaches are poorly integrated with urban analyses (Haase & Schwarz, 2009). Integrated dynamic models that capture both feedbacks and emergent behavior are especially relevant to urban systems but have been little used (Kolosz et al., 2018). Closing this gap is critical to creating quantitative scenarios for transitions to sustainable futures.

An **implementation** gap: Sustainability is often included as a normative goal in planning and innovation processes, but a deeper understanding of how sustainability can be effectively implemented in these processes is lacking. City planners and policymakers currently have an incomplete understanding of how to best implement sustainability policy innovations to maximize climate benefits while reducing potential tradeoffs such as gentrification, compromises in social equity and access to green space (Keeler et al., 2019; Shi et al., 2016; van den Bosch & Ode Sang, 2017). The interactions, synergies, and trade-offs between green infrastructure policy innovations as a climate change adaptation measure and other societal goals are poorly understood (Kabisch et al., 2016).

4. Research questions

From these research gaps, I identify a main research question: How can systems approaches help understand and inform transitions towards sustainability? Within that broad question are a number of more specific research questions. Numbers in parentheses refer to the articles that relate to the question.

Sustainability in a systems perspective

A. What are the key characteristics of sustainability that need to be considered when innovating or planning, and how do systems approaches relate to key sustainability characteristics? (1, 2)

B. How can a systems approach aid understanding and visibility of sustainability? (1, 2)

C. How can a systems approach be practically integrated into and enhance existing innovation and policy processes? (0, 1, 2, 3)

Policies and planning in social-ecological-technological systems (SETS)

D. How can urban sustainability policies be understood and implemented in a SETS? (3)

E. How can a systems approach aid understanding and optimization of policies for sustainability? (1, 2, 3)

5. Methodological approaches

This thesis incorporates a number of different systems thinking methods in order to illuminate and engage with multiple aspects of sustainability. Jackson (1994) makes a useful distinction between methodological pragmatism (mixing approaches without reference to their theoretical underpinnings) and pluralism (in which distinct theoretical positions of various systems approaches are respected and, to a degree, mediated) (Jackson, 1994). Methodological pluralism demands engagement in debates and self-reflection on theoretical and ethical stances. Though demanding, a commitment to pluralism can strengthen systems thinking as a set of practices and worldviews. Pluralism allows for diverse approaches to the subject at hand, and can potentially reduce the negative side effects of investing in a single methodology.

Further, this work takes inter- and transdisciplinary approaches to knowledge generation. Systems methods are usually applied to issues that cut across academic disciplines, and they therefore require interdisciplinary approaches that integrate knowledge across disciplines and disciplinary traditions. Parts of this thesis also include working with non-academic stakeholders and practitioners. In these processes, in which practitioners develop their own insights into complex issues and incorporate their own normative perspectives on sustainability, my work can be considered transdisciplinary. Indeed, sustainability, with its strongly normative orientation, is inherently transdisciplinary (Stock & Burton, 2011). In the spirit of methodological pluralism and transdisciplinarity, a description of the specific systems methods used in this the thesis, along with a justification for the choice of methods, follows.

5.1 Systems mapping (group model building)

Systems mapping (also called group model building in this thesis, see section 1.3) is one of a suite of tools for supporting a group model building process. It is a participatory and transdisciplinary approach aimed at developing a shared understanding of and effective communication about complex and dynamic problems (Videira et al., 2010). The tool can be used on its own to support a stakeholder engagement process or as a starting point for developing a system dynamics model. Systems mapping includes a toolbox of scripts, or activities, that can be implemented with a variety of stakeholder groups. Through engaging in systems mapping, facilitators and participants can elicit understanding of a complex problem and identify leverage points for intervention (P. Hovmand et al., 2011; P. S. Hovmand et al., 2012). Systems mapping is often considered a tool for implementing systems thinking.

Systems mapping's strengths include eliciting a shared, visual understanding of a problem and how that problem is interconnected across disciplinary and sectoral boundaries. Further, through engagement in systems mapping, forums for discussion that can enable collaboration and formalize comprehension of complex problems are created (Scott, Cavana, & Cameron, 2016; Videira et al., 2017; Videira et al., 2010; Webb et al., 2018). The resulting systems map typically has a focus on feedback within the system and on adequate system boundaries. It visualizes causal relationships and can serve as a reference point and boundary object for further discussions of leverage points and interventions in the system. Systems mapping's emphasis is on the aggregated structure of a complex issue rather than the individual's experience. In contrast to typical, empathetic innovation approaches such as design thinking, systems mapping's aggregated perspective can provide a "helicopter view" of a complex problem.

In this thesis, I used systems mapping as a stakeholder engagement tool, and my primary role as researcher was as facilitator and observer. I introduced small groups of participants in innovation processes to systems mapping, then facilitated their use of the methodology. I employed this methodology both in person and online. Consistent with the “critical systems thinking” wave, my aim was to generate a shared learning process in which participants come to understand and appreciate each others’ worldviews and develop a shared definition of a complex problem. This method explicitly values non-expert knowledge and participation, and as a facilitator, I aimed to carefully support the group process via the methodology while not intervening on questions of content.

5.2 Online group model building

The covid pandemic forced adjustments in research plans and methodologies in this thesis. In particular, several planned workshops needed to be adjusted and some needed to be moved online. As there was little documentation and guidance for how to run systems mapping workshops online, I and other researchers needed to take a step back to reconfigure and redesign aspects of standard systems mapping approaches to migrate workshops to digital platforms. In order to implement systems mapping we had to first develop new methodologies appropriate for digital participation. The resulting methodology, based on careful planning and reflections on practice, is outlined in Wilkerson et al. (2020). This methodology is used in Wilkerson and Trellevik (2021) in line with the “critical systems thinking” approach as described in the previous section.

5.3 System dynamics modeling

Computer models are an essential tool for capturing the mutual causal relations between human activities and environmental impacts (Mooij et al., 2019). A range of modeling techniques have been applied to urban areas, including cellular automata, spatial economics/econometrics, system dynamics, and agent-based modeling (Haase & Schwarz, 2009). There is no standard approach for modeling urban landscapes and human-nature interactions (Haase & Schwarz, 2009).

Models – and modeling methodology – need to be flexible enough to capture boundedly rational human behavior, market volatility, stochastic events, and local and global effects (Kolosz et al., 2018). Successful models must incorporate the dynamic and varying needs of societies that shape ecosystem service use and drive impacts on the environment (Mooij et al., 2019). Dynamic modeling is particularly well suited to capture and explore the complex dynamics created by changing land use in urban areas.

System dynamics is a methodology for analyzing and managing complex systems. The system dynamics approach highlights feedbacks in the system, and it is especially well suited for exploring systems with long time delays and nonlinearities (Sterman, 2000). System dynamics models can be useful for exploring tradeoffs and synergies across sectors and across time scales at the aggregate level. This modeling approach is also able to integrate quantitative and qualitative data with a range of precision and can be used to generate and analyze quantitative scenarios. It can also be used as a project integration tool, in which data and insights generated from multiple different research approaches can be integrated into a single model to provide a more holistic picture and highlight interactions among different parts of a larger system.

Modeling is an inherently normative activity that is bound to a certain viewpoint. Integrated, multidisciplinary models can encompass a broader range of views and facets of a system, but a model's depiction of a system needs to be grounded within the scope for which it was developed (Kolosz et al., 2018). Decision makers should understand the model – and not just the model outputs – to ensure the relevance of the model to the problem(s) at stake and decision context (Kolosz et al., 2018).

In this thesis, I use system dynamics modeling as a means of integrating diverse quantitative and qualitative data sources to gain a more complete and nuanced perspective on a complex system. The model scope was drawn with decision makers and administrators in mind, and we aimed to maximize insights while not adding unnecessary complexity. The researcher position as the “objective” knowledge-holder in this methodology was tempered by several feedback sessions with researchers in other relevant domains and public administrators to assess the quality of the model and its assumptions, test the comprehensibility of the model, and discuss the relevance of the model and its results.

6. Results

This thesis consists of three articles, two of which are published in peer-reviewed journals and one which is currently in review. In addition, a published research note that outlines a methodology used in other articles is included. Each article's aim, results, and contribution to the thesis are summarized below.

0. **Wilkerson**, B., A. Aguiar, C. Gkini, I. Czermainski de Oliveira, L.-K. L. Trellevik, and B. Kopainsky. 2020. Reflections on adapting group model building scripts into online workshops. System Dynamics Review. (Wilkerson 30%, Aguiar 30%, Gkini 25%, Czermainski de Oliveira 5%, Trellevik 5%, Kopainsky 5%) (Research note)

System mapping, also called group model building (GMB), is an important social process in system dynamics (SD) for creating a shared understanding of complex systems and providing a platform for stakeholders to exchange information and ideas (Antunes 2015; Sedlacko et al. 2014). While online meeting platforms and collaborative tools have made great leaps forward in recent years, systems mapping has largely continued with in-person facilitation. This research note outlines a detailed methodology for running GMB workshops online. Online GMB can open up for a larger breadth of interactions, by including people who, because of time, finances, or distance, would otherwise be excluded. We propose that online GMB, a practice with its own set of strengths and weaknesses, should be further developed as its own set of methodologies parallel to traditional (in-person) GMB. This research note includes a practical description of our experiences and lessons learned as well as areas for further development. The methodology described in this research note is used in Wilkerson and Trellevik (2021).

1. **Wilkerson**, B., *In review*. Advancing sustainability-oriented innovation practice with quality criteria for problem definitions. Heliyon. (Wilkerson 100%)

In this article, I consider the facets of sustainability that should be considered in a robust innovation process. Defining the problem is a key step in sustainability-oriented innovation (SOI), yet practitioners often have little guidance on what qualities a problem definition should or could have. This can result in problem definitions that are poorly specified or underdeveloped, which can negatively affect the quality of the innovation process and narrow sustainability impact.

Drawing on innovation and sustainability science literature, I first operationalize the concept of sustainability for an innovation context and then propose a list of quality criteria which can support development of a SOI problem definition and provide opportunities for critical reflection. Criteria include: systemic, stakeholder-informed, cross-sectoral, temporal, evidence-based/context-specific, and coherent. The criteria are presented with key features, guiding questions to support their use, and literature supporting their selection.

I then implement the criteria in a case study with university students and gather data about the use and applicability of the quality criteria. Results indicate that quality criteria can guide more nuanced and structured thinking and improve problem definition quality, but that some practitioners may meet a tradeoff between meeting all criteria and moving forward in the SOI process. This supports the role of quality criteria as a guidance and support tool rather than a tool for evaluation of problem definitions.

This synthesis-oriented article summarizes the key aspects of sustainability for innovation processes and addresses research questions related to sustainability in a systems perspective. As the quality criteria form a practical tool, this article also addresses how sustainability can be operationalized and applied to specific contexts.

2. **Wilkerson**, B., and L.-K. L. Trellevik. 2021. Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches. Thinking Skills and Creativity. (Wilkerson 50%, Trellevik 50%)

In this article, my co-author and I implement and test integrating systems mapping into innovation processes. Sustainability-oriented innovation (SOI) is receiving increased focus, as sustainability takes a more central role in business, development, and education arenas. SOI processes typically draw from design thinking toolkits, with a focus on the user's needs and experiences. While this is an effective way to ensure that the innovation process is grounded in real, definable needs, it's also limited in its ability to place the problem in a larger societal and systemic context. This can lead to a narrow or incomplete problem definition.

We designed and tested a new approach for eliciting and defining problems for SOI. We present this combined methodology and implement it in two hackathon-type case studies, one with participants from the private sector and one with university students. These examples illustrate the potential of design thinking and systems mapping to support and enhance problem definition for SOI and provide the basis for discussing future research directions. Our work shows that using systems mapping in the problem definition phase of SOI helps set adequate boundaries for the problem space and increases understanding of how the system influences itself over time. As "sustainability" is a systems property, we find that the "helicopter view" provided by systems mapping complements the empathetic design thinking approach to form a more robust problem definition.

Results from this research indicate that the addition of systems mapping to the problem definition steps in a standard innovation process provided value both as a capacity building process and as a tool for highlighting sustainability aspects in problem definitions. Participants indicated that they valued and learned from this new approach and that it supported communication both during and after the workshop.

This article addresses research questions posed in this thesis related to systems approaches to sustainability and provides insights into the values and limitations of systems methods in innovation processes.

3. **Wilkerson**, B., E. Romanenko, and D. N. Barton. 2022. Modeling reverse auction-based subsidies and stormwater fee policies for Low Impact Development (LID) adoption: a system dynamics analysis. Sustainable Cities and Society. (Wilkerson 55%, Romanenko 40%, Barton 5%)

Many urban areas around the world are facing increasing pressure on stormwater management systems due to urbanization and extreme weather events caused by climate change. Low impact development (LID), including blue-green infrastructure such as rain gardens, has become an attractive addition to traditional gray infrastructure for managing stormwater. Municipalities have a limited suite of policy instruments for incentivizing installation of LID on private property. In this article, we discuss barriers to implementing LID in established residential areas and how various policies can address those barriers.

Fine-scale LID on private property requires widespread adoption in order to have a meaningful impact. Thus implementation of LID cannot consider only infrastructural and technical aspects as social aspects of adoption also play a decisive role. Implementation and adoption of LID should be understood as complex, interconnected social, ecological, and technological systems (SETS).

We built a system dynamics model of integrated socio-economic and hydrologic systems in Oslo, Norway to illustrate implementation of two innovative economic incentive mechanisms: subsidies based on reverse auctions and stormwater fees. We use scenarios to explore adoption and diffusion of stormwater policies both alone and in concert with each other. We find that policy effectiveness depends on 1) communicating realistic expectations of LID performance to landowners and 2) municipal subsidies to reach landowners without intrinsic interests in LID. Under certain conditions, lower municipal economic incentives can outperform higher economic incentives and lead to sustained long-term adoption of LID on private property. This work illustrates the importance of considering social aspects such as diffusion and adoption of novel policies in discussions of climate change adaptation.

As a contribution to the thesis, this article addresses questions of how innovative policies can be understood and implemented in a SETS and illustrates the role that quantitative systems approaches can play in understanding and optimizing policy interventions for sustainability.

7. Discussion

The articles in this thesis combine to illuminate the challenge and promise of operationalizing sustainability to support decision-making in various contexts. As Donella Meadows wrote almost thirty years ago, “those of us who have talked about sustainability for a long time have stopped defining it” (Meadows, 1995). Sustainability is a shifting and expanding concept. Its use and meaning are often context dependent, and metrics for how to measure or characterize it often fall short (Ramsey, 2015). It’s a word that can be casually tossed into political rhetoric to justify almost any policy or callously used to veil contradictory intentions (Ben-Eli, 2018).

And yet not attempting to operationalize and implement such an important concept will inevitably also fall short (White, 2013). These challenges of definition and context make it more – not less – important to engage with sustainability. We need words and concepts that can be guideposts as we attempt to move towards a desirable future. Those guideposts may be unclear or imperfect, yet without them, we’ll be completely lost.

The broad research themes addressed in this thesis include systems approaches to sustainability-related innovation and planning, and policies and planning in urban SETS. In this section, I return to the research gaps I identified in section 3.0 and consider my research as a collective body of work in light of those gaps. I then present some broader reflections on working with sustainability and the research process.

7.1 Research implications

Here, I purposely frame my discussion around the larger conceptual, methodological, and implementation research gaps from section 3.0, as opposed to the specific research questions in section 4.0, in order to better address cross-cutting results and themes and identify remaining challenges and topics.

7.1.1 Conceptual implications

The conceptual gap outlined in this thesis centers on the challenges of conceptualizing sustainability and sustainability's implications as a concept for informing innovation processes and urban sustainability policies. Sustainability is normative and will always be elusive, yet teasing apart some of its constituent elements can help illuminate how the concept can be understood and eventually put into practice. The ambition in addressing this gap has been to contribute to clarifying sustainability as a concept, with a focus on two contexts in which such clarity is especially important: innovation processes and urban planning.

This thesis contributes to filling this conceptual gap through bringing together SOI and sustainability science literatures to illuminate sustainability as a dynamic and relational concept. Much of the academic literature on design and innovation is descriptive, without formal means of understanding or evaluating methods (Cash, 2018), yet SOI practitioners are in need of rigorous tools to support innovation processes and reflective learning (Gaziulusoy & Brezet, 2015). While recognizing its ephemeral and contextual qualities, I identify key aspects of sustainability that should be considered when defining an innovation problem. These criteria provide value in considering how sustainability can be conceived, especially in innovation contexts, and in guiding users to a more coherent and multi-faceted definition of a complex problem.

Through taking a systems perspective on sustainability, my work has emphasized sustainability's dynamic qualities. This is especially relevant to urban SETS contexts, as SETS literature includes few examples in which the systems aspects have been clearly illustrated, though systems methods are widely understood as integral to the SETS framework (Chester et al., 2023; McPhearson et al., 2022). This is addressed further in discussions of the methodological and implementation gaps. The systems aspects of SETS are also a focus in forthcoming work on systems archetypes for SETS (presented in section 8.1), in which system archetypes are a conceptual counterpoint to the complexity and entanglement framing increasingly applied to SETS.

7.1.2 Methodological implications

The methodological gap addressed in this thesis includes a need for tools that support engaging with sustainability and applying the concept to specific problems and contexts. This is both a general challenge for approaching sustainability and a specific challenge that's integral to innovation processes and dynamic urban systems. In the context of this thesis, I point to three methodological contributions that address the need to facilitate engagement with sustainability and system approaches to sustainability.

First, as outlined above, the quality criteria for SOI provide a way of structuring and illuminating multiple facets of sustainability in innovation processes. Defining a sustainability problem is the first and critical step to addressing it. Thus, in the case of SOI, the conceptual gap of needing clarity for sustainability's constituent attributes is tightly linked to the methodological gap of needing tools that enable engagement with sustainability. The quality criteria for SOI provide a literature-informed method for defining a SOI problem, and thereby open up the potential for more durable and coherent sustainability innovations.

The SOI quality criteria are a first attempt at defining and structuring aspects of SOI problem definitions. As discussed in the literature review (section 2.1), there is a tension between the desire to be prescriptive in order to provide concrete guidance for how to operationalize sustainability and the acknowledgment that definitions of sustainability are inescapably shifting and context dependent. The structured approach of the SOI quality criteria can potentially be perceived as cutting across the grain of open-ended design approaches, though my hope is that the criteria can complement and support other approaches with conceptual clarity. Only by explicitly articulating a problem definition for SOI can one hope to develop a relevant and coherent solution. One key caveat with the quality criteria presented in this thesis is that not all criteria will be equally relevant for all types of sustainability-related problems. As a tool, they may need to be adjusted in response to specific contexts. The criteria would benefit from more studies of their validity and applicability under different conditions towards establishing the criteria as a robust tool for research and practice.

Second, incorporating systems mapping into design thinking methodologies for SOI provides an activity that highlights sustainability aspects in the problem definition phase of an innovation process. It also contributes to capacity building through training participants in a new tool and generating discussions across roles and backgrounds. Tools that improve systems literacy can complement existing innovation approaches and support problem definitions. Systems mapping is, however, more cognitively demanding than many other activities in an innovation process, so successful implementations of this approach depends on support from trained facilitators.

Both integrating systems mapping into innovation processes and applying criteria to problem definitions show promise in enabling more comprehensive understandings and definitions of sustainability problems. These methods may also illuminate aspects of sustainability that may otherwise be under-considered. As these methods are new developments, they have only been tested in a limited way in this thesis. Thus, there is a remaining gap in testing and refining these methodologies in different contexts and with different user groups.

Third, while many system dynamics models have been built to examine different urban sustainability issues, the model in this thesis makes a unique contribution in examining optimization of stormwater policy implementation in a concrete case. The methodological contribution includes advancing a systems understanding of SETS. Urban SETS exhibit emergent properties, including nonlinear dynamics and feedbacks, and have high levels of interconnectivity and unpredictability (McPhearson, Haase, et al., 2016). In building a system dynamics model of stormwater policy adoption, we integrate disparate sources of knowledge to capture feedbacks and policy synergies in a complex system. This work illustrates the value and potential in using system dynamics modeling as a method for engaging with and increasing understanding of SETS dynamics. It also demonstrates, more generally, the value that system dynamics modeling can provide as a project integration tool that can integrate results from multiple fields.

7.1.3 Implications for implementation

Effective implementation of sustainability in planning and innovation contexts constitutes the final gap. Large sustainability goals will require multiple policies to achieve, and it's important to understand and anticipate how these policies can function in concert (Barton, Ring, & Rusch, 2017). While prerequisites to implementation include defining the SOI problem and developing solutions for that problem, how suites of policy solutions could be optimally implemented also requires careful attention.

In developing quantitative scenarios for stormwater policy adoption, we provide an analysis for understanding and optimizing policy implementation. By considering two stormwater policies in concert, we contribute to ongoing research agendas on urban policy mixes in urban stormwater systems, where hydrological, socio-economic, and governance subsystems are tightly interlinked.

The scenarios presented in this work can provide input into anticipatory planning for stormwater management under a variety of environmental, social, and technological conditions. However, the limitations of the model should be considered in how results are interpreted and used to inform policy actions. For example, social variables such as households' perceptions, capabilities and motivations, including the potential role of motivational crowding, can be difficult to parameterize or generalize from other cases (Ezzine-de-Blas, Corbera, & Lapeyre, 2019; Ureta, Motallebi, Scaroni, Lovelace, & Ureta, 2021). Collecting different types of data and incorporating more social variables into the existing model could provide more nuance to household decision-making under different policy conditions.

Further, aspects of social sustainability, including the stormwater policies' potential impact on house prices and housing affordability were not included in the scope of the model but may be crucial to understanding sustainability in practice (Keeler et al., 2019). A growing body of research indicates that new green infrastructure in service of environmental sustainability can contribute to social and racial disparities, thereby undermining social sustainability (Venter, Figari, Krange, & Gundersen, 2023). The forthcoming work on systems archetypes (section 8.1) addresses in part these interactions between environmental and social sustainability. More broadly, it demonstrates the potential of this systems approach to illuminate central tradeoffs and inform policy decisions in stormwater policy implementation.

In practice, no matter what data is gathered and which tools are employed, understandings and definitions of sustainability will always be incomplete. Assessing how to take action responsibly when coping with incomplete knowledge of complex sustainability issues is a major persistent gap.

In sum, results from this research indicate that:

- Systems thinking and system methods have the potential to improve problem definitions for SOI and generate shared learning about complex issues.
- Tools that support thinking about sustainability in more nuanced and complex ways are perceived as useful by various types of practitioners.
- Though sustainability is difficult to define and operationalize, attempts to do so can still provide valuable guidance.
- Understanding policy innovations from a systems perspective can help identify potential goal conflicts and help optimize implementation.

Given the broad scope of this thesis and the unfolding nature of research, it is inevitable that research gaps are addressed but not completely filled. Enduring and emerging research gaps include:

- New methods for operationalizing sustainability should be tested with a broader range of user groups and problem types.

- The balance point between being prescriptive and being open in sustainability-related processes can be difficult to find. Research that tests that balance point under different conditions could help illuminate the best ways to support groups working on sustainability issues.

- Further explorations of how multiple sources of uncertainty, especially around perception and behavior, interact in urban SETS could help inform how to ethically and responsibly manage stormwater policies towards both environmental and social sustainability.

In the following sections I provide some broader reflections on my research, including working with sustainability as a transdisciplinary concept, the insights and limitations of system approaches, and the relationships between theory and practice.

7.2 Sustainability as a transdisciplinary concept

Working from a transdisciplinary perspective has added a layer of challenge to navigate in producing this thesis. Bringing together literature from multiple disciplines is an inherently pedagogic endeavor that involves defining terms and concepts that may appear obvious or simple from a single perspective. Sustainability science can help illuminate sustainability, but disciplinary perspectives on innovation processes, urban contexts, and policy implementation are needed to move towards normative sustainability goals. Further, though researchers may wrestle with the academic nuances of sustainability, it is at its core a transdisciplinary concept that is shaped and reshaped by practitioners who employ the concept (Stock & Burton, 2011).

As an inherently normative concept, sustainability depends on generating a shared vision of and vocabulary for a desirable future. Desirability depends on perspective. Thus generating a refined vision for sustainability depends on active participation from multiple societal actors. Systems methods, which are fundamentally networked and interdisciplinary, can help facilitate understanding and actions. The scholarly contribution of this thesis is derived from bringing multiple literatures in dialogue with each other and ensuring that readers can follow arguments and recognize their value regardless of disciplinary backgrounds.

Alongside other terms such as resilience and transformation, sustainability can be considered a boundary object (Brand & Jax, 2007; Star & Griesemer, 1989). Sustainability's resistance to static definitions gives it a malleability that can create common ground for fruitful discussions around, for example, the needs of future generations (Brand & Jax, 2007). As a boundary object, sustainability's interpretive flexibility can provide a "good enough" roadmap for all parties to facilitate identification of shared interests and stimulate collaboration (Fischer & Riechers, 2019; Star & Griesemer, 1989). The open and nebulous definitions of sustainability also enable it to be adapted to local conditions and contexts.

Yet ambiguity will inevitably have drawbacks as well. As a boundary object, sustainability can enable collaboration among disparate parties, yet the collaboration will be limited in effectiveness without a core nexus of understanding and shared vocabulary (Brand & Jax, 2007; Franco-Torres, Rogers, & Ugarelli, 2020; Lundgren, 2021). Boundary objects can be a hindrance to progress when the meaning of a term such as sustainability becomes highly diluted and unclear (Brand & Jax, 2007). Employing sustainability as a boundary object can also hide conflicts and power relations, when both parties agree that sustainability is the goal but mean different things by the term (Lundgren, 2021). “I know it when I see it" perspectives, though common, can be an ineffective or even hazardous framing. Thus working with sustainability requires iterative reflection around how the term is actively being defined and employed in specific contexts. Indeed, one could argue that this need for iterative reflection is one of the concept’s strengths. The quality criteria for SOI as well as the systems mapping intervention for SOI are intended, among other aims, to provide room for and support this iterative reflection.

Operationalizing sustainability will always be “in process” and the knowledge and insights generated by this thesis, or any body of work on a similar topic, will continue to evolve or be replaced as new insights are generated. Visions of what a desirable, sustainable future could look like, and therefore what our societal goals are, will continue to evolve. Indeed, I would argue that it is these visions, and not traditional academic research, that will push sustainability forward and that has the largest potential to bring a theoretical construct into livable fruition. Such transformative visions towards sustainability will require not only transdisciplinarity but also new paradigms for academia as a loyal helpmeet in support of societal visioning.

7.3 Systems approaches as a lens

My work has primarily relied on systems approaches to try to understand and apply sustainability. I’ve applied a pluralism approach to my selection of systems methodologies (Jackson, 1994). System dynamics modeling was used to generate quantitative scenarios and provide policy guidance to decisionmakers. Systems mapping was used to engage stakeholders in defining their problem of interest, to gain a more comprehensive perspective, and to generate a shared understanding of a complex issue. Systems archetypes (discussed below under future research) has been preliminarily used to zoom out from the level of individual cases and ask questions about patterns in the structural challenges of implementing sustainability-oriented policies. These various approaches have been applied to different contexts and have illuminated different aspects of sustainability in ways that would not have been possible with a narrower selection of methodologies.

Yet within the scope of a PhD, there is an inevitable tradeoff between depth and breadth of approaches. The scope of my PhD has been broad, both in terms of subject matter and methodologies. From my perspective, this has been a useful approach to get bearings on complex and multifarious issues for which our knowledge will never be comprehensive. An alternative approach would have been to apply a single methodology (for example, system dynamics modeling) to a single problem (such as urban stormwater management). This approach would have generated valuable insights of a fundamentally different character and likely would not have had sufficient breadth to consider sustainability outside of this specific context.

However, any disciplinary approach, no matter how broad, will necessarily circumscribe one's view. As a lens on the world, systems approaches bring certain aspects of sustainability into focus (such as feedbacks and tradeoffs) while leaving others outside the field of vision. For example, aspects of human emotions and subtleties of human interactions can be more difficult to incorporate. Systems approaches, especially modeling, can be biased towards what's measurable, observable, and quantifiable. Actively engaging with and supporting knowledge generation from stakeholders is one way to reduce this bias and incorporate more nuance into systems perspectives.

Further, though systems approaches are often described as comprehensive, they are necessarily bounded. As Helfgott (2018) clearly illustrates, there is an inescapable tension between systems thinking's frequent claim to holism and the necessity of drawing boundaries around a problem. Holism may be a worthy goal, but it is unachievable in practice in a world in which all things are fundamentally interdependent and interrelated (Helfgott, 2018). System boundary judgements are therefore inevitable, and these judgements are not only practical but also profoundly ethical. Rather than holistic, systems methods should be considered "critically reductionist." Indeed, it is only through ethically simplifying a rich reality that systems methods can provide value.

Despite our best efforts, we will only ever have a partial view of a complex system. Any intervention in such a system will almost certainly have unanticipated consequences. As researchers and practitioners, we must learn to deal critically and reflexively with that partial view, and to draw conclusions and take actions cautiously and pragmatically in light of that incomplete understanding. Thus working with systems and working with sustainability demands humility and reflexivity throughout the research process.

7.4 Theory and practice in dialogue

Two related tensions between theory and practice emerged in the course of producing this thesis. First, there is a tension between the desire to structure sustainability to facilitate its application on the one hand and an acknowledgement that the term cannot be defined "from above" on the other. Sustainability is normative and will be defined and redefined by the individuals and groups that employ the term. Thus operationalizing sustainability requires both a willingness to identify parameters (a core nexus of understanding as discussed above) and an openness to new impulses informed by practitioners and context. In working with stakeholders and in generating academic outputs, this is not always an easy balance to strike. Moving the understanding and application of sustainability forward will require developing deeper understandings of this balance point and how it may shift in different contexts, as well as where researchers could facilitate its placement to maximize benefits to practitioners and to sustainability as a goal.

Second, there is a tension between embracing the complexity of SETS and the desire to provide straightforward explanations and digestible policy guidance to decision makers. SETS framing has broadened our understanding of interactions among humans and their environment, especially in urban areas, where infrastructure creates path dependencies and can constrain policy options (Markolf et al., 2018). Yet communicating complexity and extrapolating useful policy inputs for decisionmakers remains a challenge. The links between SETS complexity and actionable policy guidance thus far are tenuous, and it's unclear what methods can support a productive flow of ideas from complexity to policy. Until that link is more firmly established, the contributions of the SETS framework will be limited.

Theory and practice do not exist independently from each other. Rather they are frequently in dialogue and inform each other's trajectories. With both sustainability and SETS, this thesis makes a clear contribution to this ongoing dialogue. These tensions, though, extend far beyond the scope of this thesis or any body of research. While these frictions between academic understandings and ambitions for application are perhaps not surprising, they were felt acutely in producing this thesis. These tensions bring to the fore questions about the contributions and value of research to addressing sustainability issues, and it is important that they be addressed continuously and reflexively (Schrage, Barraclough, Wilkerson, Cusens, & Fuller, 2023). This is an active, ongoing reflection that should be integral to any research career in transdisciplinary issues. Indeed, it is a lifelong research question.

8. Future research directions

While the work in this thesis has contributed to filling important sustainability-related research gaps, significant research challenges and opportunities remain to further build on the contributions of this PhD. Research is a continuous process, and as insights are generated, so too are further research questions. This section contains some general reflections on how my existing work in this thesis could be strengthened and advanced, followed by a more detailed proposal for future research that applies systems archetypes to urban stormwater management to generate policy insights.

Innovations, including policy innovations, are processes that unfold over time, and an innovation implemented today may only make an impact in the near or distant future. In general, there is a significant challenge in measuring the impacts (positive or negative) of an innovation, as those impacts may be diffuse and vary over time or across sectors. Progress in connecting SOI problem definitions to their resulting innovation, and to that innovation's impact, would advance understanding of which aspects of sustainability are decisive in steering SOI processes in a desirable direction. Yet such work should be approached cautiously, and with the recognition that diligently tracing antecedents to an impact may produce a muddled map of multiple intersecting pathways that fails to generate real insights. While there is often academic pressure to tell a clear and compelling (and, often, linear) story of "problem leads to innovation leads to impact," the reality is often more difficult to discern and communicate.

The tools presented in this thesis, including SOI quality criteria and systems mapping within innovation processes, would benefit from further testing in different contexts and with different participant groups. In particular, it would be exciting to test these tools with more heterogenous (in terms of cultural background and education level) groups to see how these tools facilitate or inhibit collaboration. In larger workshop settings it would be interesting to run more structured experiments in which different groups are given different tools and processes for defining a problem. This work could be used to adjust and refine the tools and gain a better understanding of under which circumstances the tools are most beneficial.

Significant opportunities remain in exploring and raising visibility of systems aspects of SETS. In quantitative modeling of stormwater policy implementation, expanding model boundaries to include more facets of human emotions and decision-making could yield interesting insights. Adding more detail to the model presented in this thesis in terms of more types of LID could also yield insights into synergies and tradeoffs among different combinations of LID and a deeper understanding of the perceived benefits and attractiveness of different suites of LID infrastructure. Lastly, placing this model within a larger urban planning framing could aid understanding of potential tradeoffs of LID implementation with other aspects of social sustainability, including housing prices, green gentrification, access to green space, and displacement.

8.1 Proposed research: generating policy insights with systems archetypes to SETS

One especially fruitful future research direction I identify is conducting a system archetype analysis of BGI goal conflicts. This work would build on and strengthen connections among the topics and ideas presented in this thesis, including problem definitions for sustainability issues, BGI policy implementation in urban areas, systems approaches to sustainability, and furthering a systems understanding of SETS. The SETS framework demands a systemic perspective, yet much of the SETS literature focuses on case studies, or takes a purely theoretical approach. While the richness and specificity of case studies provides a deep understanding of specific situations, this can make it difficult to draw generalizations and understand the relevance of a case to other contexts. As applications of SETS and case studies accumulate and theory development matures, one can begin to detect patterns in the underlying structures of these cases. This proposed research uses system archetypes to understand and illustrate urban stormwater management issues across cases in a SETS perspective.

As in ecosystem management, there have been relatively few examples of research in urban BGI implementation that engages actively with feedback loops and system leverage points, despite the recognition of the importance of these features (Hallett & Hobbs, 2020). The explanation for why this is the case may be simply that it’s hard to do this effectively (Hallett & Hobbs, 2020). Especially in the urban BGI context, there are numerous social and situational components that may be difficult to quantify or characterize. Perhaps most prominently, almost any decision on where to implement or upgrade BGI has justice implications in addition to sustainability considerations (Kronenberg et al., 2021). These complex, emergent, and nonlinear interactions among social, ecological, and technological aspects can make urban systems difficult to understand and govern, and investigating urban systems in the context of normative goals such as sustainability requires new methods (McPhearson, Haase, et al., 2016).

In addition to calls for better methods for addressing the systems aspects of SETS, recent SETS literature has argued for a nuanced and “entangled” perspective on SETS (Chester et al., 2023). While there is legitimacy in this complexity framing, such a perspective can be difficult to translate into a decision-making context. Decisionmakers may prioritize methods that are simple and able to provide actionable and understandable results, and may be less concerned with accuracy, precision, or completeness (Di Lucia, Slade, & Khan, 2022). Thus the aim of this proposed work is to preserve the essence of SETS and acknowledge its inherent complexity while meeting the realities of decisionmakers’ decision contexts. One may reasonably argue that a system archetypes understanding of SETS risks oversimplifying the snarled reality of complex problems, yet I would counter that they nevertheless serve an important pedagogic function in illuminating some essential “knots” in the larger entangled perspective.

8.1.1 Method: systems archetypes analysis

Archetype analysis is an approach that seeks to identify generalizable patterns among cases to generate insights. It fills a vital niche through synthesizing accumulated evidence in case study research and making it accessible for researchers and policymakers (Oberlack et al., 2019). By definition, archetypes are not comprehensive. Rather, they generate insights in their simplicity and provide only qualitative understandings of complex realities.

Though the idea of system archetypes has been around for many years (developed by Meadows (1982) and popularized by Senge’s *The fifth discipline* (1990)), the approach has recently gained traction within sustainability science to address the limitations of case studies. System archetypes are a specific type of archetype that is concerned with causal pathways (Eisenack, Oberlack, & Sietz, 2021). System archetype analysis characterizes the generic structures and behaviors of a system and investigates recurrent patterns at an intermediate level of abstraction to explain phenomena, striking a balance between the richness of case studies and generalizable patterns (Oberlack et al., 2019). As a tool, system archetypes enable researchers to represent feedback loops, explain the potential behavior of a system over time, and formulate policies to intervene in the system towards desirable results (Brzezina et al., 2017).

This aggregated, structural level perspective can highlight relationships among primary parts of the system and serve as “templates” that can be matched with more complex real cases (Brzezina et al., 2017). A systems archetype approach can aid in anticipating and visualizing challenges to green infrastructure implementation at the structural level, rather than a linear, cause-and-effect level. To my knowledge, system archetypes have not yet been applied to understanding SETS stormwater policy contexts.

8.1.2 Anticipated results and example SETS archetypes

In this section I present two brief examples that illustrate the potential of a system archetypes approach to SETS. These examples are not intended to be comprehensive but rather give an indication of the direction this research could take.

Cost-sharing

As blue-green infrastructure is largely distributed and decentralized, successful implementation typically requires collaboration with multiple landowners across a larger area. Cost-sharing programs for BGI are funds from governments or municipalities that are allocated to subsidize infrastructure on private property. Programs typically require that funding goes to property owners, and renters are often ineligible.

Further, many types of BGI installed through cost-sharing programs can actually increase property values. For example, Wilbers et al. (2022) found that green roofs increase home values in Oslo and Nordman et al. (2018) found similar results for rain gardens in Grand Rapids, Michigan, USA. Hoover et al. (2023) find that that BGI is often rationalized by municipalities based on expected impacts on property values. Thus, the potential for an increase in property values is used to "market" BGI to private landowners.

In order to qualify for cost-sharing, property owners must have a suitable location for BGI. Typically this means having a lawn or garden space that is large enough to accommodate BGI (such as a rain garden) or a roof that is large and sturdy enough for green roof installation. In other words, cost sharing programs have a built-in bias towards larger and wealthier properties. Brent et al. (2022) find that eligibility for cost-sharing in the US is positively correlated with wealthier and whiter areas. As BGI can increase property values, this creates a reinforcing feedback loop in which wealthy landowners receive a BGI subsidy that further increases their property value (and accumulated wealth) while renters (who typically cannot afford to buy large proper

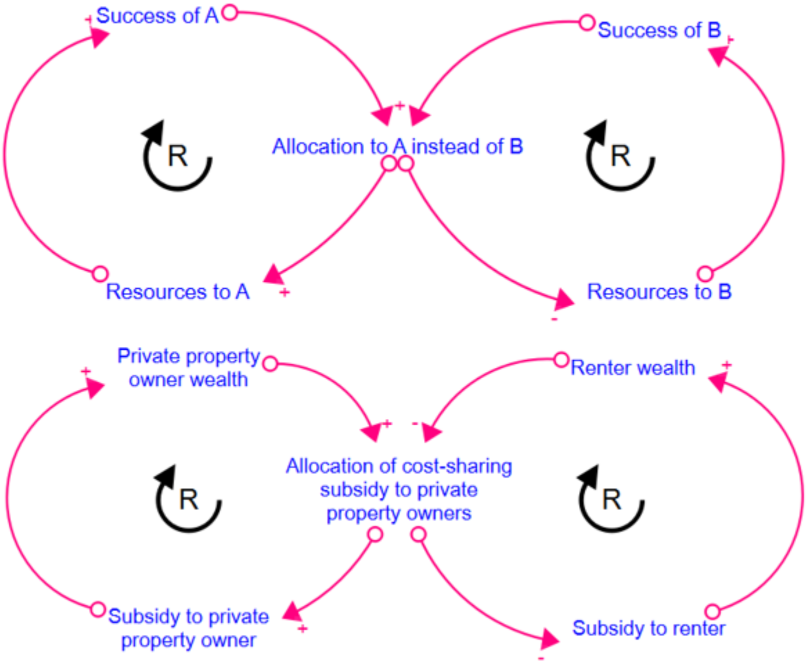


Figure 6, Success to the successful generic archetype and archetype for cost-sharing subsidies ties) remain excluded from this potential wealth accumulation. This dynamic structure resembles the success to the successful system archetype (figure 6).

Examples of cost sharing programs that could lead to these dynamics include Oslo’s reverse auction program in which landowners bid on subsidizing BGI on their properties, with the municipality covering the remaining cost (Furuseth, Seifert-Dähnn, Azhar, & Braskerud, 2018; Wilkerson, Romanenko, & Barton, 2022). BGI cost-sharing subsidies are also a common policy mechanism in many municipalities in the US, including Seattle and Washington, DC (Lieberherr & Green, 2018). The policy implications of such cost sharing programs become more clear in light of the system archetype. While cost sharing can be an efficient way to achieve distributed BGI on private property, municipalities should be aware of the potential of such programs to increase housing costs and decrease social equity.

Stormwater pumping

Stormwater pumping is typically installed as a short-term solution for dealing with acute flooding issues. For example, the city of Miami Beach, USA, is increasingly experiencing “sunny-day floods” in which large high tide events cause backups in stormwater outlets and can cause water to bubble up through stormwater drains and onto streets (Markolf et al., 2018). The pumps are intended as a short-term solution to sea level rise, and the pumps are designed to handle only up to 15 cm in sea level rise, a level that could be exceeded by 2030 (Markolf et al., 2018). But for many in the area, the pumps have effectively hidden tidal flooding and the problem can appear “solved.” For property developers, building in valuable but vulnerable coastal areas can continue to be attractive, even though fundamental changes in where and how land is developed are needed to fundamentally address tidal flooding problems. As land development increases, the damage caused by flooding, and therefore the dependence on stormwater pumping, also increases. This problem, in which a temporary solution can delay or mask the need for a permanent solution is emblematic of the shifting the burden archetype (figure 7).

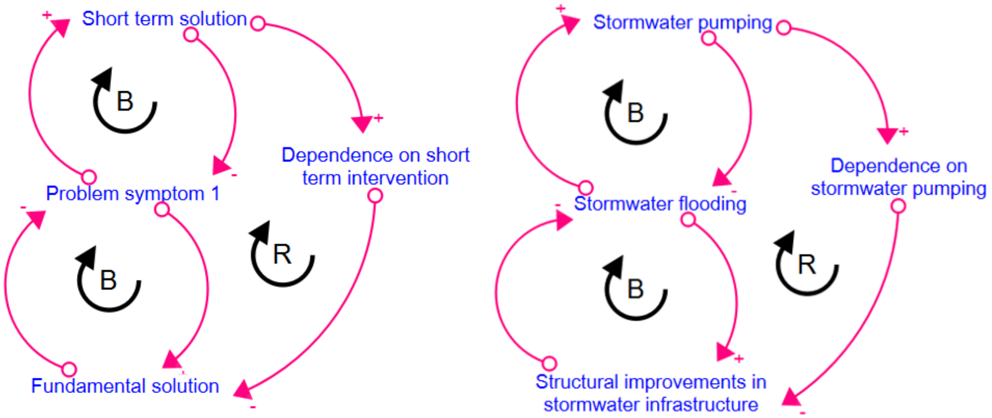


Figure 7, Generic structure for shifting the burden archetype and archetype for stormwater pumping dependency

Another example that fits this archetype include beach re-nourishment in coastal areas, in which sand from offshore is used to replenish beaches that have eroded due to sea level rise. Coastal communities can become dependent on re-nourishment, which is an extremely costly and short-term solution, instead of investing in longer-term solutions (Griggs, 2022). Further, protection of these areas can encourage additional development and increase future vulnerabilities and liabilities (Griggs, 2022).

SETS is a powerful framework for understanding interrelationships and interactions among technology, nature, and society, but the complexity inherent in the framework can intimidate policymakers and others from engaging in it. This research aims to address this need. As a lens, archetypes both simplify and sharpen our perspectives. By reducing SETS complexity to simple structures, system archetypes can aid policymakers in understanding elemental aspects of a complex system, enhance understanding of the system structure, and create opportunities for anticipatory planning for future needs and extreme events. This intentional simplification of complexity can provide a "common vocabulary of attributes" to identify recurrent factors, processes, and outcomes and to facilitate communication (Oberlack et al., 2019).

There are some important cautions in moving forward with this work. Moving from a richly detailed case to a greatly simplified archetype is a normative process that requires numerous judgement calls about which details are essential and which are superfluous. This type of archetype analysis can be susceptible to biases, misjudgment, and overfitting in simplifying to archetypes (Moallemi et al., 2022). There is a real danger that the desire to identify system archetypes can blind researchers to important factors that don't neatly fit into an established archetype narrative. It's vitally important that crafting of archetypes be done transparently and drawing on multiple sources of expertise. Further, archetype analysis is based on the assumption that insights from one case can be transferred to another case if the same archetypes apply to both cases. In further developing this work, this assumption needs to be justified and tested (Oberlack et al., 2019).

9. Concluding remarks

This thesis addresses the broad research question: how can systems approaches help understand and inform transitions towards sustainability? Reflecting on sustainability and how it is understood and applied from conceptualization to implementation reveals both the challenge of working with a constantly evolving concept and the importance of developing processes that enable fruitful engagement with the concept.

The results from this work demonstrate the value that system methods can bring to illuminating sustainability problems. Systems thinking and system methods can foster collaborative learning in SOI contexts, improving problem definitions and providing opportunities for shared reflection on the sustainability issue at hand. Approaching policy innovations from a systems perspective can reveal synergies and conflicts and aid anticipatory planning to optimize implementation. This perspective becomes especially relevant when operating within a complex SETS environment. The tools and discussions developed in this thesis support a reflexive approach to understanding, operationalizing, and implementing sustainability in a complex and dynamic reality.

This thesis, as all theses, represents a snapshot of research insights that will continue to be cultivated and deepened in ongoing research. As the gap between our current status and a desirable, sustainable future widens, the need for tools and perspectives on how we can meaningfully take steps towards sustainability will grow. This thesis contributes to that need with conceptual understandings and pragmatic tools for defining the sustainability problems we want to solve and anticipating the goal conflicts and tradeoffs we may meet along the way. This research agenda, already urgent now, will continue to become more relevant.

10. References

Adams, R., Jeanrenaud, S., Bessant, J., Denyer, D., & Overy, P. (2016). Sustainability-oriented Innovation: A Systematic Review. *International Journal of Management Reviews, 18*(2), 180-205. doi:https://doi.org/10.1111/ijmr.12068

Anguelovski, I., Connolly, J. J. T., Cole, H., Garcia-Lamarca, M., Triguero-Mas, M., Baró, F., . . . Minaya, J. M. (2022). Green gentrification in European and North American cities. *Nature Communications, 13*(1), 3816. doi:10.1038/s41467-022-31572-1

Barbrook-Johnson, P., & Penn, A. S. (2022). *Systems Mapping: How to build and use causal models of systems*: Springer Nature.

Barton, D., Ring, I., & Rusch, G. (2017). Policy Mixes: Aligning instruments for biodiversity conservation and ecosystem service provision. *Environmental Policy and Governance, 27*, 397-403. doi:10.1002/eet.1779

Ben-Eli, M. U. (2018). Sustainability: definition and five core principles, a systems perspective. *Sustainability Science, 13*(5), 1337-1343. doi:10.1007/s11625-018-0564-3

Bennett, N. J., Blythe, J., Cisneros-Montemayor, A. M., Singh, G. G., & Sumaila, U. R. (2019). Just Transformations to Sustainability. *Sustainability, 11*(14). doi:10.3390/su11143881

Bertalanffy, L. v. (1968). *General system theory: Foundations, development, applications*: G. Braziller.

Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences, 104*(17), 7301. doi:10.1073/pnas.0610172104

Brand, F. S., & Jax, K. (2007). Focusing the Meaning(s) of Resilience: Resilience as a Descriptive Concept and a Boundary Object. *Ecology and Society, 12*(1).

Branny, A., Møller, M. S., Korpilo, S., McPhearson, T., Gulsrud, N., Olafsson, A. S., . . . Andersson, E. (2022). Smarter greener cities through a social-ecological-technological systems approach. *Current Opinion in Environmental Sustainability, 55*, 101168. doi:https://doi.org/10.1016/j.cosust.2022.101168

Brent, D. A., Cook, J. H., & Lassiter, A. (2022). The Effects of Eligibility and Voluntary Participation on the Distribution of Benefits in Environmental Programs: An Application to Green Stormwater Infrastructure. *Land Economics, 98*(4), 579-598. doi:10.3368/le.98.4.102920-0166R

Brundtland, G. H. (1987). Our Common Future—Call for Action. *Environmental Conservation, 14*(4), 291-294.

Brzezina, N., Biely, K., Helfgott, A., Kopainsky, B., Vervoort, J., & Mathijs, E. (2017). Development of organic farming in Europe at the crossroads: Looking for the way forward through system archetypes lenses. *Sustainability, 9*(5), 821.

Buhl, A., Schmidt-Keilich, M., Muster, V., Blazejewski, S., Schrader, U., Harrach, C., . . . Süßbauer, E. (2019). Design thinking for sustainability: Why and how design thinking can foster sustainability-oriented innovation development. *Journal of Cleaner Production, 231*, 1248-1257. doi:https://doi.org/10.1016/j.jclepro.2019.05.259

Cabrera, D., Cabrera, L., & Midgley, G. (2021). *The Four Waves of Systems Thinking*.

Cash, P. J. (2018). Developing theory-driven design research. *Design Studies, 56*, 84-119. doi:https://doi.org/10.1016/j.destud.2018.03.002

Cavicchia, R. (2021). Are Green, dense cities more inclusive? Densification and housing accessibility in Oslo. *Local Environment, 26*(10), 1250-1266.

Ceschin, F., & Gaziulusoy, İ. (2019). *Design for sustainability: a multi-level framework from products to socio-technical systems*: Routledge.

Chester, M. V., Miller, T. R., Muñoz-Erickson, T. A., Helmrich, A. M., Iwaniec, D. M., McPhearson, T., . . . Markolf, S. A. (2023). Sensemaking for entangled urban social, ecological, and technological systems in the Anthropocene. *npj Urban Sustainability, 3*(1), 39. doi:10.1038/s42949-023-00120-1

Churchman, C. W. (1968). *The systems approach* (Vol. 8459): Dell Publishing Company.

Clark, W., & Harley, A. (2019). Sustainability science: Towards a synthesis. *Sustainability Science Program Working Papers*.

Cosens, B., Ruhl, J., Soininen, N., Gunderson, L., Belinskij, A., Blenckner, T., . . . Doremus, H. (2021). Governing complexity: Integrating science, governance, and law to manage accelerating change in the globalized commons. *Proceedings of the National Academy of Sciences, 118*(36), e2102798118.

Costanza, R., & Patten, B. C. (1995). Defining and predicting sustainability. *Ecological Economics, 15*(3), 193-196. doi:https://doi.org/10.1016/0921-8009(95)00048-8

Jacobellis V. Ohio, 378 US 184, (1964).

Di Lucia, L., Slade, R., & Khan, J. (2022). Decision-making fitness of methods to understand Sustainable Development Goal interactions. *Nature Sustainability, 5*(2), 131-138. doi:10.1038/s41893-021-00819-y

Eisenack, K., Oberlack, C., & Sietz, D. (2021). Avenues of archetype analysis: roots, achievements, and next steps in sustainability research. *Ecology and Society, 26*(2). doi:10.5751/ES-12484-260231

Ezzine-de-Blas, D., Corbera, E., & Lapeyre, R. (2019). Payments for Environmental Services and Motivation Crowding: Towards a Conceptual Framework. *Ecological Economics, 156*, 434-443. doi:https://doi.org/10.1016/j.ecolecon.2018.07.026

Faber, N., Jorna, R., & Van Engelen, J. (2005). The sustainability of" sustainability"—A study into the conceptual foundations of the notion of" sustainability". *Journal of environmental assessment policy and management, 7*(01), 1-33.

Fischer, J., & Riechers, M. (2019). A leverage points perspective on sustainability. *People and Nature, 1*(1), 115-120.

Forrester, J. W. (1961). *Industrial dynamics*: Productivity Press.

Franco-Torres, M., Rogers, B. C., & Ugarelli, R. M. (2020). A framework to explain the role of boundary objects in sustainability transitions. *Environmental Innovation and Societal Transitions, 36*, 34-48. doi:https://doi.org/10.1016/j.eist.2020.04.010

Furuseth, I. S., Seifert-Dähnn, I., Azhar, S. Q., & Braskerud, B. C. (2018). Overvann i bebygde strøk - tid for å involvere innbyggerne. *Vann, 53*(4).

Gaziulusoy, A. I. (2015). A critical review of approaches available for design and innovation teams through the perspective of sustainability science and system innovation theories. *Journal of Cleaner Production, 107*, 366-377. doi:https://doi.org/10.1016/j.jclepro.2015.01.012

Gaziulusoy, A. I., & Brezet, H. (2015). Design for system innovations and transitions: a conceptual framework integrating insights from sustainablity science and theories of system innovations and transitions. *Journal of Cleaner Production, 108*, 558-568. doi:https://doi.org/10.1016/j.jclepro.2015.06.066

Gibson, R. B. (2006). Sustainability assessment: basic components of a practical approach. *Impact Assessment and Project Appraisal, 24*(3), 170-182. doi:10.3152/147154606781765147

Griggs, G. (2022). Is Building Walls around Our Threatened Coastal Cities the Best Long-Term Solution to Extreme Events and Rising Sea Level? *Coastal Management, 50*(1), 75-78. doi:10.1080/08920753.2022.2006872

Gullett, H. L., Brown, G. L., Collins, D., Halko, M., Gotler, R. S., Stange, K. C., & Hovmand, P. S. (2022). Using Community-Based System Dynamics to Address Structural Racism in Community Health Improvement. *Journal of Public Health Management and Practice, 28*(4).

Gunder, M. (2006). Sustainability: Planning's Saving Grace or Road to Perdition? *Journal of Planning Education and Research, 26*(2), 208-221. doi:10.1177/0739456X06289359

Gómez-Baggethun, E., & Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological Economics, 86*, 235-245. doi:https://doi.org/10.1016/j.ecolecon.2012.08.019

Haase, D., & Schwarz, N. (2009). Simulation Models on Human--Nature Interactions in Urban Landscapes: A Review Including Spatial Economics, System Dynamics, Cellular Automata and Agent-based Approaches. *Living Rev. Landscape Res., 3*.

Hallett, L. M., & Hobbs, R. J. (2020). Thinking systemically about ecological interventions: what do system archetypes teach us? *Restoration Ecology, 28*(5), 1017-1025.

Hansen, R., & Pauleit, S. J. A. (2014). From Multifunctionality to Multiple Ecosystem Services? A Conceptual Framework for Multifunctionality in Green Infrastructure Planning for Urban Areas. *43*(4), 516-529. doi:10.1007/s13280-014-0510-2

Helfgott, A. (2018). Operationalising systemic resilience. *European Journal of Operational Research, 268*(3), 852-864. doi:https://doi.org/10.1016/j.ejor.2017.11.056

Hjorth, P., & Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures, 38*, 74-92. doi:10.1016/j.futures.2005.04.005

Hoolohan, C., & Browne, A. L. (2020). Design thinking for practice-based intervention: Co-producing the change points toolkit to unlock (un)sustainable practices. *Design Studies, 67*, 102-132. doi:https://doi.org/10.1016/j.destud.2019.12.002

Hoover, F.-A., Meerow, S., Coleman, E., Grabowski, Z., & McPhearson, T. (2023). Why go green? Comparing rationales and planning criteria for green infrastructure in U.S. city plans. *Landscape and Urban Planning, 237*, 104781. doi:https://doi.org/10.1016/j.landurbplan.2023.104781

Hovmand, P., Rouwette, E., Andersen, D., Richardson, G., Calhoun, A., Rux, K., & Hower, T. (2011). Scriptapedia: A Handbook of Scripts for Developing Structured Group Model Building Sessions. *Social Science & Medicine - SOC SCI MED*.

Hovmand, P. S. (2014). *Community Based System Dynamics*(1st ed. 2014. ed.).

Hovmand, P. S., Andersen, D. F., Rouwette, E., Richardson, G. P., Rux, K., & Calhoun, A. (2012). Group Model-Building 'Scripts' as a Collaborative Planning Tool. *Systems Research and Behavioral Science, 29*(2), 179-193. doi:10.1002/sres.2105

Jackson, M. C. (1994). Critical systems thinking: Beyond the fragments. *System Dynamics Review, 10*(2-3), 213-229. doi:https://doi.org/10.1002/sdr.4260100209

Jerneck, A., Olsson, L., Ness, B., Anderberg, S., Baier, M., Clark, E., . . . Persson, J. (2011). Structuring sustainability science. *Sustainability Science, 6*(1), 69-82. doi:10.1007/s11625-010-0117-x

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., . . . Bonn, A. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society, 21*(2).

Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Meza Prado, K. A., . . . Wood, S. A. (2019). Social-ecological and technological factors moderate the value of urban nature. *Nature Sustainability, 2*(1), 29-38. doi:10.1038/s41893-018-0202-1

Kim, Y., Carvalhaes, T., Helmrich, A., Markolf, S., Hoff, R., Chester, M., . . . Ahmad, N. (2022). Leveraging SETS resilience capabilities for safe-to-fail infrastructure under climate change. *Current Opinion in Environmental Sustainability, 54*, 101153. doi:https://doi.org/10.1016/j.cosust.2022.101153

Kolosz, B. W., Athanasiadis, I. N., Cadisch, G., Dawson, T. P., Giupponi, C., Honzák, M., . . . Balbi, S. (2018). Conceptual advancement of socio-ecological modelling of ecosystem services for re-evaluating Brownfield land. *Ecosystem Services, 33*, 29-39. doi:https://doi.org/10.1016/j.ecoser.2018.08.003

Kronenberg, J., Andersson, E., Barton, D. N., Borgström, S. T., Langemeyer, J., Björklund, T., . . . Wolff, M. (2021). The thorny path toward greening: unintended consequences, trade-offs, and constraints in green and blue infrastructure planning, implementation, and management. *Ecology and Society, 26*(2). doi:10.5751/ES-12445-260236

Kuhn, T. S. (1970). *The structure of scientific revolutions* (Vol. 111): Chicago University of Chicago Press.

Lanhoso, F., & Coelho, D. A. (2021). Emergence fostered by systemic analysis—Seeding innovation for sustainable development. *Sustainable Development, 29*(4), 768-779. doi:https://doi.org/10.1002/sd.2173

Leach, M., Stirling, A. C., & Scoones, I. (2010). *Dynamic sustainabilities: technology, environment, social justice*: Taylor & Francis.

Lieberherr, E., & Green, O. O. (2018). Green Infrastructure through Citizen Stormwater Management: Policy Instruments, Participation and Engagement. *Sustainability, 10*(6). doi:10.3390/su10062099

Lundgren, J. (2021). The Grand Concepts of Environmental Studies Boundary objects between disciplines and policymakers. *Journal of Environmental Studies and Sciences, 11*(1), 93-100. doi:10.1007/s13412-020-00585-x

Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., . . . Chang, H. (2018). Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience. *Earth's Future, 6*(12), 1638-1659. doi:https://doi.org/10.1029/2018EF000926

McPhearson, T., Cook, E. M., Berbés-Blázquez, M., Cheng, C., Grimm, N. B., Andersson, E., . . . Troxler, T. G. (2022). A social-ecological-technological systems framework for urban ecosystem services. *One Earth, 5*(5), 505-518. doi:https://doi.org/10.1016/j.oneear.2022.04.007

McPhearson, T., Haase, D., Kabisch, N., & Gren, Å. (2016). Advancing understanding of the complex nature of urban systems. *Ecological Indicators, 70*, 566-573. doi:https://doi.org/10.1016/j.ecolind.2016.03.054

McPhearson, T., M. Raymond, C., Gulsrud, N., Albert, C., Coles, N., Fagerholm, N., . . . Vierikko, K. (2021). Radical changes are needed for transformations to a good Anthropocene. *npj Urban Sustainability, 1*(1), 5. doi:10.1038/s42949-021-00017-x

McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., . . . Qureshi, S. (2016). Advancing Urban Ecology toward a Science of Cities. *BioScience, 66*(3), 198-212. doi:10.1093/biosci/biw002

Meadows, D. H. (1982). Whole earth models and systems. *CoEvolution Quarterly, 34*, 98-108.

Meadows, D. H. (1995). Definition of Sustainability. *Dear Folks Newsletter*.

Meadows, D. H. (2008). *Thinking in systems: A primer*: chelsea green publishing.

Midgley, G. (2001). Rethinking the unity of science. *International Journal of General Systems, 30*(3), 379-409. doi:10.1080/03081070108960713

Moallemi, E. A., Hosseini, S. H., Eker, S., Gao, L., Bertone, E., Szetey, K., & Bryan, B. A. (2022). Eight Archetypes of Sustainable Development Goal (SDG) Synergies and Trade-Offs. *Earth's Future, 10*(9), e2022EF002873. doi:https://doi.org/10.1029/2022EF002873

Mooij, W. M., van Wijk, D., Beusen, A. H. W., Brederveld, R. J., Chang, M., Cobben, M. M. P., . . . Teurlincx, S. (2019). Modeling water quality in the Anthropocene: directions for the next-generation aquatic ecosystem models. *Current Opinion in*

Environmental Sustainability, 36, 85-95. doi:https://doi.org/10.1016/j.cosust.2018.10.012

Nagatsu, M., Davis, T., DesRoches, C. T., Koskinen, I., MacLeod, M., Stojanovic, M., & Thorén, H. (2020). Philosophy of science for sustainability science. *Sustainability Science, 15*(6), 1807-1817. doi:10.1007/s11625-020-00832-8

Nikulin, G., Kjellstro, E., Hansson, U., Strandberg, G., & Ullerstig, A. (2011). Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. *Tellus A: Dynamic Meteorology and Oceanography, 63*(1), 41-55. doi:10.1111/j.1600-0870.2010.00466.x

Nordman, E. E., Isely, E., Isely, P., & Denning, R. (2018). Benefit-cost analysis of stormwater green infrastructure practices for Grand Rapids, Michigan, USA. *Journal of Cleaner Production, 200*, 501-510. doi:https://doi.org/10.1016/j.jclepro.2018.07.152

Oberlack, C., Sietz, D., Bonanomi, E. B., de Bremond, A., Dell'Angelo, J., Eisenack, K., . . . Villamayor-Tomas, S. (2019). Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making. *Ecology and Society, 24*(2).

Oslo kommune. (2018). *Norm for blågrønn faktor i boligprosjekter i Oslo*.

Ramsey, J. L. (2015). On Not Defining Sustainability. *Journal of Agricultural and Environmental Ethics, 28*(6), 1075-1087. doi:10.1007/s10806-015-9578-3

Ruggerio, C. A. (2021). Sustainability and sustainable development: A review of principles and definitions. *Science of The Total Environment, 786*, 147481. doi:https://doi.org/10.1016/j.scitotenv.2021.147481

Savaget, P., Geissdoerfer, M., Kharrazi, A., & Evans, S. (2019). The theoretical foundations of sociotechnical systems change for sustainability: A systematic literature review. *Journal of Cleaner Production, 206*, 878-892. doi:https://doi.org/10.1016/j.jclepro.2018.09.208

Schifman, L. A., Herrmann, D. L., Shuster, W. D., Ossola, A., Garmestani, A., & Hopton, M. E. (2017). Situating Green Infrastructure in Context: A Framework for Adaptive Socio-Hydrology in Cities. *Water Resources Research, 53*(12), 10139-10154. doi:https://doi.org/10.1002/2017WR020926

Schlaile, M. P., Urmetzer, S., Blok, V., Andersen, A. D., Timmermans, J., Mueller, M., . . . Pyka, A. (2017). Innovation Systems for Transformations towards Sustainability? Taking the Normative Dimension Seriously. *Sustainability, 9*(12), 2253.

Schlüter, M., Caniglia, G., Orach, K., Bodin, Ö., Magliocca, N., Meyfroidt, P., & Reyers, B. (2022). Why care about theories? Innovative ways of theorizing in sustainability science. *Current Opinion in Environmental Sustainability, 54*, 101154. doi:https://doi.org/10.1016/j.cosust.2022.101154

Schneider, F., Kläy, A., Zimmermann, A. B., Buser, T., Ingalls, M., & Messerli, P. (2019). How can science support the 2030 Agenda for Sustainable Development? Four tasks to tackle the normative dimension of sustainability. *Sustainability Science, 14*(6), 1593-1604. doi:10.1007/s11625-019-00675-y

Schrage, J., Barraclough, A. D., Wilkerson, B., Cusens, J., & Fuller, J. (2023). Developing positional awareness in sustainability science: four archetypes for early career scientists working in an SDG world. *Sustainability Science, 18*(2), 1053-1058. doi:10.1007/s11625-022-01239-3

Scott, R. J., Cavana, R. Y., & Cameron, D. (2016). Recent evidence on the effectiveness of group model building. *European Journal of Operational Research, 249*(3), 908-918. doi:https://doi.org/10.1016/j.ejor.2015.06.078

Senge, P. (1990). *The fifth discipline: The Art & Practice of Learning Organization*. London: Random House.

Seto, K. C., Reenberg, A., Boone, C. G., Fragkias, M., Haase, D., Langanke, T., . . . Simon, D. (2012). Urban land teleconnections and sustainability. *Proceedings of the National Academy of Sciences, 109*(20), 7687. doi:10.1073/pnas.1117622109

Shahadu, H. (2016). Towards an umbrella science of sustainability. *Sustainability Science, 11*(5), 777-788. doi:10.1007/s11625-016-0375-3

Shi, L., Chu, E., Anguelovski, I., Aylett, A., Debats, J., Goh, K., . . . VanDeveer, S. D. (2016). Roadmap towards justice in urban climate adaptation research. *Nature Climate Change, 6*, 131. doi:10.1038/nclimate2841

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social studies of science, 19*(3), 387-420.

Sterman, J. (2000). *Business Dynamics*: McGraw-Hill, Inc.

Stock, P., & Burton, R. J. F. (2011). Defining Terms for Integrated (Multi-Inter-Trans-Disciplinary) Sustainability Research. *Sustainability, 3*(8), 1090-1113.

Ureta, J., Motallebi, M., Scaroni, A. E., Lovelace, S., & Ureta, J. C. (2021). Understanding the public's behavior in adopting green stormwater infrastructure. *Sustainable Cities and Society, 69*, 102815. doi:https://doi.org/10.1016/j.scs.2021.102815 van den Bosch, M., & Ode Sang, Å. (2017). Urban natural environments as nature-based solutions for improved public health – A systematic review of reviews. *Environmental Research, 158*, 373-384. doi:https://doi.org/10.1016/j.envres.2017.05.040

van den Hove, S., McGlade, J., Mottet, P., & Depledge, M. H. (2012). The Innovation Union: a perfect means to confused ends? *Environmental Science & Policy, 16*, 73-80. doi:https://doi.org/10.1016/j.envsci.2011.11.006

Venter, Z. S., Figari, H., Krange, O., & Gundersen, V. (2023). Environmental justice in a very green city: Spatial inequality in exposure to urban nature, air pollution and heat in Oslo, Norway. *Science of The Total Environment, 858*, 160193. doi:https://doi.org/10.1016/j.scitotenv.2022.160193

Videira, N., Antunes, P., & Santos, R. (2017). Engaging Stakeholders in Environmental and Sustainability Decisions with Participatory System Dynamics Modeling. In S. Gray, M. Paolisso, R. Jordan, & S. Gray (Eds.), *Environmental Modeling with Stakeholders: Theory, Methods, and Applications* (pp. 241-265). Cham: Springer International Publishing.

Videira, N., Antunes, P., Santos, R., & Lopes, R. (2010). A participatory modelling approach to support integrated sustainability assessment processes. *Systems Research and Behavioral Science, 27*(4), 446-460. doi:https://doi.org/10.1002/sres.1041

Webb, R., Bai, X., Smith, M. S., Costanza, R., Griggs, D., Moglia, M., . . . Thomson, G. (2018). Sustainable urban systems: Co-design and framing for transformation. *Ambio, 47*(1), 57-77. doi:10.1007/s13280-017-0934-6

West, S., Haider, L. J., Stålhammar, S., & Woroniecki, S. (2020). A relational turn for sustainability science? Relational thinking, leverage points and transformations. *Ecosystems and People, 16*(1), 304-325. doi:10.1080/26395916.2020.1814417

White, M. A. (2013). Sustainability: I know it when I see it. *Ecological Economics, 86*, 213-217. doi:https://doi.org/10.1016/j.ecolecon.2012.12.020

Wilbers, G.-J., de Bruin, K., Seifert-Dähnn, I., Lekkerkerk, W., Li, H., & Budding-Polo Ballinas, M. (2022). Investing in Urban Blue–Green Infrastructure—Assessing the Costs and Benefits of Stormwater Management in a Peri-Urban Catchment in Oslo, Norway. *Sustainability, 14*(3), 1934.

Wilkerson, B. (unpublished manuscript). *Advancing sustainability-oriented innovation practice with quality criteria for problem definitions*.

Wilkerson, B., Aguiar, A., Gkini, C., Czermainski de Oliveira, I., Lunde Trellevik, L.-K., & Kopainsky, B. (2020). Reflections on adapting group model building scripts into online workshops. *System Dynamics Review, 36*(3), 358-372. doi:https://doi.org/10.1002/sdr.1662

Wilkerson, B., Romanenko, E., & Barton, D. N. (2022). Modeling reverse auction-based subsidies and stormwater fee policies for Low Impact Development (LID) adoption: a system dynamics analysis. *Sustainable Cities and Society, 79*, 103602. doi:https://doi.org/10.1016/j.scs.2021.103602

Wilkerson, B., & Trellevik, L.-K. L. (2021). Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches. *Thinking Skills and Creativity, 42*, 100932. doi:https://doi.org/10.1016/j.tsc.2021.100932

Wolfram, M. (2019). Assessing transformative capacity for sustainable urban regeneration: A comparative study of three South Korean cities. *Ambio, 48*(5), 478-493.

Paper 0

NOTES AND INSIGHTS

Reflections on adapting group model building scripts into online workshops

Brooke Wilkerson,[a,b†*] Anaely Aguiar,[a†] Christina Gkini,[a]
Igor Czermainski de Oliveira,[a] Lars-Kristian Lunde Trellevik[a,c] and
Birgit Kopainsky[a]

Syst. Dyn. Rev. **36**, 358–372 (2020)

Introduction

Group model building (GMB) is an important social process in system dynamics (SD) for creating a shared understanding of complex systems and providing a platform for stakeholders to exchange information and ideas (Antunes *et al.*, 2015; Sedlacko *et al.*, 2014). Gathering stakeholders around the table to discuss a contentious issue can provide important insights for SD modeling (Hovmand, 2014; Rouwette and Vennix, 2006; Van den Belt and Dietz, 2004; Vennix, 1996; Vennix *et al.*, 1992).

While online meeting platforms and collaborative tools have made great leaps forward in recent years, systems mapping has largely continued with in-person facilitation. And with good reason: in-person facilitation has proven to be an effective way to generate discussions among stakeholders (Stave, 2010). Many in the SD community have long seen the potential in using interactive platforms for GMB with stakeholder participation (e.g. Kenzie *et al.*, 2018). Yet, to our knowledge, there are no documented efforts of a fully online GMB workshop. In our case, the COVID-19 virus and sudden change in travel and work patterns meant that an anticipated GMB workshop could not be executed as planned. Instead of canceling or postponing the workshop, we used this disruption as an opportunity to test the potential of running GMB processes online.

One key advantage of online GMB is that it can make room for more—and more diverse stakeholders—at the table, no matter where they may be in the world. This can improve access and participation, although groups with strong power dynamics may require skillful facilitation. Online GMB can also greatly reduce the need for travel, which could reduce the amount of time and money needed for a workshop in addition to reducing carbon

[a] System Dynamics Group, Department of Geography, University of Bergen, Bergen, Postbox 7802, 5020, Norway
[b] Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, Bergen, Postbox 7802, 5020, Norway
[c] K.G. Jebsen Centre for Deep Sea Research, Department of Earth Science, University of Bergen, Bergen, Postbox 7803, 5020, Norway

* Correspondence to:Brooke Wilkerson, System Dynamics Group and Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway.
E-mail: brooke.wilkerson@uib.no

[†]Joint first authors.

Accepted by Luis Luna-Reyes, Received 7 July 2020; Revised 29 July 2020 and 28 August 2020; Accepted 7 September 2020

System Dynamics Review
System Dynamics Review vol 36, No 3 (July/September 2020): 358–372

footprints. The lack of travel logistics can also mean that workshops could be planned with less advance notice and perhaps be more responsive to current issues.

In order to move an interactive GMB workshop online, we needed to:

- Find an online architecture that supports divergent activities (e.g. drawing graphs) in a collaborative and interactive way;
- Adapt standard GMB scripts to online interactions; and
- Develop and define roles within our group to support the various challenges we could face before, during, and after the workshop.

Online GMB, with stakeholders sitting alone in front of their computer screens, is fundamentally different from in-person GMB workshops, and there are limitations to how much one can substitute for the other. We found, however, that we could recreate many of the strengths of an in-person GMB workshop in an online environment.

Our positive initial experiences with online GMB indicate that it's worthwhile to build on and further develop methodologies for online stakeholder engagement. We propose that online GMB, a practice with its own set of strengths and weaknesses, should be further developed as its own set of methodologies parallel to traditional (in-person) GMB. This research note includes a description of our experiences and lessons learned as well as areas for further development.

Context

The workshop was planned to gather representatives from the business sector, public policy sector, and academia to work on two cases. The first case addressed the Bergen, Norway, goal of becoming "fossil fuel free" by 2030, and the second case focused on innovation across sectors for ocean technology and offshore industry. The workshop was the first phase in a larger project. Subsequent phases include a hackathon in which SD students and practitioners use the causal loop diagrams from the workshop to generate models and ideas for policy interventions. In phase three of the project, winning submissions from the hackathon are refined and presented at an "innovation festival" in Bergen.

Objectives of the workshop:

- Introduce systems thinking and system dynamics to participants;
- Engage diverse stakeholders;
- Build a shared understanding of a complex issue; and
- Motivate participants to consider where and how to intervene in the system to achieve systemic change.

DOI: 10.1002/sdr

The workshop had been planned for early June 2020 as an in-person, five-hour GMB session with a focus on systems mapping. When it became clear that the workshop could not be held as planned due to Covid-19 and social-distancing requirements, we assembled an international team to redesign the session as an online workshop on the same date.

Participants had little or no previous experience with systems mapping, systems dynamics, or systems thinking. The workshop was advertised as a “Crash Course in Systems Thinking,” and all participants referred to the possibility of learning a new skill or perspective (as opposed to having strong stakes in the issue we were mapping) as a major reason for registering. Our participants were fairly homogeneous in education levels and technological savvy. Further, all participants were from Norway, a society typically characterized as egalitarian and “flat,” with an expectation that everyone’s contribution should be heard. Working with more diverse (ethnicity, familiarity with technology, language abilities, etc.) groups, or groups with more complex power dynamics, in an online environment will require more sophisticated facilitation techniques, but that is not the focus of this research note.

Creating a workable architecture

The first step in moving our workshop online was finding a digital platform that could support the activities and interactions in a GMB workshop. Particularly, we were looking for a collaborative platform that could ideally support both divergent and convergent activities:

- For divergent activities, we needed a workspace that allows for independent, synchronous work by the participants. This includes tools for drawing graphs, adding variable names or other information as text, as well as for easy navigation across the mentioned elements.
- For convergent activities, we needed a platform that allowed for different view levels, both a full-frame view of activity areas or the causal map, as well as the opportunity to “zoom in” and focus on specific areas. Specific features to draw causal maps were also a significant requirement, including arrows that could “stick” to text boxes and graphs, to allow for easy rearrangement of elements in the systems map.

A significant consideration for our design was to minimize the transitions between workspaces and the learning curve for participants. While existing SD softwares offer increasingly sophisticated causal-loop diagram abilities, they do not allow for real-time group editing. Some members of the group had experience with other online tools such as Kumu, Sheetless, Padlet, Loopy, Mental Modeler, and Meetingsphere, but none of those platforms met all our needs for divergent and convergent activities.

DOI: 10.1002/sdr

After much searching, we realized that there was no perfect online platform, but that one platform, Miro (miro.com), came close. Miro is a very flexible, collaborative, and interactive online platform that includes a large board, onto which different types of notes, discussions, and diagrams can be placed. Everyone with access to the board can add or take away text or drawings. Other valuable features include a timer and a "share screen" feature that allows a facilitator to bring everyone to the same part of the board. Miro includes a video chat function, though it only shows the videos of up to three people at a time, and the facilitator could not mute all participants at once. Lastly, although Miro's tools include "sticky" arrows, we could not easily assign +/− symbols to the arrows (though arrow color could be changed to show polarity). Another important limitation of Miro is that it does not offer the possibility for turning the systems map into a simulatable model in later stages of the GMB process.

As Miro could not meet all our needs, it was used in conjunction with Zoom, email, Google Drive, and WhatsApp during various phases of workshop planning and execution (Figure 1).

Preparing for the workshop

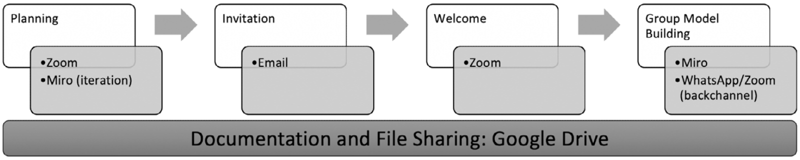
Both divergent and convergent group activities were selected from standard scripts, which define essential elements of the GMB workshop, the steps needed to complete the script, and the outputs produced from the scripts (Andersen and Richardson, 1997; Hovmand *et al.*, 2011; Hovmand *et al.*, 2012). The modeling team then adapted the scripts to the online workshops and developed the workspace.

Every aspect of the workspace layout had to be built "by hand," as Miro does not include empty graphs or other templates that we needed. The main design challenge was to find ways the platform could support the strengths of the different activities. For divergent activities, we needed to give control to the participants to produce their ideas. For this, we designed individual workspaces that the participants could zoom in to and work without disruption or distraction. For convergent activities, a balance was necessary between viewing large clustering or mapping spaces with the minimum possible loss of information on individual variables. Text boxes that automatically resize depending on the zoom were particularly useful in this respect, and a more "tight" design was selected to reduce information loss.

All members in the modeling team were trained in GMB methods, and the entire team needed to be familiarized with the online workspace and their roles to generate the best results. The roles included meeting opener/closer, facilitators, modelers, and recorders, as indicated in the scripts. We also included an additional role specific to the online architecture: the stage manager who controlled the view of the workspace areas. The stage manager

DOI: 10.1002/sdr

Fig 1. Applications used in different phases of online group model building.



used the "Share Screen" mode and the "Bring-To-Self" feature to guide stakeholders to different parts of the board while activities were described and demonstrated with examples. For individual activities, the "Share Screen" mode was turned off, and participants could navigate and zoom in and out of the board as they desired.

Adapting GMB scripts

We used established scripts from Scriptapedia to facilitate the GMB workshop (Andersen and Richardson, 1997). The main steps, time required during the session, and outcomes, were essentially the same from the original scripts. The scripts we used are:

a. Graphs Over Time;
b. Variable Elicitation;
c. Initiating and Elaborating a Causal Loop Diagram;
d. Model Review;
e. Action Ideas;
f. Next Steps and Closing.

The differences between the original and adapted scripts for the virtual environment, were (i) the materials, which were replaced by the tools in Miro and (ii) some parallel activities in Miro that needed to be paired with the corresponding step in the script. We created a Google document with the steps in each script, timing, and the specific activities that the stage manager and modeler needed to follow in Miro along with the facilitator's activities. This adapted script was applied in both case studies.

As an illustration, we present an example of how we adapted the Graph Over Time script to Miro's workspace. For practical reasons, we combined the Graphs Over Time script with the Variable Elicitation script. Participants first generated a set of graphs with the key factors they considered were causing the problem, and we used those graphs as a starting point to elaborate the CLD. Participants could then add variables using a text box as they were building the diagram with the modeler's help.

DOI: 10.1002/sdr

To develop the layout and material for the script in Miro, the design team focused on what usually “works” in the in-person execution of the script and attempted to mimic, to the extent possible, the experience of a GMB workshop. Due to the small size of the group, we were able to create individual virtual desks for independent work. Graphs Over Time templates were placed on each workspace to reduce the need for moving elements in the platform, and a “stack” of additional templates was placed next to each desk. Following the script, a board for clustering ideas and a large area for systems mapping were developed, accompanied by “parking lot” and “duplicates” areas (Figure 2). In Table 1, we detail the activities and roles for online implementation of the Graphs Over Time script.

After the Miro layout and the script were adapted, the entire team conducted two practice rounds to test technical issues, visibility and ease of use of elements on the board, and timing for different steps in the process. Through the trials, the entire team could test the workshop experience in real time and practice using tools and navigating the board as a participant. In addition, team members developed familiarity with the script, roles, and tasks and practiced interactions among each other to ensure a smooth experience for participants. These practice rounds resulted in a number of ideas and adjustments for streamlining the workshop and improving user experience.

During the workshop: the stakeholders’ experience

The day before the workshop, participants were sent an email with instructions for creating an account on Miro, a brief video (made by a team member) showing participants how to use some of the tools on Miro, and links to a Zoom meeting and the Miro board. The participants also received a workshop agenda describing each activity (see Table 1).

The workshop started in Zoom, a platform we knew most stakeholders were familiar with (Figure 1). Here, we introduced the workshop and the GMB process. We then asked participants to join their relevant board in Miro via a link that had previously been sent to them in an email. A facilitator stayed on Zoom to chat with participants who had trouble accessing the Miro board and joining the video chat there.

The first activity on Miro was an icebreaker in which participants drew a picture about their interests and wrote a few words about themselves. In addition to getting people familiar with each other, this had the advantage of encouraging participants to use the writing and drawing tools in Miro that they would be using in the workshop activities (Figure 3). The modeling team then followed the adapted scripts according to their roles. A summary of the activities of the workshop is presented in Table 2.

DOI: 10.1002/sdr

OVERVIEW OF ACTIVITY 1 - GRAPHS OVER TIME

OUTLINE

Goals:
Identify important factors around our problem & their development over time

Tools:
Behavioural Graphs (Graphs Over Time)

SCHEDULE

11:00-11:10
Introduction & Instructions
11:10-11:25
Developing the graphs
11:25-11:45
Discussion of identified factors

GUIDELINES

1. **Pick a Graph** from the Stack **& bring to your desk**
2. Write the **name** of the variable & its **behaviour over time**
    a. use green for hope
    b. use red for fear
3. Arrange the graphs from **most to least favourite**

Fig 2. The full view of the Graphs Over Time activity. [Color figure can be viewed at wileyonlinelibrary.com]

During the workshop: behind the scenes

The workshop team used communications apps (Zoom and WhatsApp) to communicate privately both during active parts of the workshop and during breaks (Figure 1). Direct messaging via WhatsApp allowed us to discuss issues related to the workshop without disturbing participants and give each other feedback on what we were observing. During breaks, we used Zoom to discuss and edit the CLD. By muting ourselves in Miro, we could discuss freely and collaboratively without disturbing participants who kept their sound on. Facilitators, modelers, and stage managers accessed the prepared scripts via Google Drive, and the same service was used by recorders to document the session. As members of the workshop team were using Miro, Google Drive, and a separate communications app at the same time, we found having two screens very helpful.

After the workshop: lessons learned

Planning and conducting an online GMB workshop provided a rich learning experience for facilitators and modelers in addition to participants. In a

DOI: 10.1002/sdr

Table 1. Graphs Over Time script adaptation

Time (min) (total) 11:00 11:35	Activity	Facilitator	Stage manager	Modeler
2	Introduction	Introduction and activity description	[Share Screen mode] Frame: Graphs Over Time overview	
5	Example	Description of Graphs Over Time template	[Share Screen mode]	
		Description of example factor	Frame: Example factor	Draw example from facilitator's description
3	Instructions	Introduce workspace and stack	[EXIT Share Screen mode]	
		Describe moving templates	Zoom to table (follow facilitator's description)	
		Instruct participants to find the desk with their name and zoom in		
		Remind timing	Zoom out to see all desks + Bring-to-Self so participants see entire space to easily identify their desk	
10	Individual work	Team is muted and available for questions		
15	Group work	Inform that time is up and remind next steps.		
		Call on first participant to describe a factor. Move to second participant, etc.	Zoom to described factor on desk + Bring-To-Self	Move described variable to Clustering Area and cluster. Use Duplicates Area if needed
			[Share Screen mode] Top-View of Clustering Area and zoom in following modeler's descriptions	Describe themes and confirm. If needed, merge or create themes

DOI: 10.1002/sdr

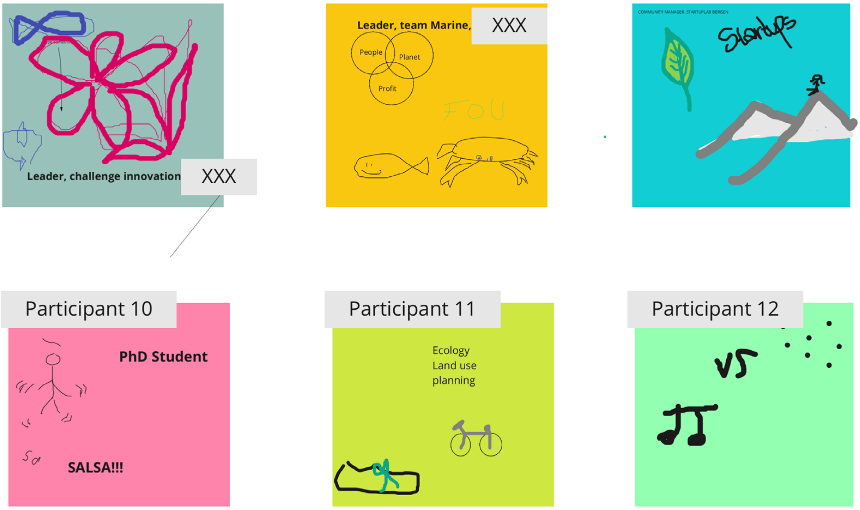


Fig 3. Example of results of the icebreaker activity. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2. Summary of workshop activities

Activity	Description	Time (min)
Miro workspace/Zoom setup	Modeling team prepares the workspace and initial Zoom call.	30
Welcome, Introduction, Plan of the day	Project leader welcomes participants and opens the meeting. Introduction of modeling team and brief introduction to the activities that will be completed along the workshop.	10
Introduction to ST/SD—Group formation	Systems thinking and system dynamics are introduced by one member of the modeling team. Participants then directed to their respective workspaces in Miro.	15
Move between platforms	Modeling team ensures that all participants have migrated to Miro and joined the video call.	5
Icebreaker activity in Miro—within each case study (Figure 3)	Participants introduce themselves using Miro features while familiarizing themselves with the Miro's tools.	20
Problem articulation	Brief introduction of each case's problem to be addressed during the workshop.	10
Graphs Over Time (Figure 4)	Participants identify key factors around our problem and their development over time. Factors are clustered in a group discussion.	35
Break	Modeler moves the clusters to the large CLD area.	5
Causal Mapping/Feedback loop identification	Facilitator and modeler help participants find the connections between different concepts or variables that contribute to or are affected by the problem variable.	30
Lunch Break	Modeling team reconvenes over Zoom to clean and update the CLD	30
Model review		15

(Continues)

DOI: 10.1002/sdr

Table 2. Continued

Activity	Description	Time (min)
	Facilitator gives a brief overview of how the map was updated during lunch break. The facilitator also checks and confirms the map together with participants in case there is something that needs to be added, removed, or changed.	
Action ideas	Participants identify possible actions that can alleviate the problem and how those fit into the systems map.	35
Model presentation (Figure 5)	Facilitator summarizes the map cocreated during the workshop and allows for further comments from participants.	10
Next Steps and Closing	Project leader thanks participants for their time, informs them of how their contributions will be carried forward, and invites them to stay after if they have feedback or questions.	15

debriefing after the workshop, we collated a list of insights that we would take forward into future online workshops. While some of these lessons learned are general "best practices" for any stakeholder engagement exercise, we highlight them here because we found them to be especially important in an online environment.

Lessons: preparing for the workshop

- Standard facilitation scripts used for GMB workshops are a good starting point for designing online workshops, but each activity needs to be

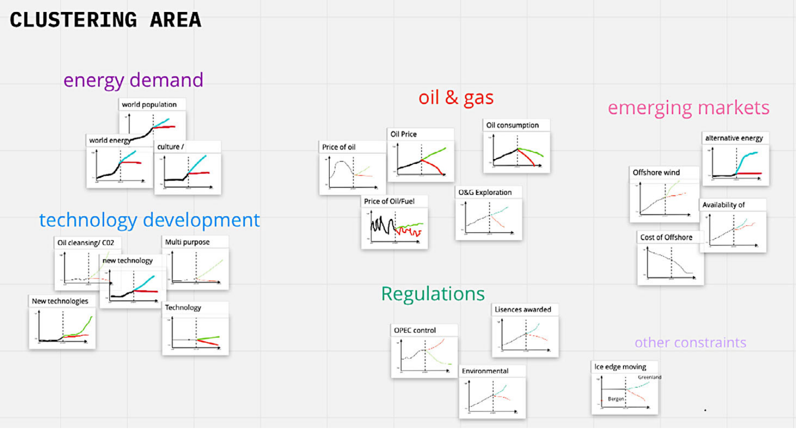


Fig 4. Behavior over time graphs, clustered (ocean business group). [Color figure can be viewed at wileyonlinelibrary.com]

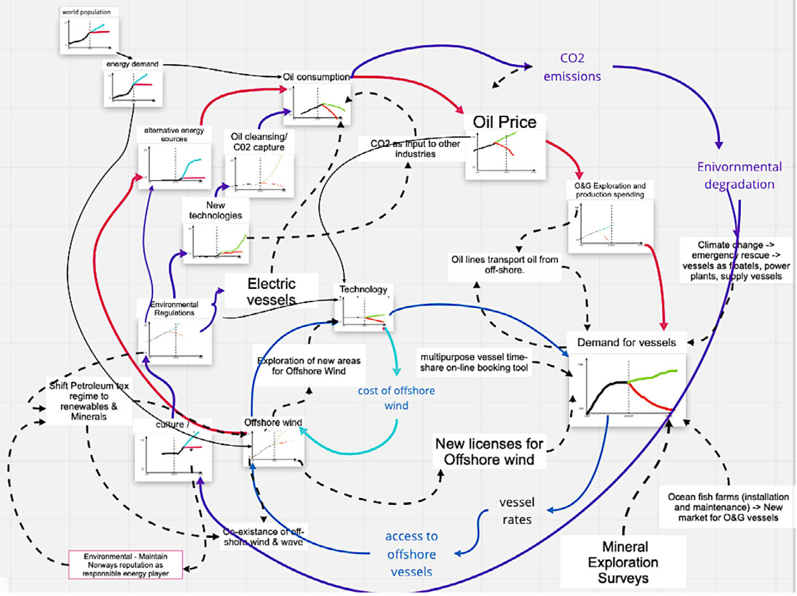


Fig 5. Model presentation (ocean business group). [Color figure can be viewed at wileyonlinelibrary.com]

carefully aligned with actions in the online platform. The script and online workspace need to be tightly coupled and tested iteratively before the workshop.

- The board should have a simple, intuitive layout that helps participants know where to look and what to do.
- The interface design team can become very familiar with the platform and its specific tools so that those seem more intuitive than they would be for users. It is especially important, therefore, to test the workshop activities and platform from a user's perspective to avoid overestimating usability.
- The modeler and facilitator need to collaborate effectively and efficiently during the workshop. The entire team should test and rehearse together prior to the workshop.

Lessons: during the workshop

Technical

- Allow time for technical problems, especially when migrating between platforms. Participants will need time to adjust audio and video settings,

DOI: 10.1002/sdr

and so on. In general, limiting the number of platforms and transitions reduces the chances for problems.

- Different stakeholders will have different comfort levels with technology, and facilitators need to ensure that this does not impact one's ability to participate. Some participants felt comfortable moving their written ideas around the board, while others needed assistance to move their contribution to the right place. The workshop team needs to adapt to participants' needs.
- The screen sharing bring-to-me features on Miro are especially useful for ensuring that everyone was looking at the same place at the same time while we explained activities, and so on.
- Facilitators need to find the balance between letting participants manipulate the environment themselves versus moving elements on the board for participants. This balance point will depend on many factors including comfort with technology, time pressure, and a reading of participants' energy levels.

Facilitation

- Icebreakers are especially important in online environments. Having an icebreaker that encouraged people to use the tools on Miro that were relevant for the planned activities was very useful.
- Good facilitation is enhanced by in-person interaction with participants, and it is shaped by how we use our body and voice and read verbal and nonverbal cues. In an online context, facilitators can only rely on participants' voices and faces in a video frame. Facilitators need to find ways to compensate for the lack of physical presence, such as checking in with participants more frequently. Building a good rapport with participants in the beginning of the workshop can support active participation throughout the workshop.
- Online dialog is more formal. People can be more hesitant to speak up and more concerned about speaking over others. Asking for volunteers, especially in a larger group, can result in silence. Instead, the facilitator may need to proactively ask specific people to share their work or ideas. We used several rounds of sharing ideas to build up dialog.
- Our groups of stakeholders were relatively small (between 5 and 10 participants) and came from similar organizations and backgrounds. Participants communicated effectively with us and with each other throughout the workshop. Larger or more diverse groups will likely need more formal/advanced facilitation techniques.
- Small, frequent breaks for stretching, coffee, and checking email are necessary. We posted the schedule within the Miro board, so it could always be referred to. In general, participation in online workshops can be more

energy demanding than participation in in-person workshops, and this should be a consideration when designing the schedule.

- Convergent activities are more challenging to facilitate than divergent activities in this setting. Facilitators need to be clear about who is speaking (e.g. ask the participant to repeat their name) and may need to assist the speaker in directing the focus to the part of the map or board that they want to discuss.
- Online script templates could be shared and reused in future workshops with context-specific modifications. As online GMB becomes more established, we envision that online scripts and templates could be paired and made freely available, much the way Scriptapedia functions today.

Further development and concluding remarks

We see several facets of online GMB that should be further explored and developed. Our experience points to the importance of good facilitation techniques. GMB likely works best with stakeholder groups with low levels of power differences (Vennix, 1996). It would be especially valuable to explicitly test to what degree facilitation techniques could address power dynamics in an online workshop. We also see the benefit in creating a guide or training to learn facilitation techniques for GMB in online environments.

Further research could also determine optimum group sizes for this methodology. Small groups allow for easier online dialog, yet larger groups can provide a greater diversity of perspectives and contexts. This balance point will depend on the chat and video capabilities of the online platforms in addition to the usual considerations for a workshop (e.g. topic complexity, group heterogeneity). Our workshop used common scripts (such as Graphs Over Time and Action Ideas), and we would welcome further explorations of implementing other GMB scripts (e.g. Causal Mapping with Seed Structure) virtually or even asynchronously.

Evaluations of long-term mental model changes, especially as compared to in-person workshops, would improve our understanding of the impact of online systems mapping on stakeholders. Surveys before and several weeks after the workshop could assess levels of engagement and information retention (Scott *et al.*, 2013). Paired studies, with some stakeholders assigned to an online workshop and others assigned to an in-person workshop on the same topic, could aid this understanding. If conditions in a multisession workshop allow, approaches that combine initial in-person meetings with subsequent online meetings, or that combine in-person convergent activities with online divergent activities, could be investigated. Due to power dynamics and facilitation challenges, we do not recommend having some participants in person and others online in the same workshop session. As more examples of online GMB workshops are assembled,

DOI: 10.1002/sdr

we'd like to see more systematization and standardization of approaches in order to ensure comparability across workshops (McCardle *et al.*, 2009; Scott *et al.*, 2016).

Moving GMB workshops online is not without challenges, but we feel that the significant time and effort invested in bringing a system's mapping experience into an online environment was worth it. Our initial instinct was confirmed: online GMB works! We received positive feedback from a number of participants, including "I came out of [the workshop] with very useful experience and ideas for how we can carry out workshops and think holistically about our customers' problems" and "I learned a lot about systems thinking and system dynamics and want to learn even more now." This relatively simple workshop allowed us to test the possibilities we saw in online GMB and develop ideas for further exploration.

Choosing between online or in-person GMB depends on workshop aims. In-person experiences provide a wealth of interactions that open the space for creating a rich understanding of the issue at hand. That same depth of interaction cannot be recreated online, at least not with today's technology. Online GMB can, however, open up for a larger breadth of interactions by including people who, because of time, finances, or distance would otherwise be excluded. As online GMB takes place in a "neutral" space, it may also make it easier to bring people together from across organizations and institutions. In short, online GMB offers significant advantages that are fundamentally different from the advantages of in-person GMB.

We believe that further explorations of how best to include this breadth in a digital platform can enrich the practice of GMB as a whole. We view online group model building as a parallel methodology that warrants further development, and we look forward to learning from each other's' experiences in the system dynamics community as this methodology advances.

Acknowledgements

The authors would like to thank the city of Bergen for providing support and funding and Sanjeet Jaiswar for assisting in the workshop. We thank the editors of the *System Dynamics Review* for their comments on an earlier version of this note.

References

Andersen DF, Richardson GP. 1997. Scripts for group model building. *System Dynamics Review* **13**(2): 107–129.

DOI: 10.1002/sdr

Antunes P, Stave K, Videira N, Santos R. 2015. Using participatory system dynamics in environmental and sustainability dialogues. Matthias R. (Ed.), In *Handbook of Research Methods and Applications in Environmental Studies*. Cheltenham, UK: Edward Elgar; 346–374.

Hovmand PS. 2014. *Community Based System Dynamics*. Springer New York: Imprint: Springer: New York.

Hovmand PS, Andersen DF, Rouwette E, Richardson GP, Rux K, Calhoun A. 2012. Group model-building 'scripts' as a collaborative planning tool. *Systems Research and Behavioral Science* **29**: 179–193.

Hovmand P, Rouwette E, Andersen D, Richardson G, Calhoun A, Rux K, Hower T. 2011. Scriptapedia: A handbook of scripts for developing structured group model building sessions. In Lyneis J. M. and Richardson G. P. (Eds.), *Proceedings of the 29th International Conference of the System Dynamics Society* (pp. 1476–1491). Washington DC.

Kenzie ES, Parks EL, Bigler ED, Wright DW, Lim MM, Chesnutt JC, Hawryluk GWJ, Gordon W, Wakeland W. 2018. The dynamics of concussion: mapping pathophysiology, persistence, and recovery with causal-loop diagramming. *Frontiers in Neurology* **9**: 203.

McCardle M, Rouwette E, Vennix J, Jacobs H. 2009. Is group model building worthwhile? Considering the effectiveness of GMB. *Proceedings of the 27th International Conference of the System Dynamics Society*, pp. 2367–2398. Albuquerque, New Mexico.

Rouwette EAJA, Vennix JAM. 2006. System dynamics and organizational interventions. *Systems Research and Behavioral Science* **23**: 451–466.

Scott RJ, Cavana RY, Cameron D. 2013. Evaluating immediate and long-term impacts of qualitative group model building workshops on participants' mental models. *System Dynamics Review* **29**: 216–236.

Scott RJ, Cavana RY, Cameron D. 2016. Recent evidence on the effectiveness of group model building. *European Journal of Operational Research* **249**: 908–918.

Sedlacko M, Martinuzzi A, Røpke I, Videira N, Antunes P. 2014. Participatory systems mapping for sustainable consumption: Discussion of a method promoting systemic insights. *Ecological Economics* **106**: 33–43.

Stave K. 2010. Participatory system dynamics modeling for sustainable environmental management: observations from four cases. *Sustainability* **2**: 2762–2784.

Van Den Belt M, Dietz T. 2004. *Mediated Modeling: A System Dynamics Approach to Environmental Consensus Building*. Island Press: Washington.

Vennix JAM. 1996. *Group Model Building: Facilitating Team Learning Using System Dynamics*. Wiley: Chichester.

Vennix JAM, Andersen DF, Richardson GP, Rohrbaugh J. 1992. Model-building for group decision support: Issues and alternatives in knowledge elicitation. *European Journal of Operational Research* **59**: 28–41.

DOI: 10.1002/sdr

Paper 1

Paper 2

Thinking Skills and Creativity 42 (2021) 100932

Contents lists available at ScienceDirect

Thinking Skills and Creativity

journal homepage: www.elsevier.com/locate/tsc

Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches

Brooke Wilkerson [a,b,1,*], Lars-Kristian Lunde Trellevik [a,c,1]

[a] System Dynamics Group, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway.

[b] Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, Norway P.O. Box 7800, 5020 Bergen, Norway [c] Centre for Deep Sea Research, Department of Geography, University of Bergen, Norway

ARTICLE INFO

Keywords:
Systems thinking
Design thinking
Sustainability
Innovation
Systems mapping

ABSTRACT

Sustainability-oriented innovation (SOI) is receiving increased focus, as sustainability takes a more central role in business, development, and education arenas. SOI processes typically draw from design thinking toolkits, with a focus on the user's needs and experiences. While this is an effective way to ensure that the innovation process is grounded in real, definable needs, it's also limited in its ability to place the problem in a larger societal and systemic context. This can lead to a narrow or incomplete problem definition.

We designed and tested a new approach for eliciting and defining problems for SOI. Our work shows that using systems mapping in the problem definition phase of SOI helps set adequate boundaries for the problem space and increases understanding of how the system influences itself over time. As "sustainability" is a systems property, we find that the "helicopter view" provided by systems mapping complements the empathetic design thinking approach to form a more robust problem definition. We present this combined methodology and provide examples of where and how it's been used. These examples illustrate the potential of design thinking and systems mapping to support and enhance problem definition for SOI and provide the basis for discussing future research directions.

---

* Corresponding author.

E-mail address: brooke.wilkerson@uib.no (B. Wilkerson).

[1] Joint first authors.

https://doi.org/10.1016/j.tsc.2021.100932
Received 31 May 2021; Received in revised form 15 August 2021; Accepted 17 August 2021

1. Introduction

Adequate and comprehensive problem definition is a key step in any type of innovation process, but it is particularly true when innovating for sustainability. Sustainability-oriented innovation (SOI) has defined characteristics that distinguish it from other types of innovation processes, including the need to include a long time horizon, examine the problem in a larger context, and consider multidimensional targets (ie, environmental, social, and economic impacts) (Buhl et al., 2019).

Innovation processes typically draw from design thinking toolkits. The design thinking approach focuses on the user’s needs and experiences, which provide valuable insights that guide innovation development (Carlgren, Rauth, & Elmquist, 2016; Roth, Globocnik, Rau, & Neyer, 2020). While this approach is an effective way to ensure that the innovation process is grounded in real, definable needs, it’s also limited in its ability to place the problem in a larger societal and systemic context (Hoolohan & Browne, 2020). This can lead to a narrow or incomplete problem definition. The unique characteristics of SOI heighten the importance of developing a holistic problem definition, yet current SOI development is usually characterized by ill-specified problem statements (Buhl et al., 2019).

Systems mapping is a group model building approach that focuses on empowering participants to create a shared understanding of a complex problem (Hovmand, 2014; Hovmand et al., 2012; Videira, Antunes, Santos, & Lopes, 2010). The approach to and understanding of systems is an outgrowth of systems thinking and system dynamics. The suite of tools implemented in systems mapping are particularly helpful in creating consensus around adequate system boundaries and understanding how the system influences itself over time from an aggregated and cross-disciplinary perspective (Videira et al., 2010). This approach addresses some of the key needs of SOI, but on it’s own, systems mapping can lack the specificity and empathetic perspective that design thinking engenders (Buchanan, 2019). We assert that an approach that includes both design thinking and systems mapping can create a more in-depth and richly detailed problem description that includes both individual perspectives and systemic understanding.

Our approach, called systems sustainability-oriented innovation (SSOI), builds on the strengths of design thinking and systems mapping practices to create a more robust problem statement. We present the theory behind this approach and discuss the practical considerations of employing such an approach. Finally, we provide two empirical examples of a combined approach in problem definition workshops. These examples illustrate the potential of SSOI to support and enhance problem definition for sustainability innovation and provide the basis for discussing future research directions.

1.1 Sustainability and innovation

Sustainability is increasingly identified as a key driver of innovation for companies, and environmental and social criteria have been incorporated into default design criteria, in addition to traditional criteria such as profitability, aesthetics, etc. (Gaziulusoy, 2015). Sustainability is a broad and normative concept, with a problem- and process-oriented application that has grown out of a desire to ensure that both current and future generations can meet their own needs without compromising planetary life support systems (Brundtland, 1987; Nagatsu et al., 2020; Shahadu, 2016). Innovation that accounts for sustainability requires explicit consideration of sustainability's defining characteristics.

"Sustainability" is a system property, rather than a property of elements in the system. Only when the system as a whole is sustainable can the individual components of the system be considered sustainable (Gaziulusoy, 2015). This has implications for individuals embedded in a society and what level(s) of society a SOI should target. Innovation for sustainability needs a systems vantage point to evaluate the product/service innovation within the system in which they will be produced and consumed (Gaziulusoy, 2015; Gaziulusoy & Brezet, 2015).

In addition, the emergent qualities of systems mean that the consequences of working towards or achieving sustainability may be different at the individual versus the societal level, raising questions of social justice (Bennett, Blythe, Cisneros-Montemayor, Singh, & Sumaila, 2019). Individuals may need to change their lifestyles and livelihoods in ways that are difficult or uncomfortable in order to move towards sustainability at the societal level. Changes that may be experienced as negative at the individual level may have emergent positive impacts at the societal level, reinforcing the need for SOI to consider both individuals and society in an explicitly systems perspective (Bennett et al., 2019).

"Sustainability" is inherently multidimensional, and working towards sustainability innovation requires consideration of multidimensional targets (Buhl et al., 2019; Videira et al., 2010). Operationalizing sustainability requires a comprehensive consideration of actions and impacts across sectors (such as environment, society, and economy) and a recognition of interrelations and interdependency across spatial and temporal scales (including future generations) (Gibson, 2006; Hjorth & Bagheri, 2006; Videira et al., 2010).

These characteristics of sustainability have consequences for designing an appropriate innovation process. Typical innovation processes are focused on individual products or services. These innovations result in only minor improvements in sustainability terms (Gaziulusoy & Brezet, 2015), yet sustainability-oriented innovation (SOI) will often require solutions that move beyond incremental adjustments on a product or technology level (Buhl et al., 2019). Explicitly incorporating and addressing the distinctive aspects of sustainability, described above, in the innovation process is necessary for SOI. Innovation aimed at sustainability should have a systems and societal scope that accounts for multidimensional targets (Buhl et al., 2019).

In particular, problem definition is an often neglected phase in SOI, and current SOI processes are usually characterized by poorly- specified problem statements (Buhl et al., 2019). Defining the scope of the problem defines the space in which innovative solutions can be developed. A problem defined too narrowly limits the space of available solutions and might therefore lead to solutions that are too confined to have a meaningful impact (Hoolohan & Browne, 2020). Traditional approaches to innovation tend to focus on individual users and their needs when defining the problem. This focus, though valuable, can exclude the broader, cross-sectoral and systems perspectives needed to adequately define a sustainability related problem.

1.2 Current approaches to problem definition

The innovation and design fields are characterized by plurality and, as a result, ambiguity in terms and approaches (Buchanan, 2019). While other academic fields typically emphasize convergence on canonical theories, the shifting and distributed nature of social innovation's theoretical foundation is often viewed as an asset for further development (Bijl-Brouwer & Malcolm, 2020). Approaches overlap (and complement) in name and methodology, with some based in theories of constructivist learning and others derived from practice and experience (Buchanan, 2019; Sevaldson, 2018). Rather than defined methodologies, design tools can be better understood as a suite of adaptive practices tailored to the specific needs of the problem being examined (Bijl-Brouwer & Malcolm, 2020).

Among these many adaptive practices, we focus on design thinking as a well-established and widely applied approach within the design practitioner SOI community. Design thinking is a suite of practitioner-based, problem solving approaches that typically emphasizes a user-centered, empathetic process (Buhl et al., 2019). The approach is loosely characterized by a blend of creative and analytic modes of reasoning and various hands-on tools and techniques (Buhl et al., 2019). As a suite of practices, design thinking implementation varies across contexts, with some practices emphasizing iteration and others focused on deep user empathy and understanding (Carlgren et al., 2016). As such, there is no single accepted definition of design thinking (Buhl et al., 2019; Carlgren et al., 2016; Jones, 2014). Most existing literature on design thinking is aimed at practitioners rather than academics, and it tends to emphasize tools and activities rather than theoretical foundations (Buhl et al., 2019).

Design thinking projects typically start with an exploratory phase that seeks to empathetically understand the given problem from the user's perspective. Through observing users in real-life situations in context, the practitioner defines an adequate problem and solution space (Buhl et al., 2019; Carlgren et al., 2016). This focus on immediate users can infuse the design process with empathy and realism, providing valuable insights into what people do, value, and desire (Hoolohan & Browne, 2020).

One common, established expression of design thinking is the "double diamond" (Clune & Lockrey, 2014; Conway, Masters, & Thorold, 2017) (Fig. 1). As a practice, the double diamond is typically defined as having five steps that are iteratively applied. The five steps are divided into diverging and converging phases, where diverging phases widen perspectives and converging phases increase focus.

Within these double diamonds, five steps are typically defined. (1) Empathy: the point of view of the user is elicited.(2) Define: Knowledge about the user is distilled and formulated as specific needs, wants or requirements (problem definition). (3) Ideation: ideas for solutions are formulated based on the specific needs and requirements one is aiming to satisfy.(4) Prototyping: ideas are implemented in first stage products or services.(5) Testing: potential users and other relevant stakeholders test and provide feedback on the prototypes. These five steps are iterative and the process may be partially or completely revisited several times.

We recognize that the double diamond approach is one of many approaches to design thinking, and design thinking is only one of many approaches to innovation. Still, many SOI processes are framed around design thinking methodologies (Buhl et al., 2019). While design thinking tools are commonly used for innovation processes, a user-focused innovation process such as design thinking can limit the innovation scope in ways that exclude multidimensional targets, societal impacts, and systemic understanding, further contributing to poorly defined problems (Buhl et al., 2019; Hoolohan & Browne, 2020). This limitation of design thinking to meet the needs of SOI are well documented in the academic literature, yet there are few studies that propose or implement methodologies to address that gap (Jones, 2014; Pourdehnad, Wexler, & Wilson, 2011). A key research question for SOI is how design thinking can progress beyond its focus on individual users and also engage in reconfiguring social, political, and material systems (Hoolohan & Browne, 2020).

1.3 The systems mapping intervention in SOI

Systems approaches to design have long been seen as valuable for placing design processes and products in larger contexts (Buchanan, 2019), and the benefit of combining elements of design thinking with elements of systems methodologies as a path towards robust innovation processes for complex challenges is highlighted in several studies (Bausch, 2002; Conway et al., 2017; Jones, 2014; Pourdehnad et al., 2011).

A number of systems-oriented methodologies have been developed to aid in problem definition, including systems mapping, gigamapping and synthesis maps. These methodologies vary in scope, stakeholder involvement, and required resources and skills (Jones & Bowes, 2017). All three approaches produce a collaborative visual artifact that represents the participants' learning and understanding of a complex system. Gigamapping demands the most time and expertise, and results in the highest level of detail of the three approaches, while systems mapping, the focus of our research, requires the least time and no expertise and produces a lower level of detail in the resulting map (Jones & Bowes, 2017).

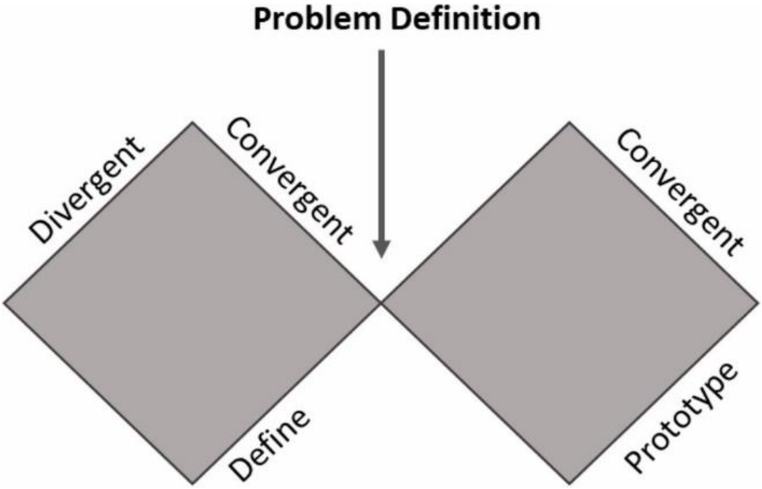


Fig. 1. A typical representation of the design thinking "double diamond" (adapted from Conway et al., (2017)).

Systems mapping, one of a suite of tools for group model building, is a participatory approach to creating a shared understanding of and communication about a complex problem (Videira et al., 2010). Systems mapping can be a stand alone stakeholder engagement process or a starting point for developing a system dynamics model, which is a mathematical model based on differential equations. Systems mapping includes a toolbox of scripts, or activities, that can be implemented in a variety of stakeholder contexts to elicit understanding of a complex problem, identify leverage points for intervention, and more (Hovmand et al., 2011, 2012). Systems mapping is often considered a tool for implementing systems thinking. Though systems thinking is poorly defined in the literature, it's broadly understood as an approach to complexity that emphasizes feedback and an awareness that a system's structure creates its behavior.

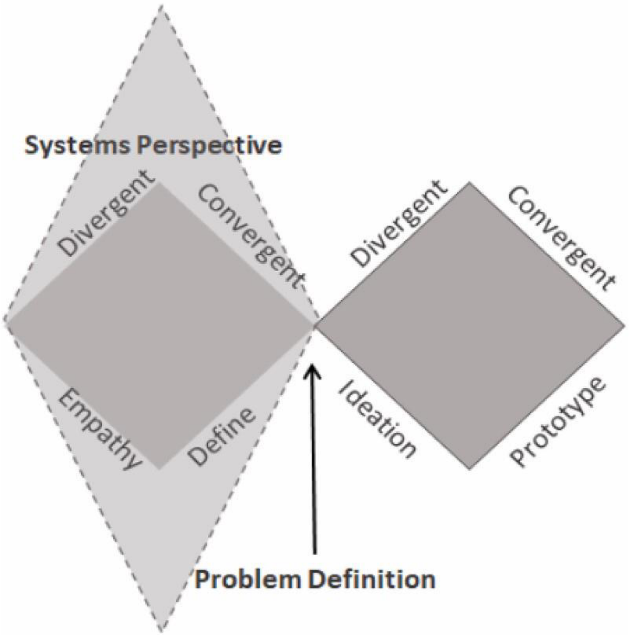
Systems mapping's particular strengths include eliciting a shared, visual understanding of a problem and its interconnections across disciplinary and sectoral boundaries. Further, through that process, the systems mapping creates a forum for discussion that can formalize understanding of a complex problem (Scott, Cavana, & Cameron, 2016; Videira et al., 2010; Videira, Antunes, & Santos, 2017). The resulting systems map typically has a focus on feedback within the system and on developing an adequate system boundary. It makes causal relationships explicit and can function as a reference point and boundary object for further discussions of leverage points and interventions in the system. In systems mapping, emphasis is not on the individual's experience but on the aggregated structure of a complex issue. In contrast to design thinking, systems mapping takes an aggregated perspective and can provide a "helicopter view" of a problem.

The systems mapping intervention as implemented in this study is a "quick and dirty" approach, especially when compared with approaches such as gigamapping and synthesis maps. Designers implementing gigamapping or synthesis mapping can use months to create a comprehensive and visually detailed map (Jones & Bowes, 2017; Sevaldson, 2018). Our implementation of systems mapping (outlined in the following section) generally takes less than two hours and requires no formal training for participants. Though less richly detailed than other approaches, the systems mapping intervention is designed to quickly give non-experts an aggregated and dynamic perspective on their sustainability issue.

2. Method: applying systems sustainability-oriented innovation

We propose employing systems mapping in the problem definition phase of design thinking as a way to address the user-focused limitations identified above. We call this approach systems sustainability-oriented innovation (SSOI). We modified the standard five step design thinking approach by adding a systems mapping activity in the first divergent phase of the design thinking process (Fig. 2). By adjusting and adding to the design thinking practitioner process, we were able to enlarge and contextualize the problem scope for SOI.

Our systems mapping activity was based on the open source "Initiating and Elaborating a Causal Loop Diagram" facilitation guide (also called a script) in Scriptapedia (Hovmand et al., 2011). This script is especially valuable for creating consensus and improving communication around a problem. While systems mapping facilitation guides are intended to be implemented in person, in our case, we modified the guide to move the process online due to Covid-19. Online systems mapping is a relatively new practice, but has been shown to provide valuable experiences and insights for participants (Wilkerson et al., 2020).



In the facilitation guide, participants are asked to identify a key problem variable for the specific case they are working on. Once participants agree on the variable, they start tracing causality by asking “what causes this variable to change?” This question helps identify the variable(s) that influence the original variable. As each new variable is added to the map, the group connects it to existing variables with arrows to indicate influence (Fig. 3). This process is informally referred to as “mapping backwards,” as chains of influence are traced back from the key variable.

Fig. 2. Elaborating on (Conway et al., 2017) - introducing a systems perspective in the early phase of an innovation process allows for sustainability to be more fully considered throughout the process.

By repeating this process, the systems map evolves. Participants are further challenged to consider polarity of relationships by asking “ if there is an increase in variable A, is that causing an increase or a decrease in variable B?” Through noting variables’ relationships and polarities, participants build the systems map. Towards the end of the process, participants are asked to identify loops, or cyclically chained variables, in the system. Feedback loops are also classified as either “balancing” or “reinforcing,” where balancing loops dampen and reinforcing loops amplify phenomena over time. Identifying loop characteristics helps participants understand how the system influences itself over time.

The output of this SSOI process is a systems map (also known as a causal loop diagram) that illustrates relationships among major variables in the system and clearly delineates the system boundaries (i.e. the problem space) relevant to the key variable. The systems map provides a “helicopter view” of the problem that complements the empathetic, individual perspective in design thinking.

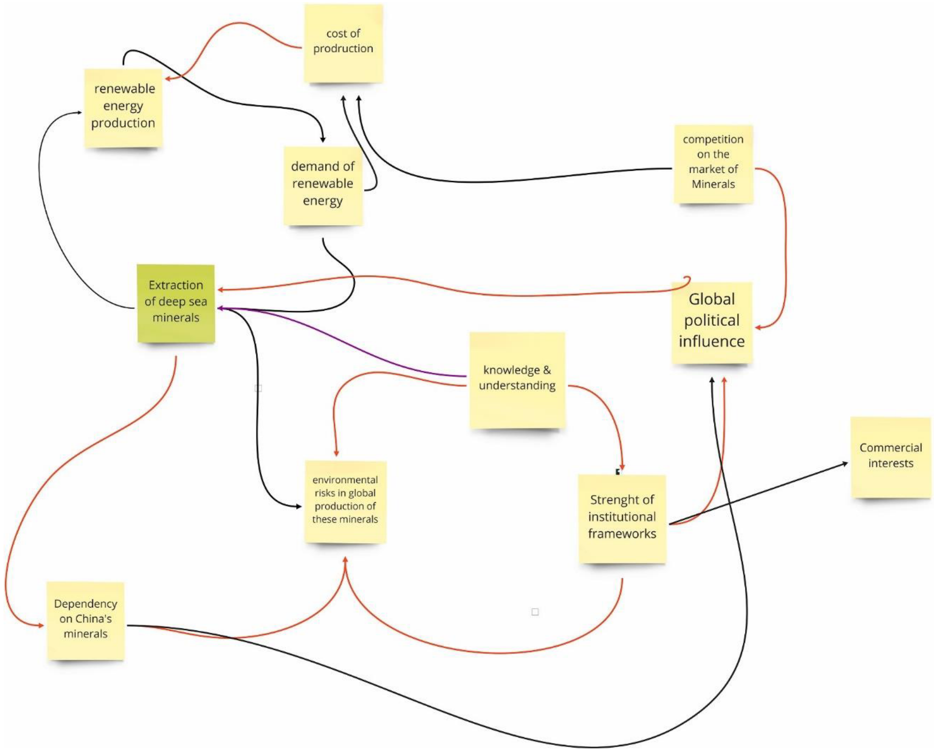


Fig. 3. Example systems map developed by students.

The systems map is one of several inputs into following design thinking exercises, where participants conduct interviews and explore the points of view of people within various parts of their system map. The aim of including systems mapping in design thinking is not to seamlessly integrate the two methodologies. Rather, the systems map participants produce is intended to provide a new perspective that can both enhance and disrupt the standard empathetic, human-centered perspective of design thinking.

3. Examples SSOI in practice

To test the potential of SSOI, we applied the methodology and collected data on the process and results in two settings: a problem- definition workshop for sustainable business innovation and a sustainable innovation course for bachelor degree students. Both cases were run online, using Zoom (zoom.us) for communication and Miro (miro.com) for activities.

3.1 SSOI in business settings

The Bergen2030 innovation competition was run by a business incubator that gathered sustainability “headaches” from businesses and a municipality. Examples of headaches included emissions from construction sites, waste material from Omega-3 fish oil production, and electricity management in housing associations. The aim of the competition was to gather and refine the sustainability problems, then allow interdisciplinary teams to compete to solve or improve the problem. The organizations with the headaches first gathered in a workshop to refine their problem description, and then the team competition took place several weeks later. In relation to the double diamond, the problem description workshop corresponded to the first diamond, while the team competition corresponded to the second diamond.

We applied the SSOI methodology in the problem description workshop. The explicit aims of the two day workshop were to 1) Further develop and increase the quality of the organization’s problem description to be used in the following phases of the innovation process; and 2) provide training in a set of activities and tools that participants could use independently in other innovation processes. Each of the five participating organizations (total of 20 participants) had different levels of experience and formal competence in innovation practice. The participating organizations included large corporations with business activities within shipping, aquaculture, real estate, and power-grid services. A municipal public management body also participated. The team members represented a wide array of professions and experience levels within innovation processes. One team consisted of a company’s internal innovation department, where all members had both experience and academic training in design thinking and product/services design, while other teams included accountants, marketing-personnel, VPs, engineers and architects – all with widely varying previous training or experience with innovation and product/service design.

The problem definition workshop consisted of a series of exercises that built on each other. At the start of each exercise, participants were given a brief introduction to the activity and its aims and purpose. Participants then worked within their groups with facilitators circulating to provide assistance as needed. Exercises included traditional design thinking activities, such as “empathetic interviews” and “points of view,” in addition to the systems mapping exercise. The outcome of the two day workshop was a comprehensive problem description that could be delivered to teams working on the problem in the competition.

Table 1

Workshop Summary.

Activity	Description	Prompts	Time (minutes)
Introduction	Presentation by facilitators. Introduction to systems mapping with two examples of systems maps: one addressing population dynamics and one addressing urban housing development. Focus on understanding: • A Variable as a phenomenon, element, or entity that can be measured and either increase or decrease in magnitude. • A Causal Link as a connection between Variables that indicates how a change in one variable would affect another variable. • A Feedback Loop as a circular arrangement of causally connected variables.		15
Identify a key variable	Facilitated group discussion. Identify key variable as a point of departure for the mapping exercise.	• Business case: Is there anything in the material produced in the previous exercises that you consider a key variable particularly important for your understanding of your challenge? Or can you think of something completely new that would be important for your challenge? • Student case: Can anyone suggest a relevant key variable to start with here? It does not have to be the most critical or most important, but we need a place to start.	5

Causal mapping	Facilitated group discussion. Team members add variables and connect them via causal links; thereby iteratively expanding the systems map in a "mapping backwards" process as described in section 2.	• What causes your variable to change? Or is your variable causing a change in another variable? • Is the change in the same or in the opposite direction? • What else can cause a change in X variable? • What would a change in X cause down the line?	40-50
Identify Feedback Loops	Facilitated group discussion. Participants are challenged to identify closed loops where chains of variables are linked together to form full circles. Facilitator may identify first feedback loop and emphasize the "story" each loop tells (ie, how it relates to the larger system).	• What is the feedback story here? • What is the nature of this feedback loop is it reinforcing or is it balancing?	10
Debrief	Facilitator summary and facilitated group discussion. Facilitator summarize the findings in the Systems Map focusing on identified feedback loops and loose ends. Facilitator highlights that the work is not complete and encourages the participants to keep working to expand the Systems Map to be more comprehensive, and to use it as a boundary object for their further work with the innovation challenge.	• What system behaviors have we found that should be considered when we move forward with our innovation process? • Are there any counter-intuitive or potentially un- desired effect loops we should be aware of?	15

3.2 SSOI in educational settings

The Sustainable Innovation course at the University of Bergen is an optional course for bachelor level students from all faculties, and students must apply and be accepted into the course. The focus of the course is teaching students innovation methodologies and sustainability concepts. The bulk of the course is a project in which students work in teams with five to seven members to address a "real world" sustainability challenge presented by a client.

In 2021, the course had 30 students from four faculties. Almost none of the students had previous experience or training in systems mapping or design thinking. The systems mapping workshop was the first exercise the students did in their teams and the first activity related to their innovation challenge.

The workshop consisted of a 15 minute introduction to systems mapping by the authors, one hour of facilitator-assisted workshop in the teams, and a 15 minute plenary debrief. In the workshop, the teams agreed on a key variable for their problem, then built a systems map using that variable as a starting point. Though the workshop was short, many teams continued to work on their systems map after the workshop had ended. In class meetings subsequent to our workshop, students received training and facilitation in design thinking.

3.4 Workshop structure

The idea of expanding the traditional design thinking approach to include a systems perspective in SOI emerged in discussions between the business workshop organizers and the authors. In preparation for the business workshop, the authors worked closely with the workshop organization team and facilitators. The workshop program was developed over a period of four months and was considered a pilot project for innovation.

The student systems mapping workshop built on the experience, feedback and evaluation of the business workshop. Few adaptations were necessary, though the participants and starting points were different in this setting. In both cases, the systems mapping workshop was based on the "Initiating and Elaborating a Causal Loop Diagram" facilitation guide in Scriptapedia (Hovmand et al., 2011) (Table 1).

After the business workshop the system maps remained available for the participating teams. They were also collated into a more comprehensive insight report (including the results of exercises they did prior to systems mapping) that was delivered to the teams. Teams continued work with the "second diamond," where solutions to the predefined "headaches" were sought over the course of a 48 hour hackathon.

Students in the academic course maintained access to their systems maps, and many teams continued to work on, and with, the systems maps generated through the workshop.

4. Data collection and analysis

For both cases, we analyzed the systems maps generated by participants for evidence of multidimensional perspectives and inclusion of both individual and societal aspects. We also conducted and analyzed interviews and surveys to better understand the learning process and perceived value of systems mapping for problem definition. The systems maps provide insights into the problem descriptions, while surveys and interviews provide insights into the process.

4.1 SSOI in business settings

After the workshop, we conducted semi-structured interviews of five professionals (one from each participating team). The semi- structured interviews were carried out along a predefined interview protocol; all respondents were interviewed by the same protocol. The interview protocol consisted of three main lines of questions: (1) Baseline – assessing the previous experience with innovation, design and systems thinking. (2) Workshop Execution – assessing how the respondents experienced the theory, examples, exercises and facilitation of the workshop. (3) Utility – assessing to what extent components of the workshop were found to be useful by respondents. The protocol also included room for any other remarks or comments observed by the respondents.

Interviews were conducted by both co-authors via video meeting. The interviews were 30–60 min in length and were later transcribed and analyzed. The analysis was carried out in several iterations during which the authors reviewed the responses for mentioning or discussing the key elements of SOI, including longer time horizons, problem definitions spanning individual and societal aspects, and multidimensionality (Buhl et al., 2019). In addition, the systems maps generated by participants were collected for analysis and assessed for the same elements.

Of the six participating teams in the business case, all teams identified a minimum of five different sectors or dimensions intrinsic to their problem space. Typically, these dimensions included economic sectors (finance and market structures), social sectors (various user groups and government policies), and environmental sectors (for example, waste management, climate footprint, water quality).

Four out of six teams identified a minimum of two feedback loops. Of the two teams that did not identify feedback, one team did not participate in the whole workshop. The second team stated that they did not have sufficient time to complete the task during the workshop, but that they had continued to work with the systems mapping exercise after the workshop both as a team and individually, and that continued work revealed interesting and potentially important dynamics.

One team drafted a comprehensive systems map during the workshop and identified about a dozen minor and major feedback loops, straddling several dimensions. Their map included both individual and societal perspectives and identified tensions between these perspectives. This team reported that identifying causal feedback in their problem space was particularly useful for moving forward with the innovation task.

4.2 SSOI in educational settings

At the end of the course, we conducted a brief survey of students (response rate = 52%) to gauge their experience and learning. We also collected the systems maps created by the students for analysis.

Five out of six teams developed detailed systems map during the workshop, including a minimum of four and a maximum of eight dimensions spanning environmental, economic, and societal sectors. Two teams continued to work on their systems map after the workshop, and both of these teams increased the number of variables and links in their systems maps by a factor of three. All teams who successfully created a systems map also identified key feedback loops and interactions among sectors in their system.

Fig. 4 shows the work of one of the teams in the student case. The team worked on defining a SOI problem related to an emerging industry of deep water mineral extraction on the Norwegian continental shelf. None of the team members had any prior knowledge of the subject, and information about the case was given to them on the morning of the workshop. The systems map they created is not comprehensive, but instead represents the group's status at the end of the 1.5 hour workshop.

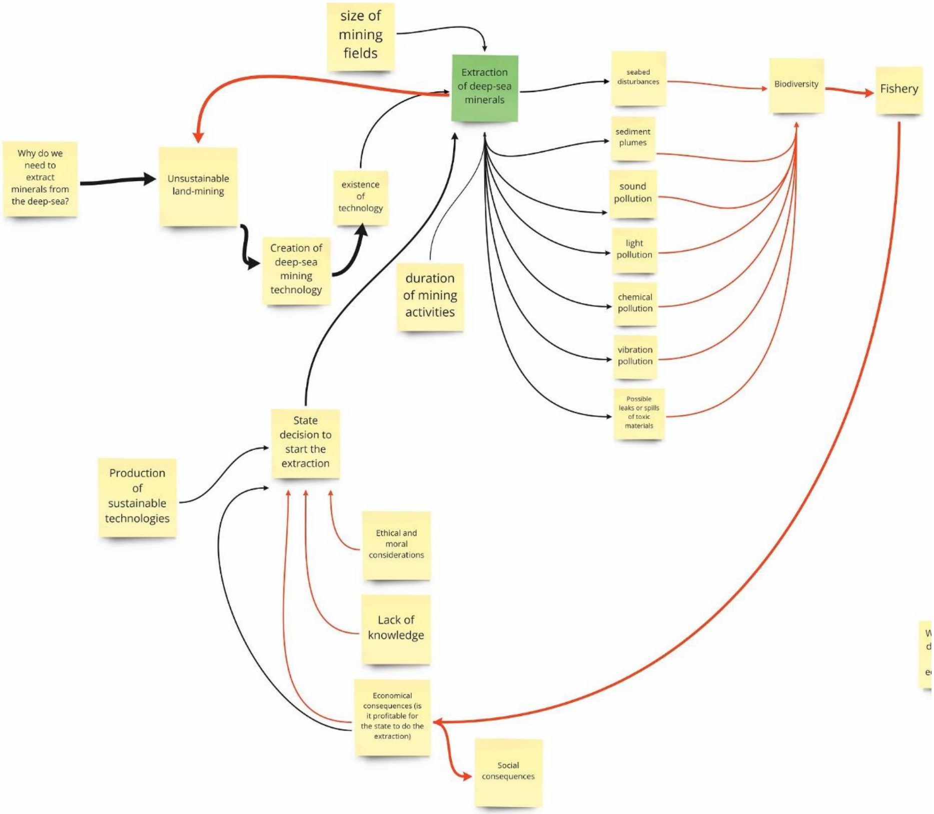


Fig. 4. Example systems map from the education case. Students identified interactions among economic, environmental, and societal sectors within their problem definition.

The systems map introduces a number of dimensions into the problem space beyond the individual “user,” in this case a company invested in deep sea minerals. The team started with the key variable “Extraction of minerals in the deep sea.” Using a “mapping backward” technique, they identified both the presence of mining technology and state policy as primary factors affecting deep sea mining. State policy is affected by technological development and knowledge status, ethical considerations, and profitability. Profitability is affected by activities in the fisheries sector (a major industry in Norway). The fisheries sector is affected by changes in the physical and biological environment, and those environmental factors are affected, in turn by deep sea mining, the key variable. Further, students identified link polarity (shown as black and red arrows in Fig. 4). Link polarity refers to the direction in which one variable affects another over time. For example, increased seabed mining increases seabed disturbances (black arrow), which has a negative impact on biodiversity (red arrow).

In sum, we can see that the students identified economic, environmental, and societal sectors and explored how those sectors relate to and influence each other. The system map identifies important dynamics in the problem space as it evolves over time. It implicitly includes a long time horizon, as the causal loop described above will play out dynamically over many years.

Survey results indicate that most students had no previous experience in system mapping or design thinking (Fig. 5). Almost all respondents found the SSOI workshop to be useful or very useful. The strongest values they reported from the workshop include using the systems map as a discussion tool and reference object and identifying innovation ideas (intervention points) within the map. Almost 30% of respondents continued to develop the systems map on their own after the workshop.

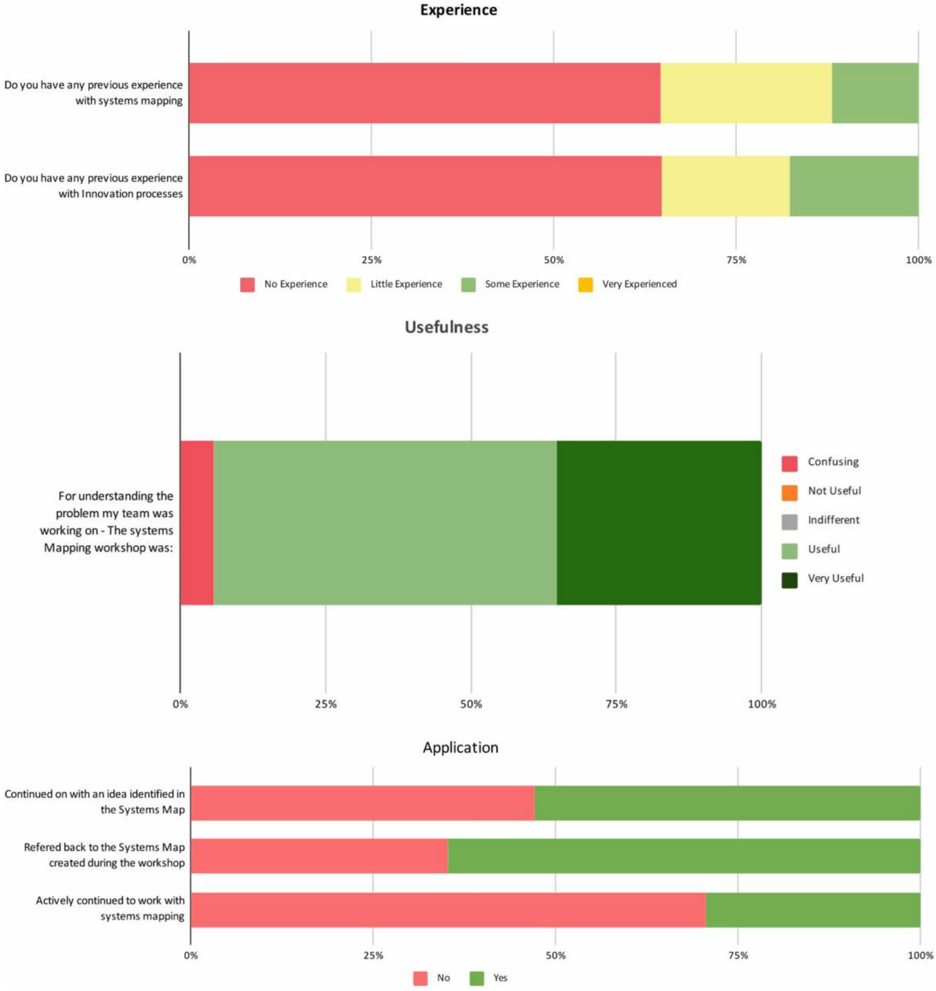


Fig. 5. Summary results from student survey after the workshop.

5. Discussion

Through employing systems mapping in the problem definition phase of design thinking, we aimed to incorporate the specific requirements of sustainability in an innovation context: a systems vantage point, individual and societal interactions, and multidimensionality. Our analysis shows that SSOI provides value as both as a capacity-building process and as a product for highlighting sustainability aspects in problem definitions.

The usefulness of design thinking for innovation processes has been well documented (Carlgren et al., 2016; Roth et al., 2020). Originally designed as methodology for product development, design thinking has been adapted and adopted to a broader range of innovation processes in recent years. While use of different design thinking tools may emphasize different qualities and criteria, the design thinking approach has remained more or less bounded within the double diamond framework. We find design thinking's simplicity and ubiquity to be advantageous, as it provides simple "scaffolding" on which to test new approaches. We recognize, however, that design thinking takes many forms, and the design thinking approach discussed in this article is not the only form of design thinking.

Our case studies illustrate the potential role of systems mapping as an intervention in design thinking innovation processes in business and educational settings. While the main goals of these two examples were different, both cases demonstrate how systems mapping can be applied to increase understanding and definition of the problem space for sustainability-oriented innovation. Further, the cases demonstrate that systems mapping methodology can be implemented by and provide useful results for participants in different phases of their education and career and with different levels of background and experience in the problem being discussed.

In both cases, systems mapping contributed to a more holistic understanding of the problem. Our analysis of the systems maps indicates that participants both expanded the boundaries of their problem and, in most cases, included environmental, economic, and social sectors. They could also see connections between elements that they hadn't focused on before, which provoked new thinking about the problem. Several groups explicitly identified tensions and interactions between individual users and broader segments of society. Though almost none of the students in the education case had previous experience in design thinking or systems mapping, 94% reported that the systems mapping workshop was useful or very useful for understanding the problem space. As one business case participant commented, "We saw complexity in the issue that we hadn't seen before, especially as we came from different perspectives… We saw that we could come to a completely different solution than what we had originally thought."

While the primary goal of SSOI has been to set the problem in a systems perspective to improve problem definition, we also found that systems mapping contributed to creating a shared understanding of a complex problem and aided communication among team members. This is a documented effect of systems mapping (Rouwette, Korzilius, Vennix, & Jacobs, 2011; Videira et al., 2017), but we argue that this effect is especially valuable in the context of SOI, where diversity in background and perspective contributes to a more holistic problem definition.

In the business case, systems mapping as a communication tool proved particularly beneficial for teams from large companies, where team members typically came from different departments, with different backgrounds and responsibilities. These teams in particular remarked on the usefulness of the systems map to create a shared understanding of a complex problem and generate discussion around how the system functions over time.

Several student teams also continued to build on and refer to their systems map throughout the innovation process. Survey results indicate that 42% of students actively used the systems map as a tool for framing discussions within their teams throughout the course. Further, more than half the students continued to refer back to the systems map they developed as the course progressed and continued to work with an idea that was identified during the brief workshop.

In the business case, both observations during the workshop and interviews confirmed that systems mapping was the most cognitively demanding step in the workshop, even with facilitator support. Connecting variables and describing relationships was new for most participants, as was the concept of feedback. In the education case, most students were able to quickly get started and work independently in teams. In both cases, facilitators periodically "checked in" with groups to ensure they understood and were making progress on the systems map. Our experiences indicate that while participants were able to successfully build a systems map in both cases, facilitators trained in systems mapping are needed to support teams through the process.

Subsequent to both of the workshops, some teams, both advanced and more inexperienced, reported that they planned on, or already had, employed the methodology in other sustainability innovation processes. This indicates that participants were able to internalize and gain confidence in the methodology despite receiving only a brief introduction. It also indicates that participants identified a clear value in the perspective and insights that systems mapping have to offer SOI. In particular, several interviewees from the business case mentioned the value of having a tool that helped them visualize connections that were often otherwise not articulated.

The SSOI approach has particular relevance to education. Systems thinking, put into practice as systems mapping, lies at the intersection of many modern higher-education priorities, including training students in collaboration, problem-based learning, and communicating across disciplines. We propose that incorporating systems mapping into innovation courses will not only improve student-generated projects, but will also strengthen students capacities to meet complex, real world challenges outside the university.

These brief (less than two hour) systems mapping interventions allowed participants to clearly see and define the sustainability aspects in their problem definition. Participants valued the actual systems map as a tool for problem definition and a boundary object for communication. They also valued the learning process and capacity building generated through creating the map. Though further development and testing is needed, our initial results indicate that systems mapping can be a valuable and efficient addition to standard design thinking approaches to SOI.

6. Conclusion

Innovating for sustainability requires a deep understanding of a system and its interactions. We present SSOI as an approach to advance the research, practice, and implementation of SOI practices. Our work demonstrates the potential of this approach to improve problem definition for sustainability innovation. Our results also show that participants valued and learned from the SSOI process, and that many planned on incorporating systems mapping into future innovation processes. Using SSOI to define the problem space supports sustainability aims by enforcing a holistic, coherent perspective that connects individuals and society.

Participants confirmed that SSOI is valued as a process for learning and internalizing a systems understanding of sustainability as it relates to innovation. As an intervention to standard design thinking practices, SSOI requires further study to evaluate how it can be used to improve SOI processes and products. Process- and results-based comparisons among various SOI approaches would be a significant contribution towards understanding how innovation processes relate and contribute to sustainability and systems perspectives. In addition, developing quality criteria for problem definition in innovation would allow for a standardized analysis of results. These are vital next steps if we expect design thinking to be a valuable tool to shape innovations for sustainability.

CRediT authorship contribution statement

Brooke Wilkerson: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Lars- Kristian Lunde Trellevik:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest None.

Funding

This work was supported by the University of Bergen, Norway.

References

Bausch, K. C. (2002). Roots and branches: A brief, picaresque, personal history of systems theory. *Systems Research and Behavioral Science, 19*, 417–428.

Bennett, N. J., Blythe, J., Cisneros-Montemayor, A. M., Singh, G. G., & Sumaila, U. R. (2019). Just transformations to sustainability. *Sustainability, 11*.

Bijl-Brouwer, M.v.d., & Malcolm, B. (2020). Systemic design principles in social innovation: A study of expert practices and design rationales. *She Ji: The Journal of Design, Economics, and Innovation, 6*, 386–407.

Brundtland, G. H. (1987). Our common future—Call for action. *Environmental Conservation, 14*, 291–294.

Buchanan, R. (2019). Systems thinking and design thinking: The search for principles in the world we are making. *She Ji: The Journal of Design, Economics, and Innovation, 5*, 85–104.

Buhl, A., Schmidt-Keilich, M., Muster, V., Blazejewski, S., Schrader, U., Harrach, C. D., et al. (2019). esign thinking for sustainability: Why and how design thinking can foster sustainability-oriented innovation development. *Journal of Cleaner Production, 231*, 1248–1257.

Carlgren, L., Rauth, I., & Elmquist, M. (2016). Framing design thinking: The concept in idea and enactment. *Creativity and Innovation Management, 25*, 38–57.

Clune, S. J., & Lockrey, S. (2014). Developing environmental sustainability strategies, the Double Diamond method of LCA and design thinking: A case study from aged care. *Journal of Cleaner Production, 85*, 67–82.

Conway, R., Masters, J., & Thorold, J. (2017). From Design thinking to systems change. *RSA Action and Research Centre, 32*.

Gaziulusoy, A. I. (2015). A critical review of approaches available for design and innovation teams through the perspective of sustainability science and system innovation theories. *Journal of Cleaner Production, 107*, 366–377.

Gaziulusoy, A. I., & Brezet, H. (2015). Design for system innovations and transitions: A conceptual framework integrating insights from sustainablity science and theories of system innovations and transitions. *Journal of Cleaner Production, 108*, 558–568.

Gibson, R. B. (2006). Sustainability assessment: Basic components of a practical approach. *Impact Assessment and Project Appraisal, 24*, 170–182.

Hjorth, P., & Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures, 38*, 74–92.

Hoolohan, C., & Browne, A. L. (2020). Design thinking for practice-based intervention: Co-producing the change points toolkit to unlock (un)sustainable practices. *Design Studies, 67*, 102–132.

Hovmand, P. S. (2014). *Community based system dynamics*. New York, NY, Springer New York: Imprint: Springer.

Hovmand, P. S., Andersen, D. F., Rouwette, E., Richardson, G. P., Rux, K., & Calhoun, A. (2012). Group model-building 'Scripts' as a collaborative planning tool. *Systems Research and Behavioral Science, 29*, 179–193.

Hovmand, P., Rouwette, E., Andersen, D., Richardson, G., Calhoun, A., Rux, K., et al. (2011). Scriptapedia: A handbook of scripts for developing structured group model building sessions. *Social Science & Medicine - SOC SCI MED*.

Jones, P. H. (2014). Systemic design principles for complex social systems. In G. S. Metcalf (Ed.), *Social systems and design* (pp. 91–128). Tokyo: Springer Japan.

Jones, P., & Bowes, J. (2017). Rendering systems visible for design: Synthesis maps as constructivist design narratives. *She Ji: The Journal of Design, Economics, and Innovation, 3*, 229–248.

Nagatsu, M., Davis, T., DesRoches, C. T., Koskinen, I., MacLeod, M., Stojanovic, M., et al. (2020). Philosophy of science for sustainability science. *Sustainability Science, 15*, 1807–1817.

Pourdehnad, J., Wexler, E., & Wilson, D. (2011). Systems & design thinking: A conceptual framework for their intergration. *55th Annual meeting of the international society for the systems sciences 2011* (pp. 807–821).

Roth, K., Globocnik, D., Rau, C., & Neyer, A. K. (2020). Living up to the expectations: The effect of design thinking on project success. *Creativity and Innovation Management, 29*, 667–684.

Rouwette, E. A. J. A., Korzilius, H., Vennix, J. A. M., & Jacobs, E. (2011). Modeling as persuasion: The impact of group model building on attitudes and behavior. *System Dynamics Review, 27*, 1–21.

Scott, R. J., Cavana, R. Y., & Cameron, D. (2016). Recent evidence on the effectiveness of group model building. *European Journal of Operational Research, 249*, 908–918.

Sevaldson, B. (2018). Visualizing complex design: The evolution of gigamaps. In P. Jones, & K. Kijima (Eds.), *Systemic design: Theory, methods, and practice* (pp. 243–269). Tokyo: Springer Japan.

Shahadu, H. (2016). Towards an umbrella science of sustainability. *Sustainability Science, 11*, 777–788.

Videira, N., Antunes, P., & Santos, R. (2017). Engaging stakeholders in environmental and sustainability decisions with participatory system dynamics modeling. In S. Gray, M. Paolisso, R. Jordan, & S. Gray (Eds.), *Environmental modeling with stakeholders: Theory, methods, and applications* (pp. 241–265). Cham: Springer International Publishing.

Videira, N., Antunes, P., Santos, R., & Lopes, R. (2010). A participatory modelling approach to support integrated sustainability assessment processes. *Systems Research and Behavioral Science, 27*, 446–460.

Wilkerson, B., Aguiar, A., Gkini, C., Czermainski de Oliveira, I., Lunde Trellevik, L.-K., & Kopainsky, B. (2020). Reflections on adapting group model building scripts into online workshops. *System Dynamics Review, 36*, 358–372.

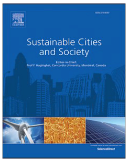
Paper 3

Sustainable Cities and Society 79 (2022) 103602

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs



Modeling reverse auction-based subsidies and stormwater fee policies for Low Impact Development (LID) adoption: a system dynamics analysis

Brooke Wilkerson [a,b,*], Eduard Romanenko [a], David N. Barton [c]

[a] *System Dynamics Group, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway*
[b] *Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway*
[c] *Norwegian Institute for Nature Research (NINA), Gaustadalleen 21, Oslo 0349, Norway*

ARTICLE INFO

Keywords:
Stormwater management
Funding strategies
Low impact development
System dynamics

ABSTRACT

Many urban areas around the world are facing increasing pressure on stormwater management systems due to urbanization and extreme weather events caused by climate change. Low impact development (LID), including blue-green infrastructure such as rain gardens, has become an attractive addition to traditional gray infrastructure for managing stormwater.

Municipalities have a limited suite of policy instruments for incentivizing installation of LID on private property. We built a system dynamics model of integrated socio-economic and hydrologic systems in Oslo, Norway to illustrate implementation of two economic incentive mechanisms: subsidies based on reverse auctions and stormwater fees. We find that policy effectiveness depends on 1) communicating realistic expectations of LID performance to landowners and 2) municipal subsidies to reach landowners without intrinsic interests in LID. Under certain conditions, lower municipal economic incentives can outperform higher economic incentives and lead to sustained long-term adoption of LID on private property.

1. Introduction

Stormwater runoff and urban flooding are an increasing threat in built environments around the world. In addition to property damage, extreme precipitation events can cause sewer overflows, which increase sewage treatment costs and threaten water quality (Goonetilleke, Thomas, Ginn, & Gilbert, 2005; Londoño Cadavid & Ando, 2013). Existing traditional (gray) stormwater infrastructure is often aging and under-dimensioned to accommodate predicted increased frequency and intensity of extreme precipitation events as a consequence of climate change (Eckart, McPhee, & Bolisetti, 2017).

Many cities have turned to low impact development (LID) to control volumes and pollutant loads of smaller storm events (Luan et al., 2019). Setting clear policies and expectations for establishing LID in new building projects is relatively straightforward, but in an urban environment, most areas are characterized by a patchwork of small, built properties managed by diverse owners. For example, Oslo, Norway, has implemented a "blue-green factor" regulation for setting minimum requirements for LID in new building projects (Oslo kommune, 2018), but lacks tools for incentivizing adoption of LID on existing built properties. Integrating any new infrastructure – even green infrastructure – into established urban areas can be costly and disruptive (Schifman et al., 2017).

Policies to increase the adoption of LID in established urban areas include raising awareness and economic instruments. Adoption of LID based solely on awareness (advertising) campaigns is quite low. For example, one study in Missouri, USA demonstrated that advertising resulted in less than 10% of households adopting rain gardens (Shin & McCann, 2018). In general, cities must institute more sophisticated combinations of policy instruments to increase likelihood of LID adoption and maintenance.

Two economic instruments explored in the literature and to some extent in practice, include reverse auctions (RA) and stormwater fees (SWF) (Kea, Dymond, & Campbell, 2016; Tasca, Assunção, & Finotti, 2018; Zhao, Fonseca, & Zeerak, 2019). In a reverse auction (also known as a procurement auction), property owners bid to finance part of the cost of establishing LID on their property. The municipality selects owners willing to pay the largest fraction of the cost and establishes the

---

Abbreviations: LID, Low impact development; SWM, stormwater management; RA, reverse auction; SWF, stormwater fee.

* Correspondence to: Brooke Wilkerson, System Dynamics Group and Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway.

E-mail address: brooke.wilkerson@uib.no (B. Wilkerson).

https://doi.org/10.1016/j.scs.2021.103602
Received 24 September 2021; Received in revised form 9 December 2021; Accepted 9 December 2021

LID on their property, with the private landowner sharing the cost of installation (Thurston, Taylor, Shuster, Roy, & Morrison, 2010). In the absence of strict regulations (such as building and development norms), Thurston et al. (2010) argue that an auction is a cost-effective tool for implementing controls on stormwater runoff quantity at the parcel level. Depending on the regulatory setting, a reverse auction may reveal an efficient subsidy mechanism, whereby municipal authorities can determine the minimum subsidy needed to realize a certain amount of LID in a given area.

Stormwater fees are paid by property owners based on indicators of the amount of stormwater the property generates. There is a large variation in the ways stormwater fees are calculated in practice and how closely they are calibrated to the variation in properties' run-off (Tasca et al., 2018). Stormwater fees are utility fees with a similar purpose to solid waste or wastewater. A principle aim of utility fees is to cover direct and indirect costs of management of run-off (Tasca et al., 2018). A secondary effect could be incentivizing landowners to install LID to reduce their stormwater runoff and obtain a discount. We note, however, that the empirical evidence on incentive effects of this kind is limited. While these economic incentives have been implemented in several cities around the world, they are far from widespread and, to our knowledge, there are no cities that have implemented both reverse auctions and stormwater fees (Lieberherr & Green, 2018; Tasca et al., 2018; Zhao et al., 2019). Little is known about how these two policies, which approach adoption of LID from different angles, would function together.

Our research tests implementation of these policies in concert with each other in order to understand policy synergies and tradeoffs and develop strategies for increasing the adoption of LID by private landowners. We particularly focus on knowledge integration in a complex social-ecological-technological system and endogenous dynamics of stakeholder motivation. Literature on policy mix analysis has called for integrated assessment tools to evaluate policy instrument interactions in socio-ecological systems (Ostrom, 2007; Ring & Barton, 2015b).

We built an interdisciplinary system dynamics model that includes hydrologic data, social survey data, results from a reverse auction, and data from spatial/GIS models to test potential impacts of these two policies. As outlined in Abebe et al. (2021) system dynamics modeling has been used in a number of water resources management contexts, including decision support for urban water/wastewater systems management and policies. System dynamics modeling has also been applied successfully to diffusion processes of new technologies (Rahmandad & Sterman, 2008). Our work contributes to this system dynamics literature by modeling diffusion processes for several stormwater management strategies to examine their interactions. The model is demonstrated using data from the Grefsen-Kjelsås neighborhood in Oslo, Norway, and results from the model are aimed at providing generalized insights about policy implementation and generating further discussion about integrated design of policy mixes for stormwater management.

1.1. Low impact development and barriers to implementation

Low impact development (LID) for stormwater includes a suite of approaches to managing stormwater that attempts to incorporate natural features and processes (such as infiltration and evapotranspiration) into stormwater management systems (Eckart et al., 2017). LID can offer many benefits in addition to stormwater management, including filtering polluted water, reducing urban heat island effects, aesthetics, and providing plant and wildlife habitat (Eckart et al., 2017; Elliott et al., 2020; Schifman et al., 2017). Typical examples of LID are small scale, distributed infrastructure such as green roofs, downspout disconnection, and rain gardens. Rain gardens, the focus of our research, are one of the most common LIDs implemented on private property. A rain garden is a man-made depression in the ground that uses plants to infiltrate stormwater and delay peak flows (Dietz, 2007).

As small-scale infrastructure, LID requires widespread adoption in order to have a meaningful impact in stormwater management systems. Infrastructure systems are not only physical and technological. They should be understood as complex, interconnected social, ecological, and technological systems (Markolf et al., 2018). Montalto et al. (2013) have demonstrated that stakeholder engagement and consideration of both physical and social characteristics of an area are key for increasing LID adoption. In this research, through taking an integrated approach, we focus on the economic and social aspects of stormwater infrastructure adoption, with consideration of ecological and technological aspects.

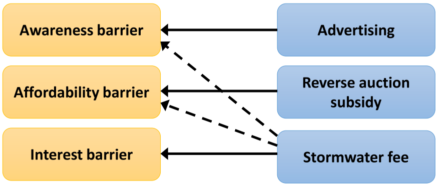


Fig. 1. Relationship between barriers to LID adoption and policies to address those barriers.

While demographic characteristics such as age and education level can influence adoption (Shin & McCann, 2018), social aspects of LID implementation also include access to information, monetary considerations, personal experiences, and influence from neighbors. On the most basic level, households must first become aware of LIDs before they can form the intention to adopt LIDs (Shin & McCann, 2018). Perceived costs and benefits are associated with LID affect adoption rates (Shaw, 2011). Decision-making is also influenced by knowledge of and experience with flooding. People who are concerned about basement floods are more likely to adopt rain gardens (Shin & McCann, 2018), and people who have experienced basement flooding demonstrate increased willingness to pay to reduce flood frequency (Londoño Cadavid & Ando, 2013). Lastly, studies have found that neighbors' use of a LID practice can positively affect adoption levels (Ando & Freitas, 2011).

For the purposes of conceptualizing these implementation challenges, we identify three key barriers to LID adoption in built up areas:

- *The "awareness barrier"*: LID is a relatively new practice and most of the households are unaware or unfamiliar with it (Cote & Wolfe, 2014; Shin & McCann, 2018).
- *The "affordability barrier"*: LID installation involves a cost, which can be substantial relative to the disposable household income (Cote & Wolfe, 2014; Shaw, 2011).
- *The "interest barrier"*: "Interest" captures the perceived utility (benefits) associated with LIDs. As confirmed by the surveys and reverse auctions conducted in the area, some of the households exhibit intrinsic interest in LID as a stormwater management solution that has potential to mitigate combined sewer overflow (CSO) and household-related floods in the catchment (Furuseth, Seifert-Dähnn, Azhar, & Braskerud, 2018). According to survey results, the primary drivers of "interest" in this area are environmental attitudes and prevention of basement or garden floods. On the other hand, it is reasonable to expect that some households in the catchment may never be interested if they are not impacted by flooding. Even when provided at no monetary cost, LID requires a certain degree of modification to the property, to which a household might not agree if it has opportunity costs or non-monetary inconveniences (Londoño Cadavid & Ando, 2013; Shin & McCann, 2018).

1.2. Strategies for LID implementation

Three policy mechanisms are typically discussed in relation to enhancing LID adoption in existing built-up areas:

- *advertisement (awareness raising) campaigns* that disseminate knowledge about LIDs, their value and utilization,
- a *subsidy* that fully or partially covers the cost of LID (as revealed by the reverse auction),
- *stormwater fee* which is paid by homeowners according to how much stormwater runoff their property produces

The first two policies can be easily matched with the first two adoption barriers: advertising campaigns address the "awareness barrier" and LID subsidies address the "affordability barrier" (Fig. 1). Through increasing awareness, the advertising campaigns are able to effect adoption in households that are previously unaware of LID but do not face affordability or interest barriers. The adoption behavior of these households is captured in typical adoption rates reported as the results of advertisement campaigns (Shin & McCann, 2018).

The rest of the aware and interested households face the "affordability barrier" and need to be provided with a subsidy to become an adopter of LID. It should be expected that a fraction of the households in the catchment who are not interested will not install LID even if its cost is fully covered by a subsidy. Subsidies are typically paired with advertisement campaigns.

The third policy - *Stormwater Fee* - relates to all three barriers by:

- creating awareness about LID as an alternative to paying the stormwater fee ("awareness barrier");
- introducing a monetary benefit of not paying the stormwater fee – an avoided cost - and, thus, addresses the "affordability barrier" for households with intrinsic interest; and
- potentially motivating households without an intrinsic interest in LID as a stormwater management solution by avoiding costs from a waved stormwater fee ("interest barrier").

2. Methods

Exploration of the adoption and implementation of LID in a residential area requires an integrated approach that places the households' behavior in the context of an urban stormwater management (SWM) system. To achieve this, hydrological, socio-economic, technical, and governance sub-systems are closely interconnected and continuously exposed to both internal (policies) and external (climate) pressures in a system dynamics model.

System dynamics models are used to understand complex problems and test policy measures to address those problems, with a focus on feedback mechanisms (loops), delays and non-linear dynamic interactions between a system's components (Forrester, 1970). The model consists of a system of coupled, nonlinear, first-order differential (or integral) equations (Richardson, 1991). Our work contributes to system dynamics literature by looking at diffusion processes for several stormwater management strategies to examine their interactions. It also contributes to the stormwater management literature by exploring policy interactions and their implications among commonly discussed policies for LID implementation on private property.

2.1. The system dynamics model

The system dynamics model integrates hydrological and socio-economic sub-systems, with "slow" (yearly) dynamics (comparable with investments into stormwater management infrastructure), parametrized to the outputs of "fast" (second/minutes) runoff dynamics in hydrological models of the catchment area. The model incorporates the results of a reverse auction-based subsidy implemented in the catchment area and explores the intrinsic value that the residents of a built-up area might place on LID. The model also explores potential trade-offs, unintended effects and synergetic effects of LID policies. The model is flexible enough to simulate a variety of assumptions about the adoption potential for LIDs, thereby reflecting the high degree of uncertainty inherent in policy instrument interactions. Understanding the dynamic relationships between potential adopters, adopters, and nonadopters has been shown to be critical to understanding LID implementation (Shin & McCann, 2018).

The model is an explorative tool that generates scenarios and examines how households in an urban residential area could respond to LID implementation policies (de Gooyert, 2019). The scenario analysis of the model generates generalized insights on the LID diffusion trajectories in both the near-term and the longer-term. Data sources for our model include hydrological models (Li et al., 2020), distribution of household willingness-to-pay for rain gardens determined through a reverse auction applied by (Furuseth et al., 2018), survey data (Furuseth et al., 2018), studies of economic costs and benefits of LID implementation (Lekkerkerk, 2020), and spatial models of existing green space and infiltration capacity (Sælthun, Barton, & Venter, 2021). These data sources were supplemented with interviews with subject matter experts from water management and planning authorities (see parameter tables in Appendix A).

The model consists of 12 stocks and 172 variables, and a full model description is available in Appendix A. The model consists of three interconnected sectors: Stormwater Management (SWM), LID Adoption, and Economics (Fig. 2).

The SWM sub-model captures three important aspects of the system. It (1) tracks LID infrastructure installed on the properties of households-adopters, (2) captures the realized contribution of installed LID infrastructure to SWM goals in the catchment, and (3) links that contribution to LID attractiveness, which impacts the decision of households to become adopters or discontinue being adopters. The SWM sub-model is instrumental to operationalizing the feedback loops in Fig. 3. The LID Adoption sub-model contains the adoption structure that develops the adoption potential indicated by *LID Attractiveness* from the SWM sector. This sub-model is based on the diffusion of innovation paradigm (implemented as a modified Bass diffusion model), which is a common framework for modeling adoption and diffusion of innovation (Horvat, Fogliano, &

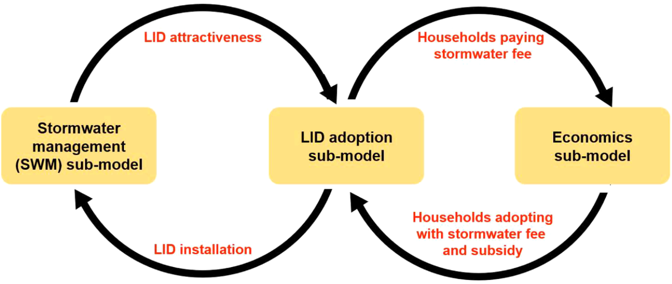


Fig. 2. Conceptual diagram of the sub-models.

Luning, 2020). We note that we use the term “attractiveness” to mean “appealing” or “desirable” in line with this paradigm. The Economics sub-model is where the SWF and RA policies, which affect LID adoption, are modeled.

The central premise of the system dynamics model is that in a residential area where some households are impacted by the consequences of stormwater runoff, including CSO and property floods, at least a fraction of these households is expected to derive benefit from LID as a stormwater management solution (Fig. 3). This premise is captured by the concept of *LID Attractiveness*, formulated in terms of a fraction of the households in the catchment who are interested in installing LID. *LID Attractiveness* essentially represents the baseline adoption potential for LIDs in a context with no existing stormwater management regulations or incentives.

The policy mechanisms we explore in our scenarios are aimed at realizing the potential indicated by *LID Attractiveness*. However, the potential itself is likely to be dynamic. Initially, the households rely on anticipated performance of LIDs to store excess stormwater during rain events, which is communicated via advertising campaigns. As more interested households become adopters, more LID infrastructure is installed in the catchment area and more experience is gained about the actual contribution of LIDs to stormwater management.

Over time, the households compare the advertised contribution of LIDs with the actual contribution, which can sustain or reduce the public acceptance of LIDs as a SWM solution. If the anticipated contribution of LID is met, public acceptance is sustained, which will stimulate further realization of LID adoption potential (illustrated as loop R1 in Fig. 3). On the other hand, if LID performance is less than anticipated, the acceptance of LID will be reduced. This would reduce LID attractiveness among households and lower adoption rates despite incentive policies. Since LIDs have a limited lifetime and need to be reinstalled, lower LID attractiveness will necessarily reduce reinstallation. Reductions in both first-time installation from adoption rates and reinstallation from existing adopters will decrease the number of LIDs in the catchment, which will lead to even lower LID contribution to SWM, lower acceptance and attractiveness and the risk of serious resistance to incentive policies (loop R2 in Fig. 3). The described feedback mechanisms are represented by two reinforcing feedback loops in Fig. 3 and form the dynamic hypothesis of the study.

The model does not explain or determine the adoption potential, but rather assumes the adoption fraction that a decision-maker (municipality) perceives to be desirable and realistic and explores the deviation of an actual adoption process from this target/fraction. The realization of the adoption potential is driven by the endogenous adoption structure of the model, which is affected by RA and SWF policies and performance of stormwater management in relation to LID adoption dynamics. Based on interviews with experts working with LID in Oslo, we assume the municipality has a target adoption fraction of 20% in our scenarios.

2.2. Study area

The city of Oslo, the capital of Norway, has ambitious plans for stormwater management in new building projects (Oslo kommune, 2013), but existing built-up areas, with no plans for transformation or development, do not fall under the stormwater regulatory requirements. Performance-based green area indicators are being introduced in parts of Norway, while economic incentives have to date not been tried in as part of the LID policy mix (Oslo kommune, 2019).

The Grefsen-Kjelsås neighborhood has a catchment area of 1,44 km^2 and consists primarily of detached and private houses with large green gardens and few residential blocks (Fig. 4). Buildings, streets and pavements cover an estimated impermeable surface of 22%. The sewer system in Grefsen-Kjelsås is 60% combined and is designed with a Combined Sewer Overflow (CSO) acting as a relief valve by allowing untreated wastewater discharge into the receiving river Akerselva.

A CSO event is normally expected to occur once every three years.

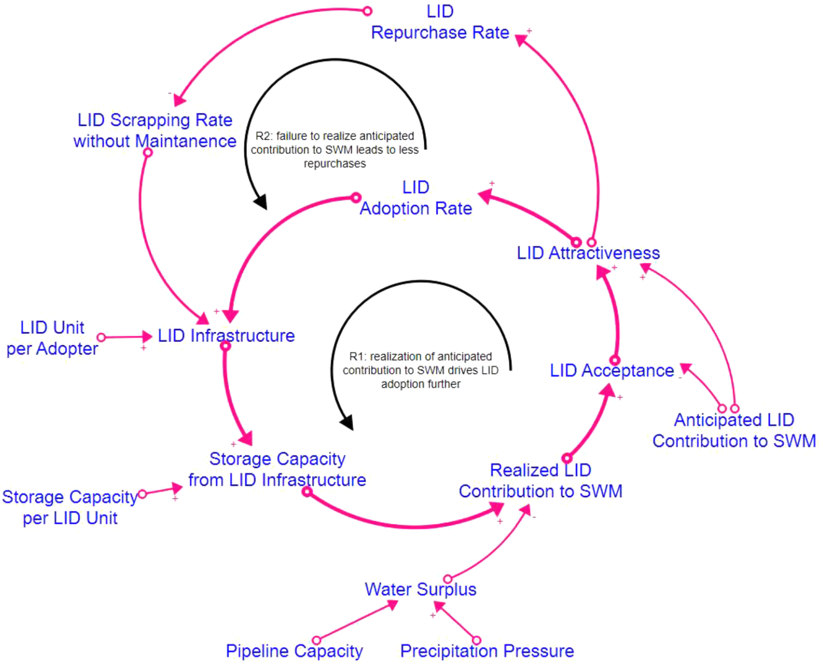


Fig. 3. The dynamic hypothesis for the model.

Fig. 4. Map of the study area in Oslo, Norway. Adapted from (Li et al., 2020).

However, under current precipitation conditions and the constrained sewer system, a CSO event occurs several times per year, including during relatively small rainfall events. The pollution resulting from CSOs affects water quality, habitats, and riparian and coastal recreation opportunities. In addition to CSOs, some properties in the catchment experience garden and basement floods during intense rainfall events. Similar to CSOs, the frequency of the property floods is considered to be higher than normal. The reduction of CSOs is recognized by municipality of Oslo as the main stormwater problem in Grefsen-Kjelsås, and LIDs, which complement the existing sewer system, are considered among the central solutions to addressing this problem (Furuseth et al., 2018).

Grefsen-Kjelsås is representative of many urban residential areas, where neighborhoods of single family homes have densified over time, and sewer systems are at times overwhelmed by precipitation events. Notably, public spaces in the area are small and diffuse, and can therefore only make a limited contribution to stormwater management. As the dominant land use, privately owned residential properties offer the greatest opportunity for implementing LID in the area.

2.3. Model parameters

With the aim of highlighting key household adoption dynamics, we made the following simplifying assumptions:

- Only rain gardens are considered as an available LID solution. Rain gardens are a common form of LID installed on private property, and relative to other types of LID, there is more data available about installation and maintenance costs and infrastructure lifetime (estimated to be 30 years; see Appendix A, section A.1 for more detail). Using a single type of LID allows for a focused analysis of adoption dynamics.
- Reference (fixed) values of stormwater fee, LID cost and LID subsidies are used in the model, and the model incorporates the effects of distribution of households around these reference values.
- The number of households in the catchment is kept constant. Only households with green space (identified by GIS mapping, see Appendix A) are counted as eligible households for rain gardens in the model.
- “Grey infrastructure” (e.g. drainage network, impermeable built surfaces) is kept constant.

Given the assumptions of a constant number of households and constant capacity of gray infrastructure, the system dynamics model is intended to be simulated for 30 years (2020-2050). A full list of parameters is included in Appendix A, model documentation. The parameters, initial values and climate scenarios of the model are calibrated to the case of Grefsen-Kjelsås (Appendix A). However, the structural mechanisms are assumed to be generic to a built urban area.

2.4. Description of scenarios

The model is used to generate scenarios that provide insights on the dynamics of realizing LID adoption potential under the two policy instruments. While reporting the scenario results, the variables of interest are the adopters of LID as a fraction of total households (*Realized Adoption Fraction*) and the water storage capacity associated with the stock of installed LID infrastructure relative to water surplus (run-off) in

Table 1
▩

Scenario set	Scenario number	RA Subsidy	Dimensioning assumption (year return period)	SWF (NOK)
Advertising and subsidy scenarios	1	–	5	–
	2A	25%	5	–
	2B	90%	5	–
	2C	90%	20	–
Stormwater fee scenarios	3A	–	5	400
	3B	–	5	800
	3C	–	20	800
Combined policies scenarios	4A	90%	5	800
	4B	25%	5	800
	4C	67%	5	800

the catchment area (*LID Contribution to SWM*). The first variable captures the extent of LID diffusion, which is typically referred to in the literature as adoption rate or implementation rate, and the second variable reflects the contribution of the installed LID infrastructure to SWM capacity.

The following variables are used (Table 1):

- *Dimensioning assumption*: captures the role of LID as a SWM solution in terms of LID's SWM capacity for rains with 5-year or 20-year return periods. 5-year rain is the default dimensioning. Dimensioning to 20-year rain represents the context in which heavier rain events may exceed LID capacity to manage stormwater.
- *RA subsidy*: reverse auction determined subsidy formulated as a fraction of LID cost; reflects the degree of cost-sharing between the households and the municipality.
- *SWF (NOK)*: expresses the stormwater fee in Norwegian kroner (NOK) per household per year. At the time of model construction, 1 NOK was equivalent to 0.10 EUR (DNB, 2021).

3. Results

We present results as three sets of scenarios (Table 1). The first set of scenarios explores the advertising and subsidy policies as well as how people's expectations of LID shape adoption trajectories. The second set of scenarios explores the effect of the stormwater fee on LID adoption. The third set explores how subsidies and stormwater fees could function in concert to optimize LID adoption.

3.1. Advertising and subsidy scenarios

Scenario 1 represents a situation with only an advertising campaign (running from 2021 to 2024) to raise awareness. The awareness campaign on its own is able to create a small increase in adoption while it's active, but within a few years of its conclusion, the LID adoption fraction begins to decline (Fig. 5). This is because the policy attracts relatively few adopters in the absence of other incentives, and, over time, a fraction of these adopters do not re-adopt LID as their LID ages.

Scenarios 2A and 2B demonstrate the result of an advertising campaign plus a reverse auction-based subsidy. As participation in the reverse auction is voluntary, households need to be made aware of the policy (through advertising) in order to participate. These scenarios present a publicly funded LID diffusion strategy that uses a minimum of willingness-to-pay by the households with intrinsic interest in LIDs and assumes that there is no limit to the municipality's budget for subsidizing LID. This is in contrast to the combined policy scenarios presented in Section 3.3, in which revenue from the stormwater fee is the financing mechanism for the reverse auction-based subsidy.

Scenario 2A introduces the reverse auction-based subsidy at a modest level of 25% (households pay 75% of the cost of installing LID). In this scenario, the *Realized Adoption Fraction* increases initially, but peaks at about 6.0% (Fig. 6). As with Scenario 1, low LID adoption fractions contribute to low perceived effectiveness of LID and low re-adoption of LID, resulting in a gradual decline in the adoption fraction for the rest of the simulation.

In *Scenario 2B*, a generous 90% subsidy policy results in sharp increases in the *Realized Adoption Fraction* within the first 6 years to about 16.7%. The adoption fraction keeps growing gradually over the rest of the scenario to slightly over 20%, which marginally exceeds the adoption target (Fig. 5). The high adoption fraction results in LID storing 100% excess water, which corresponds to the maximum *contribution to SWM* (Fig. 6). The gradual increase in adoption fraction comes from the effect of the reinforcing feedback loops. Since the adoption happens fast enough to increase the storage capacity from LID beyond the expected storage, LID attractiveness continues to increase beyond 20%. Consequently, some of the initially non-attracted households develop interest in LIDs and a fraction of them are motivated to become adopters by the subsidy.

This scenario demonstrates that high subsidies together with an effective advertising campaign that clearly communicates realistic expectations for LID as a stormwater management solution within the likely climate scenario leads to timely realization of full LID adoption

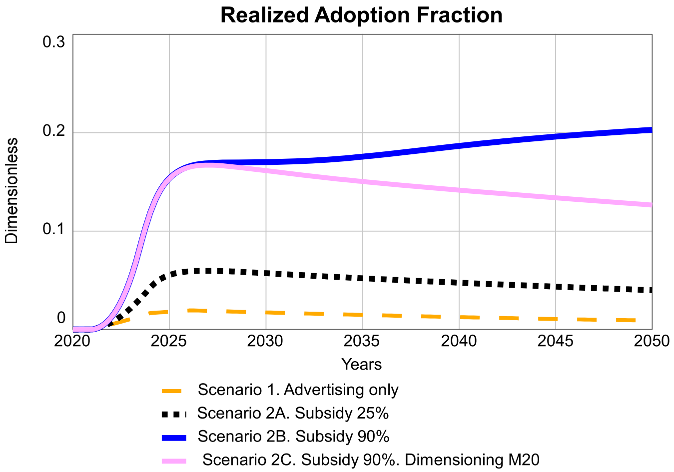


Fig. 5. Realized adoption fraction. We assume the municipality has a goal of 20% (0.2) adoption.

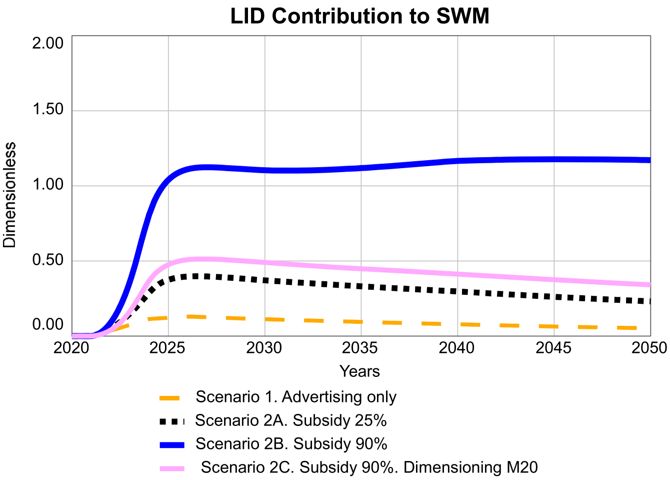


Fig. 6. LID contribution to stormwater management, where a value of 1 on the Y-axis indicates 100% of desired storage capacity from LIDs.

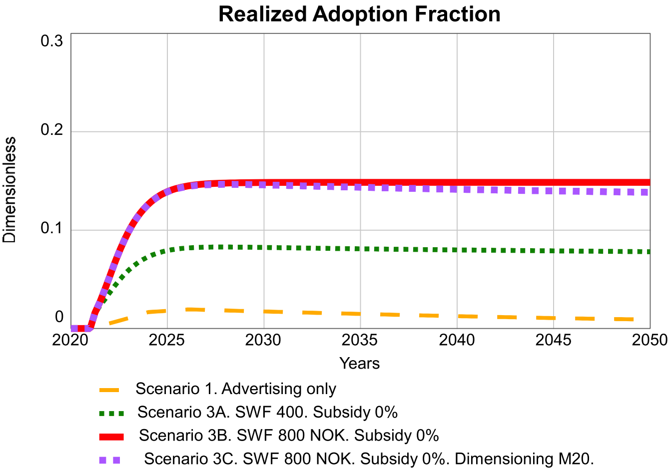


Fig. 7. Realized adoption fraction. We assume the municipality has a goal of 20% (0.2) adoption.

potential. In addition to the anticipated contribution of LID to SWM being realized, the actual performance of LID exceeds the expectations and leads to a slight positive increase in initial adoption potential. *Scenario 2B* is an ideal diffusion scenario, which, however, comes at a high public costs associated with 90% subsidies. Unsubsidized rain gardens are estimated to cost 10,000 NOK/m2 to install (Furuseth et al., 2018). In our model, an unsubsidized 7 m2 rain garden is calculated to have an annualized cost (installation and maintenance) of 3,560 NOK.

Scenario 2C demonstrates the role of dimensioning assumptions and the importance of the design of advertising campaigns. The scenario takes *Scenario 2B* as a starting point but assumes rains with 20-year return period. These heavier rains will at times exceed the capacity of LID. As a result, households form an impression that LIDs are not effective at managing stormwater. As households perceive low LID effectiveness in relation to larger rain events, the adoption fraction gradually declines. *Scenario 2C* demonstrates a considerable sensitivity to the dimensioning assumption and points to the importance of designing an advertising campaign that clearly communicates the limits of LID, in addition to the benefits.

3.2. Stormwater fee scenarios

These scenarios explore implementation of a stormwater fee without a LID subsidy. The stormwater fee promotes LID adoption among households who want to avoid the fee. For these households, avoiding the stormwater fee adds to the perceived benefit of LID in a benefit/cost ratio.

Scenario 3A presents a SWF of 400 NOK/year. The fee promotes rapid adoption of LID among the households that are sensitive to that fee level. After initial growth, the adoption fraction remains stable over time at about 8%, far below the goal of 20% adoption (Fig. 7). The stability can be explained by the fact that households are motivated primarily by the fee instead of LID performance or intrinsic interest. As a consequence, the LID contribution to stormwater management is only about 50% of the desired level (Fig. 8), which indicates that the SWF needs to be higher to realize the desired level of LID.

Scenario 3B (*SWF of 800 NOK*) tests the LID diffusion strategy that is based on a stormwater fee of 800 NOK. In this case, the realized adoption fraction is only slightly lower than in *Scenario 2B (Subsidy at 90%, with no SWF)*. While the realized adoption fraction is lower than the desired 20%, the LID contribution to SWM remains at or near 100%. This result indicates that the impact of the stormwater fee alone on LID diffusion can be comparable to the effect of 90% RA subsidies.

Scenario 3C simulates a SWF of 800 NOK but with the dimensioning assumption of 20 years. As with scenario 2C, this represents a case in which households develop falsely high expectations of LID performance under rain events with a 20 year return period. While these overly high expectations caused a drop in adoption over time in scenario 2C, in scenario 3C, they have little effect on long term results. This is because the stormwater fee is held at a constant level regardless of the actual performance of LIDs, making householders relatively insensitive to LID performance. This scenario illustrates the power of the extrinsic motivation created by the stormwater fee.

3.3. Combined policies scenarios

This set of scenarios demonstrates the effect of implementing the stormwater fee (SWF), which is set to a reference value of 800 NOK/household/year, together with the reverse auction-based subsidy. In contrast to the first set of scenarios, LID subsidies are constrained by the availability of funds in the stormwater fee account. Income from the stormwater fee accumulates in the stormwater fee account and is earmarked for LID subsidies. *Scenario 4A* portrays the reference adoption trajectory with the stormwater fee and generous subsidies (*Subsidy Fraction* at 90% of LID Cost). *Scenarios 4B and 4C* explore moderate and low subsidies.

For *Scenario 4A*, the adoption trajectory during the first 4 years is steep (Fig. 9). After year 2025, the adoption growth continues at lower yet quite moderate rates. The ultimate adoption fraction stabilizes around year 2035 and exceeds the adoption fraction achieved in *Scenario 2B* (26.6% and 20.3% respectively). LID contribution to SWM develops in a similar fashion to the adoption fraction (Fig. 10). Higher adoption fraction results

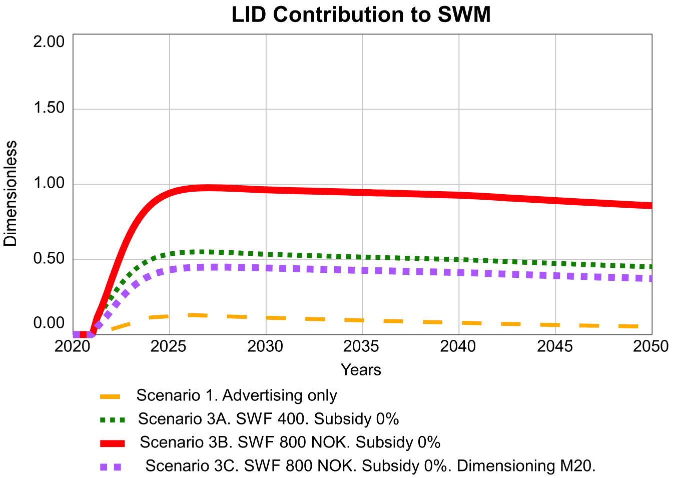


Fig. 8. LID contribution to stormwater management, where a value of 1 on the Y-axis indicates 100% of desired storage capacity from LIDs.

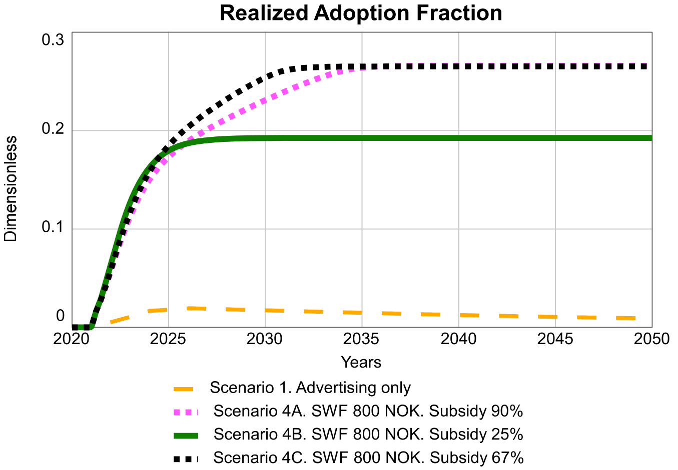


Fig. 9. Realized adoption fraction. We assume the municipality has a goal of 20% (0.2) adoption.

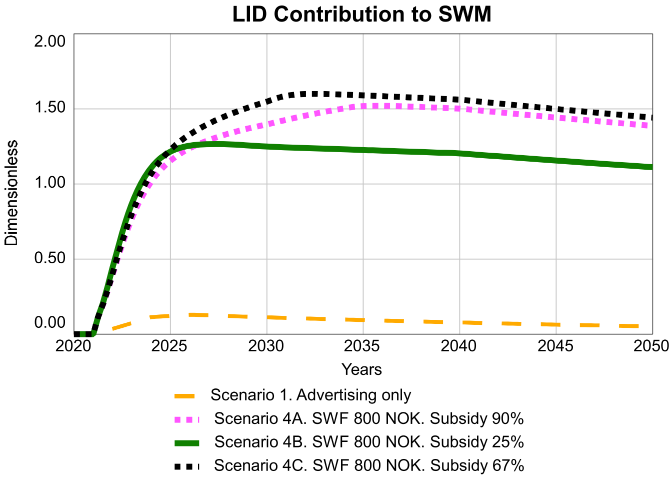


Fig. 10. LID contribution to stormwater management, where a value of 1 on the Y-axis indicates 100% of desired storage capacity from LIDs.

in very high storage capacity from LIDs providing 152% of required storage capacity in 2035. This surplus in stormwater management capacity becomes useful later when precipitation pressure grows. Even though climate change (and resulting increased precipitation) causes a decline in LID contribution to SWM, the achieved adoption fraction remains stable.

Scenario 4B and 4C experiment with different subsidy fractions. Since the reverse auction-based LID subsidies are financed by the stormwater fee income, lower subsidy fractions indicate a higher degree of cost-sharing and affect the rate at which the funds of the stormwater fee account are utilized. In other words, lower subsidy fractions mean that more households can receive subsidies. The scenarios explore the dynamic trade-off between lower subsidies which attract a lower number of adopters, and higher subsidies which attract more adopters but drain the RA budget more quickly.

Scenario 4B tests the effect of low RA subsidies, with a representative subsidy fraction of 25%. At this level of subsidies, close to 19% adoption fraction is achieved within the first 5 years, which is higher than in *Scenario 2B*. The adoption trajectory exhibits very slight decline through the rest of the scenario due to lower LID contribution to SWM which is now affected by climate change. However, in 2050, the adoption fractions are only slightly lower than in *Scenario 2B* (19.3% and 20.3% respectively). *Scenario 4B* indicates that there can be significant potential for cost-sharing when the stormwater management regulation such as the stormwater fee is a part of the LID diffusion strategy.

Scenario 4C reveals probably the most interesting insight. From a dynamic perspective, moderate subsidies (such as 67% subsidies) can improve the adoption projections relative to *Scenario 4A* (generous subsidy). As Fig. 9 shows, there is a faster and steeper adoption between years 2025 and 2030 at moderate subsidies. This is due to the dynamics of funds availability and the trade-off between the subsidy fraction and the amount of subsidies that could be supported financially. At moderate subsidy fractions, more subsidies can be allocated to more households from the stormwater fee fund, which effectively speeds up the diffusion process. The additional economic motivation that the stormwater fee provides for attracted households compensates for the loss of adopters from lower RA subsidies. Though the revenue from the stormwater fee is reduced over time (as more households adopt LID), the adoption fraction remains stable as LID is perceived as effective.

4. Discussion and conclusion

Our quantitative system dynamics model integrates quantitative and qualitative data to improve understanding of LID implementation in built up areas under different policy scenarios. We focus on the adoption process within an interlinked socio-economic and hydrologic system.

4.1. Findings and policy implications

Our modeling results suggest that a simple advertising/awareness campaign is insufficient on its own to stimulate widespread adoption of LID. Low levels of LID adoption can add to a perception of LID having limited effectiveness and further erode adoption over time. Though awareness campaigns may have limited effectiveness on their own, they are a key component of the reverse auction-based subsidy policy.

A reverse auction-based subsidy can be an effective policy (relative to a general stormwater fee) for increasing LID adoption rates because it is targeted at a specific LID measure, though high subsidies may be needed to ensure continued stable adoption and re-adoption over time. In our scenarios, subsidies of 90% were needed to reach the target adoption fraction of 20%. Further, our scenarios illustrate how households can be sensitive to LID effectiveness. When faced with 20 year rain events, LID effectiveness is reduced, which in turn reduces the attractiveness and adoption fraction of LID. This demonstrates the importance of clearly communicating realistic expectations for LID capacity and functionality in advertising campaigns.

Obtaining reductions in the stormwater fee can also serve as an effective source of motivation for LID installation, increasing adoption fractions and reaching households both with and without intrinsic interest in LIDs. Because stormwater fees are calculated on total runoff (from all surfaces, not just rain gardens), the incentive effect on LID adoption relative to a targeted payment via auction is low. Furthermore, the adoption trajectories under the stormwater fee are less sensitive to the dynamics of LID attractiveness driven by dimensioning assumptions because the fee is not tied to the effectiveness of LID under different intensities of rainfall events. This implies that the uncertainty about adoption potential and advertising the role of LID as a stormwater management solution is less critical if the stormwater fee is a part of the policy mix. We note, however, that implementing a stormwater fee may be politically difficult, as it depends on estimating the storm runoff from individual properties. In the case of Oslo, a proposal for a stormwater fee adopts a two stage approach which allows private property owners to challenge municipal calculations if land cover is inaccurate or LID measures have been implemented that have not been identified. The property owner returns a corrected description of the property and a recalculation of the stormwater fee using an online app (Barton, Venter, Sælthun, Furuseth, & Seifert-Dähnn, 2021).

A combination of the reverse auction-based subsidy and stormwater fee policies allows for a fee collected across all property owners to be reallocated to a much smaller number of cost-efficient properties, such that implementation of the stormwater fee can support implementation and expansion of LID measures, with targeted use of the subsidy. In fact, the scenarios reveal that using stormwater fee revenues to finance moderate reverse auction-based subsidies can facilitate faster adoption in the near-term without necessarily reducing the adoption potential in the long-term. Lower subsidy fractions mean that more households can receive subsidies.

Much of the existing literature on urban stormwater policies considers instruments individually, be they stormwater fees (Abebe et al., 2021; Tasca et al., 2018; Zhao et al., 2019) or reverse auction-based subsidies (Thurston et al., 2010). Tasca et al. (2018) discuss how stormwater fees operate at the interface between water management, emergency management, pollution control, and land-use management, effectively requiring a policy mix for implementation. Zhao et al. (2019) discuss the evidence that stormwater utility credits or discounts implemented with stormwater utility fees provide greater flexibility to adopting best management practices and reduce stormwater runoff at a lower overall cost to the community. To our knowledge, the present study is the first to explicitly model the interactions of stormwater fees and subsidies for LID implementation.

While system dynamics models have been built to analyze combined policy instruments in other domains (for example, Gerber, 2017), the specificity of policy instruments and environmental issues makes it difficult to draw comparisons across domains.

4.2. Limitations and future work

As a tool for investigating potential behavior patterns and how they could change over time, the model illustrates how households could react to LID implementation policies and perceived LID effectiveness. The scenarios demonstrate the model's capability to generate a wide array of LID adoption trajectories, given the assumptions about the adoption potential, the municipality's strategy to realizing this potential, and a portfolio of policies to support such strategy.

Further development of the model could include adding additional types of LID (such as green roofs or permeable pavement) and a more dynamic representation of gray infrastructure. Including population dynamics and socio-economic forces, such as housing prices, could capture larger societal impacts (including environmental justice issues) of an LID-based stormwater management strategy (Hoover, Meerow, Grabowski, & McPhearson, 2021). A better understanding of households' perceptions, experiences, and capabilities would help explain motivation and adoption, and research into "motivational crowding" in relation to LID implementation could provide a more nuanced picture of household motivation in relation to fees and subsidies (e.g., Ezzine-de-Blas, Corbera, & Lapeyre, 2019; Ureta, Motallebi, Scaroni, Lovelace, & Ureta, 2021;(Akers and Yasué, 2019)). Though the model includes LID maintenance costs, we see value in further exploration of monitoring and maintenance issues, including the perceived burden and liability of LID maintenance for private landowners that could affect adoption (Dhakal & Chevalier, 2017). Lastly, studies of reverse auction, subsidy and stormwater fee implementation and adoption rates (either alone or in concert) in other municipalities could help validate parameters in this model and strengthen model insights.

This work could also be further developed by extending the model with explicit links to regulatory frameworks and their understanding of stormwater. For example, in current Norwegian practice, municipalities are only allowed to charge water and sewer fees that are directly related to providing those services. Though they can change over time, regulatory frameworks create structures that must be navigated when considering when and how stormwater policies can be implemented. A policy mix perspective that considers multiple information, regulatory and economic instruments can help identify synergies and tradeoffs among institutional frameworks (Barton et al., 2017; Ring & Barton, 2015a, 2015b).

Further, a stormwater fee is based on a legal argument that the private property owner is responsible for external costs related to stormwater management that have been shifted to the municipal utility (akin to a "polluter pays" principle). A reverse auction-based subsidy does not explicitly rest on this argument and instead tries to allocate limited funds effectively to interested property owners, who voluntarily enter an agreement with the funder. These two approaches have therefore a fundamentally different understanding of a property owner's legal responsibilities to manage storm runoff from their property. In addition, under current regulations governing pricing of municipal utilities in our case study area, fees can only recover a utility's costs of service provision (Barton et al., 2021). Currently, regulation does not allow a stormwater fee to fund an LID subsidy to customers, even if the subsidy is aimed at reducing the utility's stormwater costs. In summary, implementation of a reverse auction-based subsidy and stormwater fee in concert may challenge existing regulatory frameworks and expose tensions in how stormwater is understood and defined in the urban context. These tensions may reduce the desirability of directly linking these policies.

This study contributes to the existing LID literature by considering LID implementation in a built-up area in the context of an urban stormwater system, where hydrological, socio-economic, and governance sub-systems are closely interconnected. The use of system dynamics methodology to develop a dynamic model allows formalizing both "hard" quantitative and "soft" qualitative aspects of LID adoption and stormwater management. The scenario analysis has been performed for the specific area of Grefsen-Kjelsås in Oslo. However, the structures developed for the system dynamics model are representative of a generic built-up area and, therefore, the model can be calibrated to other catchments, given the availability of data.

Declaration of Competing Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

Acknowledgement

This work was supported by the Norwegian research council through the project New Water Ways (270742). We wish to thank Isabel Seifert-Dahnn, Hong Li, Ingvild Skumlien Furuseth, Bent C. Braskerud, and Line Johanne Barkved for helpful comments and feedback.

Appendix A: Full model documentation

This model is built in Stella Architect. Model documentation is presented by sub-model, with visual excerpts of the model to aid understanding. In sum, the model consists of model consists of 12 stocks and 172 variables. Parameter values are listed in a table at the end of each sub-model description. Values for key parameters that are not taken from literature or expert interviews are determined by partial- and full-model calibration against available data for the study area.

A.1. Stormwater Management (SWM) Sub-Model

LID Infrastructure is tracked by a stock variable that accumulates the difference between installation rate and scraping rate (Fig. A.1). **Installation Rate** combines installations from first-time purchases and from repurchases. **Scrapping Rate** is formulated as a first-order exponential decay over specified **LID Lifetime** (Table A1).

Installations from first-time purchases are driven by **LID Adoption Rate** in **LID Adoption Sub-Model**. The parameter **LID Installation Rate per Household** converts adoption rate, which is formulated in terms of households, into LID installation rate, which is formulated in terms of LID units, and is set to value 1 to reflect the municipality's expectation that only one LID unit is likely to be installed by a household. Since the LID installation per household assumption is portrayed explicitly as a parameter, it can easily be changed by a model user. **LID Adoption Rate** combines adoption rates from all the three categories of potential adopters in the model: those attracted to LID and who do not need an incentive, those attracted to LID and who need an incentive and those whose interest in LID comes from SWM regulation (the stormwater fee).

LID Installation Rate from Repurchase is determined by LID scrapping rate and the adopters who decide to continue using LID. Current adopters decide not to repurchase LID if the conditions that impacted their previous purchase decisions have changed: LID became less attractive, an incentive decreased, or the SWM regulation became weaker (the stormwater fee amount decreased). The model tracks these changes and recalculates realized repurchase rates accordingly. Repurchases from subsidies are tracked separately since they are subject to budget constraints in a limited subsidy case.

LID Attractiveness is driven by acceptance of LID as a viable SWM solution among the households (Fig. A.2). LID Attractiveness adjusts towards the indicated value exponentially over **Time to Change LID Attractiveness. LID Acceptance** captures the propensity of the residents to participate in SWM by installing LID at their property. Note that, according to this conceptualization, even 100% subsidy requires acceptance of a household to install LID. A financial incentive that covers the full cost of LID is assumed to be sufficient to realize the full adoption potential indicated by LID Acceptance, whereas a financial incentive that covers the cost of LID partially is assumed to realize only a fraction of this potential.

LID Attractiveness is formulated in terms of **adoption potential**, that is, a fraction of all the households in the area that would install LID at 100%

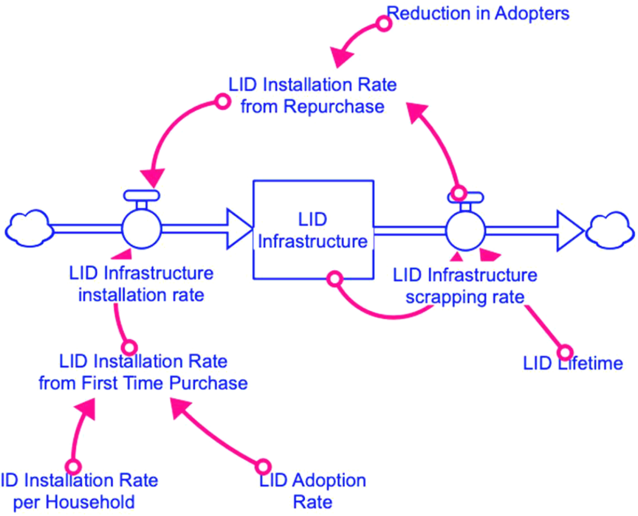


Fig. A1. Simplified stock and flow structure of LID infrastructure.

Table A1
List of important parameters for SWM sub-model

Parameter	Value	Unit	Reference
LID Lifetime	30	Year	Expert elicitation, literature review
LID Installation Rate per Household	1	LID Unit/Household	Reflects the Oslo municipality's expectation that only one LID unit is likely to be installed by a household
Time to Change LID Attractiveness	1	Year	Model calibration
Time to Perceive Realized LID Contribution to SWM	7	Year	Model calibration
Time to Change LID Acceptance	15	Year	Model calibration
Reference LID Coverage	20	Square Meters/LID Unit	(Kukadia, Lundholm, & Russell, 2018)
Reference Storage Capacity per LID	3.8	Cubic Meters/LID Unit	(Kukadia et al., 2018)
LID Coverage	7	Square Meters/LID Unit	(Furuseth et al., 2018)
MIN LID Attractiveness	0.03 (3%)	Dimensionless	Approximation of lowest reported adoption rates for rain gardens in (Shin & McCann, 2018).

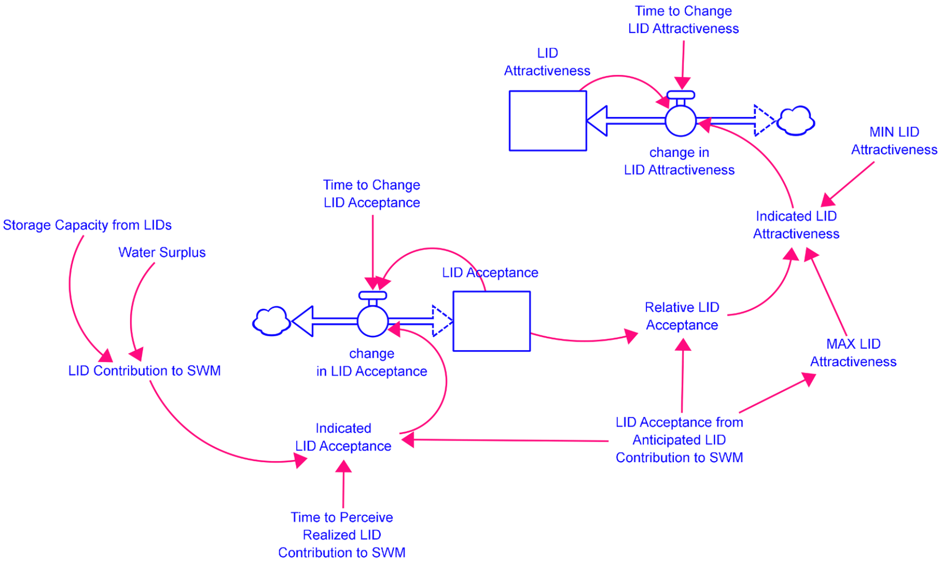


Fig. A2. Stock and flow structure of LID acceptance and LID Attractiveness.

subsidy. It is unlikely that all the households will install LID even when a financial incentive that covers the full cost of LID is provided. On the other hand, the experience of LID adoption in other countries (Shin & McCann, 2018) and the results of the survey in Grefsen-Kjelsås (Furuseth et al., 2018) indicate that some residents install LID even without any financial incentive. Therefore, the model specifies minimum and maximum LID Attractiveness. **MIN LID Attractiveness** is taken from values presented in (Shin & McCann, 2018). **MAX LID Attractiveness** indicates the maximum adoption potential from a financial incentive (and, therefore, does not include adoption potential from SWM regulation) and is influenced by anticipated role of LID in SWM.

LID Acceptance is formulated in terms of **LID Contribution to SWM**, a variable that captures the interaction of LID Infrastructure with the hydrological system of the catchment. This contribution is defined as storage capacity from all installed LIDs combined relative to water surplus in the catchment. **Storage Capacity** associated with LID infrastructure within the catchment is calculated from the stock of LID Infrastructure assuming average **Storage Capacity per LID Unit**. The unit-level storage capacity is proportional to average coverage of LID unit assumed for the catchment, given the relationship between storage capacity and coverage of a reference LID unit. **Water surplus** is excess runoff that accumulates during intense rain events and leads to combined sewer overflow (CSO). In principle, besides CSO, the access runoff has another undesirable consequence in the catchment: household-related floods, namely garden and basement floods. Household-related floods and the potential role that LID can play in reducing their extent justify the municipality's expectation of intrinsic value that some of the households might place on LIDs. However, since the available information about household-related floods is anecdotal and these floods are typically correlated with CSO events, for which more quantified evidence has been gathered by (Furuseth et al., 2018), water surplus associated with CSO is chosen to be the only reference for assessing LID contribution to SWM.

Essentially, **LID Acceptance** captures the effect of LID performance over time on **LID Attractiveness**. The dynamics of this effect is such that, when exposed to advertisement, households receive information about expected LID performance and form perception of anticipated LID contribution to SWM. As LIDs are being installed and sufficient utilization time elapses, households update their perception of LID performance. As a result, the **LID Acceptance** gradually evolves from initially formed perception of anticipated LID contribution to SWM to the perception of realized LID contribution to SWM. The potential for the described dynamics of **LID Acceptance** is inherent in the structure portrayed in Fig. A.2.

Two time constants characterize the speed of LID acceptance dynamics: **Time to Perceive Realized LID Contribution to SWM** (set to 7 years to allow for sufficient observations of rain events with 5-year return period) and **Time to Change LID Acceptance. Time to Change LID Acceptance** is set to 15 years, a half of LID lifetime. This reflects the consideration that it may take some years to experience stronger floods; households may need to experience more than one flood to understand the impact of LIDs; and households need time to adjust their beliefs/perceptions of the value of LID even after the impact/benefit of LID is clear.

A higher anticipated contribution of LID to SWM indicates a higher value for **MAX LID Attractiveness**. This relationship is portrayed by the table function (Fig. A.3) that reflects the estimated responsiveness of adoption potential to expected LID performance that is communicated to the residents during advertisement campaigns. Such relationship is necessarily an expert estimation that incorporates a number of informed assumptions, both quantitative and qualitative. The use of a table function is a convenient way to operationalize such expert estimation. Note that the model does not determine the adoption potential, but uses a decision-maker's (municipality) aim for a realistic adoption potential and simulates the trajectory of realizing this potential at various policy designs. In this sense, the table function for **MAX LID Attractiveness** is a heuristic that represents the mental model of municipality. The model then assumes that the adoption potential corresponds to this heuristic and explores the deviation of an actual diffusion process from the adoption potential driven by the endogenous adoption structure of the model, which is exposed to the impacts of policies, performance of SWM impacted by LID adoption dynamics and the exogenous pressures of climate scenarios.

LID Attractiveness is a type of variable that is typically referred to as a "soft variable". However, since it is formulated in terms of potential adoption fraction, it can be easily related to LID contribution to excess water storage. The table function assumes that LID contribution beyond the

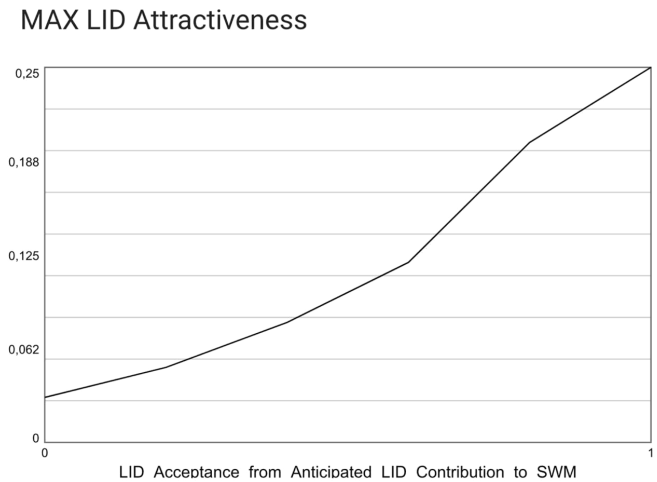


Fig. A3. Table function for Max LID Attractiveness.

excess water in the catchment (above 100%) does not have an impact on LID attractiveness. On the other hand, the interviews with Oslo municipality stakeholders revealed that 25% adoption fraction is considered to be sufficient in providing the required SWM capacity for 5-year rains. Therefore, the upper bound value for MAX LID Attractiveness is set to 25% and corresponds to 100% LID Contribution to SWM. The values for MAX LID Attractiveness for lower values of LID Contribution to SWM were estimated by simulating the model iteratively in a 90% unlimited subsidy mode (no financial constraints to realizing a given adoption potential) under various climate scenarios (see the discussion on climate scenarios below).

LID Acceptance relative to **LID Acceptance from Anticipated LID Contribution to SWM** indicates how close **LID Attractiveness** at any point in time is to **MAX LID Attractiveness**. When **LID Acceptance** is at anticipated contribution, **LID Attractiveness** takes its maximum value. If **LID Acceptance** goes below anticipated contribution, **LID Attractiveness** is between its minimum and maximum values. **MIN LID Attractiveness** is set to 3% corresponding to the lowest adoption rates observed for LIDs as a result of advertising campaigns (Shin & McCann, 2018).

By definition, the water surplus is the excess runoff relative to existing pipeline capacity in the catchment. Therefore, the variable **Water Surplus** captures precipitation profile typical for the catchment relative to the SWM capacity in place (without LIDs). Eq. A.1 formalizes this conceptualization of water surplus.

$$WaterSurplus = \frac{RunofffromaRainEvent}{PipelineCapacity} \tag{A.1}$$

Rain events vary by intensity and duration, where the intensity is characterized by a return period (3-year rains, 5-year rains, etc.) and duration is measured in time units (mins). The SWM systems are designed (dimensioned) to withstand a rain event with a specified intensity and duration characteristics. A common reference rain event commensurate with CSO problem is 60 min rain with a return period of 5 years. A more robust SWM system can be dimensioned to rain with a return period of 20 years, though LID infrastructure alone is unlikely to provide meaningful contribution to such system.

Hydrological modeling of the catchment provides a water surplus value typical for Grefsen-Kjelsås (Li et al., 2020). Due to long lifetimes, the pipeline capacity, which is the denominator of **Water Surplus**, can be assumed fixed over the model's time horizon. However, since the precipitation profile is expected to be impacted by climate change, the numerator of **Water Surplus** is both not constant and uncertain. The anticipated effect of climate change on precipitation is captured by climate factors that effectively increase the dimensioning requirements for SWM systems. In the context of Eq. A.1, an appropriate reference rain event for 2050 might be the one with higher intensity and/or duration than in 2020. The hydrological modeling incorporated climate factors in their analysis and produced water surplus scenarios for Grefsen-Kjelsås that correspond to RCP 4.5 and RCP 8.5. The water surplus scenarios were developed both for 5-year and 20-year rain events resulting in four water surplus scenarios.

A.2. LID Adoption Sub-Model

LID installations are driven by the LID Adoption Structure, which is the core of the model. Before any policy that has an impact on the awareness about LID is introduced, all the households of the catchment sit in the stock of **Unaware Households** (Fig. A.4). The stock is depleted by the **Awareness Rate**, which is the only associated flow, since migration of the population in and out of the catchment is not considered in the model. The Awareness Rate is formulated according to **Eq. A.2**.

$$\begin{aligned}&\textbf{Awareness Rate} = IF(Storm\_Water\_Fee > 0)THEN(MAX\_Awareness\_Rate)ELSE\\&\left(MIN\left(MAX\_Awareness\_Rate; Awareness\_Rate\_from\_Advertising + Awareness\_Rate\_from\_Adopters\right)\right)\end{aligned} \tag{A2}$$

$$\begin{aligned}&\textbf{Awareness Rate from Advertising} =\\&0 + STEP\left(INIT(Unaware\_Households)*Fraction\_of\_Households\_for\_Advertising\_Pulse; Advertising\_Pulse\_Year\_START\right)\\&-STEP\left(INIT(Unaware\_Households)*Fraction\_of\_Households\_for\_Advertising\_Pulse; Advertising\_Pulse\_Year\_END\right)\end{aligned} \tag{A3}$$

The formulation for the **Awareness Rate** incorporates the effect of three pressures: the effect of advertising (if subsidies are introduced, the

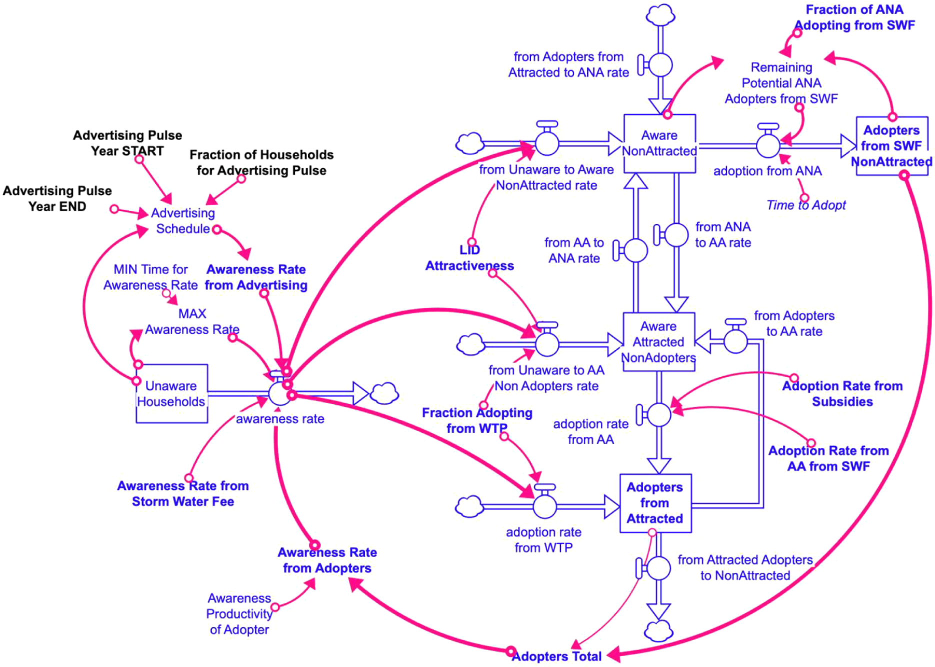


Fig. A4. Simplified stock and flow diagram of LID adoption structure.

Table A2
List of important parameters for LID adoption sub-model

Parameter	Value	Unit	Reference
MIN Time for Awareness Rate	0,25	Year	Reflects the assumption that it will take a year for all the households to become aware about LIDs
Time to Adopt	1	Year	Reflects the assumption that around 63% of attracted households will install LID within a year at full subsidy
Time to Become Attracted	1	Year	Set to be symmetrical to Time to Adopt
Total Households	873	Household	According to the GIS analysis for the catchment area, reported in (Lekkerkerk, 2020)

advertising accompanies a subsidy program), awareness from existing adopters (word of mouth) and the effect of stormwater fee. If the stormwater fee is introduced, awareness rate is determined by **MAX Awareness Rate**, given **MIN Time for Awareness Rate** (calibrated to reflect the assumption that it will take a year for all the households to become aware about LIDs) (Table A2). Without SWF, the **Awareness Rate** is the minimum of **MAX Awareness Rate** and the sum of **Awareness Rate from Advertising** and **Awareness Rate from Adopters**.

As the households are becoming aware of LIDs, they are simultaneously distributed among three groups (Fig. A.4). The households with intrinsic interest in LIDs and sufficiently high willingness to pay (WTP) become LID adopters right away and are added to the stock of **Adopters from Attracted** through **Adoption Rate from WTP**. Since this group of the households do not need a financial incentive to install LID, they can be “extracted” from the **Awareness Rate** at **Fraction Adopting from WTP**. It is these households that comprise **observed adoption rates** from advertisement campaigns.

The remaining households within the **Awareness Rate** are of either of two types: some of them have intrinsic interest in LIDs but lower WTP which has to be supplemented with financial incentive to overcome the “affordability barrier” and the others do not have intrinsic interest in LIDs and will not respond to a financial incentive. The first type is accumulated in the stock of **Aware Attracted Non-Adopters** (**AA**) by taking a fraction of potential adopters from the financial incentive from **Awareness Rate**. These non-adopters can eventually move into the stock of Adopters from Attracted if the financial incentive - whether from the subsidy or from the stormwater fee - is sufficient to overcome the “affordability barrier”. The second type is accumulated in the stock of **Aware Non-Attracted** (**ANA**) by taking a compliment of **LID Attractiveness** from **Awareness Rate**. These non-adopters can only be motivated to install LID by the stormwater fee. For clarity, **Adopters from ANA** are aggregated separately from **Adopters from Attracted**.

It is important to recognize that the allocation of aware households among the three groups is done by the model assuming the initial MAX LID Attractiveness and WTP (more specifically, the distribution of the households with intrinsic interest around average WTP). However, only the adoption rates are observed. For example, before AA and ANA households begin adopting LIDs, a municipality as a policymaker cannot differentiate between the two groups. The disaggregation of potential adopters into the stocks reflects the assumed underlying distribution of the households in terms of their intrinsic interest in LIDs and WTP for those who exhibit such interest.

Since the **LID Attractiveness** is dynamic in the model, any change in **LID Attractiveness** is accompanied by the corresponding redistribution of the households. The loss of both adopters and non-adopters that reflects lower **LID Attractiveness** adds to the stock of **Aware Non-Attracted** through **from Adopters from Attracted to ANA Rate** and **From AA to ANA Rate**. The increase in LID Attractiveness leads to **Aware Non-Attracted**

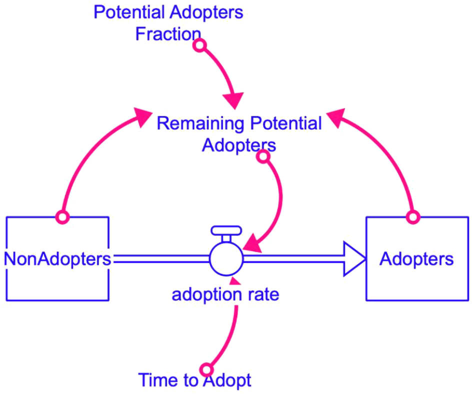


Fig. A5. Generic structure of remaining adoption potential.

households moving to the stock of **Aware Attracted Non-Adopters** through **From ANA to AA Rate**. A reduction of financial incentives (subsidy) does not impact attractiveness but redistributes the households from **Adopters from Attracted** to **Aware Attracted Non-Adopters** through **from Adopters to AA Rate**.

The flows for adoption rates are formulated based on adoption potentials associated with each of the portrayed mechanisms. These adoption potentials are determined by the split of the households in terms of their intrinsic interest in LIDs and by the cost-benefit evaluation, given the reference monetary values for incentive policies, SWM regulation policies and WTP. The cost-benefit evaluation is described in the Policy Effects Sub-Model and captured by four corresponding effects: **Effect of WTP on Adoption from Attracted, Effect of Stormwater Fee on Adoption from Attracted, Effect of Subsidy on Adoption from Attracted**, and **Effect of Stormwater Fee on Adoption from Non-Attracted** (see section A.3). The first three effects are adoption potentials formulated as fractions of attracted households and the fourth effect is an adoption potential formulated as a fraction of non-attracted households.

The application of the effects to determine actual adoption rates varies depending on whether an effect is applied to a flow or to a stock, within the scale of all the households in the catchment or within a sub-set of attracted/non-attracted households. As described above, adoption rate associated with the households who have sufficiently high WTP and do not need a financial incentive is governed by **Fraction Adopting from WTP**. This fraction is essentially the **Effect of WTP on Adoption from Attracted**, recalculated relative to the total households, since the adoption fraction is applied to the total households-level Awareness Rate. Since the adoption fraction is applied to the flow, the households that are not subjected to this adoption mechanism are accumulated elsewhere in the model and, once the stock of **Unaware Households** is depleted, cumulative adopters from WTP constitute the fraction of total households that corresponds to the adoption potential indicated by **Fraction Adopting from WTP**.

The realization of adoption potential associated with other mechanisms is formulated differently, since the households are accumulated in the stocks first and adoption potential represents only a sub-set of a respective stock. Once the adoption potential from a given monetary value of incentive policy or SWM regulation is realized, the adoption flow must cease even though the stock still contains households. A generic structure that satisfies such requirements is portrayed in Fig. A.5.

In this structure the adoption rates continues for as long as there are remaining potential adopters associated with a mechanism. For a generic structure, the remaining potential adopters are calculated according to Eq. A.4. The remaining potential adopters are added to the stock of adopters at a pace determined by **Time to Adopt**. Since the remaining potential adopters are calculated within the attracted/non-attracted sub-set of the households, the effects of respective policies determine directly the corresponding adoption fractions.

$$RemPotAdopters = (NonAdopters + Adopters) \times AdoptersFraction - Adopters \tag{A.4}$$

The calculated **Adoption From AA from SWF** is final and enters into **Adoption Rate from AA**. The **Adoption From AA from Subsidy** is final in an unlimited subsidy mode, but is indicated in a limited subsidy mode and enters the **Adoption Rate from AA** in a full or partial amount after it passes the subsidy availability check (see section A.4).

The remaining adoption potential structures for specific sub-sets of households include some modifications relative to the generic structure on Fig. A.5. For example, to account for the fact that attracted households contain households adopting from WTP, Adopters from WTP are subtracted from the adoption potential base in the equations for **Remaining Potential AA Adopters from Subsidy** and from **Stormwater Fee**.

A.3. Policy Effects Sub-Model: Subsidies and Stormwater Fee

The policies are intended to realize the adoption potential, which is indicated by **LID Attractiveness. LID Attractiveness** is conceptually paired with **Willingness to Pay (WTP)**, a variable that captures the intrinsic monetary value that attracted households place on LIDs. This value is formulated based on **LID Cost** and the fraction of the cost that attracted households are willing to cover out of pocket (Table A3).

LID Attractiveness indicates the potential for LID adoption at a point in time. The extent to which the indicated adoption potential is going to be realized is determined by the fraction of LID cost remaining after accounting for Willingness to Pay that is covered by **LID subsidy. Benefit to Cost Ratio** (Eq. A.5) is the variable that captures the monetary value associated with LIDs relative to LID cost.

$$BenefittoCostRatio = \frac{(AnnualizedWTP + SWF + AnnualizedSubsidy)}{AnnualizedLIDCost} \tag{A.5}$$

The numerator of the base Benefit to Cost Ratio combines all three potential sources of monetary value for LIDs: Willingness to Pay, Subsidy and

Table A3
List of important parameters for policy effects sub-model

Parameter	Value	Unit	Reference
LID Cost per Coverage	10,000	NOK/Square Meter	(Furuseth et al., 2018)
Fraction of LID Cost for Willingness to Pay	0.1	Dimensionless	Consistent with the average bid for rain gardens during the reverse auction conducted in 2018 as in (Furuseth et al., 2018)
Interest Rate	0.0175	Dimensionless/Year	Approximates 10-year real interest for 10-year government bonds; calculated from (Norges Bank, 2020)
Time to Perceive Costs and Benefits	1	Year	Consistent with adjustment time in LID Adoption Sub-Model
Elasticity of Adoption to Benefit to Cost Ratio for Attracted	1	Dimensionless	Assumes unit-elasticity
Elasticity of Adoption to SWF for NonAttracted	1	Dimensionless	Assumes unit-elasticity
LID Coverage/area	7	Square Meters/LID Unit	(Furuseth et al., 2018)

Stormwater Fee. Since the stormwater fee is formulated in per-year terms (unit: NOK/household/year), all the other monetary concepts are annualized based on **LID Lifetime** (discussed in section A.1.) and assumed **Interest Rate**.

The extent to which benefit to cost ratio affects the adoption potential is specified by **Elasticity of Adoption to Benefit to Cost Ratio for Attracted**. The effect is smoothed exponentially over **Time to Perceive Costs and Benefits** to account for delays associated with households obtaining knowledge about changes in monetary costs and benefits associated with LIDs and incorporating them into their decisions to install or not to install LIDs. The resulting **Effect of Benefit to Cost Ratio on Adoption from Attracted** is the combined effect of subsidy and stormwater policies. This effect captures that, in the stormwater fee context, many households will need both subsidy and stormwater fee to accrue enough monetary value to close the gap between their willingness to pay for LID and LID cost.

Some households have willingness to pay high enough to balance LID cost without an incentive policy. This fraction of attracted households is driven by willingness to pay alone as a source of monetary value and is captured by the **Effect of WTP on Adoption from Attracted**. The effect is calculated in the same way as the joint effect of stormwater fee and subsidy but based on benefit to cost ratio that has only WTP as a source of monetary value in its numerator (Eq. A.6).

$$BenefittoCostRatiofromWTP = \frac{AnnualizedWTP}{AnnualizedLIDCost} \tag{A.6}$$

In the absence of both incentive policies, the combined effect of all sources of monetary value is comprised entirely of the effect of WTP. In this case, the **Effect of WTP on Adoption from Attracted** is equal to the **Effect of Benefit to Cost Ratio on Adoption from Attracted**. The effect of WTP alone essentially captures the adoption rate typically driven by advertising campaigns. The only condition for realizing this fraction of LID adoption potential is to have a necessary number of households in the stock of **Aware Households**. This target can be achieved by stimulating **Getting Aware Rate**.

The households with the next highest WTP need an additional monetary incentive to balance LID cost, but since their WTP is still high, the stormwater fee is just enough for this purpose. In other words, a certain fraction of attracted households can be motivated to adopt LIDs by stormwater fee alone. This fraction is captured by the **Effect of Stormwater Fee on Adoption from Attracted**, which is calculated in the same way as the joint effect of stormwater fee and subsidy but based on benefit to cost ratio that has only two sources of monetary value in its numerator: **Willingness to Pay** and **Stormwater Fee** Eq. A.7.

$$BenefittoCostRatiofromWTPandSWF = \frac{(AnnualizedWTP + SWF)}{AnnualizedLIDCost} \tag{A.7}$$

The remaining attracted households with lower willingness to pay will need to be provided a subsidy to be motivated to install LID. The fraction of these households in total attracted households is captured by the **Effect of Subsidy on Adoption from Attracted**. This effect is calculated by subtracting **Effect of WTP on Adoption from Attracted** and **Effect of Stormwater Fee on Adoption from Attracted** from the combined effect of all three motivation sources.

Note that in the context of no stormwater fee, the **Effect of Stormwater Fee on Adoption from Attracted** takes on value zero and the combined effect is comprised entirely of the effect of subsidy and WTP. In this case, the **Effect of Subsidy on Adoption from Attracted** is equal to **Effect of Benefit to Cost Ratio on Adoption from Attracted** net of **Effect of WTP on Adoption from Attracted.**

When the stormwater fee is introduced, the effect of stormwater fee alone is positive, yet, by the formulation of benefit to cost ratios is less than the combined effect. In this case, the **Effect of Stormwater Fee on Adoption from Attracted** indicates the fraction of attracted households with higher willingness to pay for who the stormwater fee provides sufficient motivation to adopt LIDs. The **Effect of Subsidy on Adoption from Attracted** then indicates the fraction of attracted households with lower willingness to pay for who the stormwater fee needs to be supplemented by subsidy.

A separate mechanism in the model captures the effect of stormwater fee on households that are not attracted to LIDs and do not have a positive Willingness to Pay for LIDs. For these households, the only benefit of installing LID is to forgo paying the Stormwater Fee. Therefore, the **Effect of Stormwater Fee on Adoption from Non-Attracted Households** is based on the **Stormwater Fee to LID Cost Ratio**. While the stormwater fee is captured by one representative policy value in the model, the amount of fee paid by an individual household varies depending on the assessed contribution of its property to the stormwater runoff. For simplicity, it is assumed that one LID is expected to be installed per household and that by installing an LID, a household is exempt from paying the entire stormwater fee.

The effect of stormwater fee can be formulated in two ways. The first possibility is to follow the same approach as for attracted households and to specify the **Elasticity of Adoption to Stormwater Fee for Non-Attracted**. According to this formulation, when the stormwater fee completely covers LID cost (**Stormwater Fee to LID Cost Ratio** is one), the **Effect of Stormwater Fee on Adoption from Non-Attracted** induces all the non-attracted households to install LID. Since the properties in the region are distributed in terms of their contribution to runoff and, therefore, in terms of the fee to be paid, some households will be induced to install LID even when **Stormwater Fee to LID Cost Ratio** is below one. The **Elasticity of Adoption to Stormwater Fee for Non-Attracted** captures the extent to which the **Stormwater Fee to LID Cost Ratio**, when it is below one, impacts the adoption by non-attracted households. Similar to other economic effects in the model, this effect is capped at one.

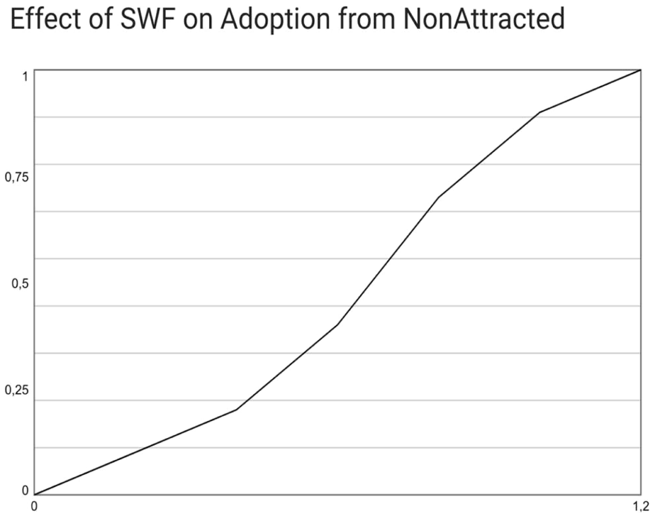


Fig. A6. Table function for Effect of SWT on Adoption from Non-Attracted

Given that the purpose of the model is to test a general response of the LID adoption to reference stormwater fee policy, the table function is constructed based on the qualitative expert assessments. The table function (Fig. A.6) assumes that 90% of non-attracted households will install LIDs when the Stormwater Fee covers LID cost completely (**Stormwater Fee to LID Cost Ratio** is one). It assumes further that the Stormwater Fee must exceed LID Cost by at least 20% (**Stormwater Fee to LID Cost Ratio** is 1.2) to induced all the non-attracted households to install LIDs. When the Stormwater Fee is 40% of LID Cost, 20% of non-attracted households are expected to install LIDs.

A.4. Stormwater Fee Account Sub-Model

To provide the possibility for simulating LID subsidies that are financially limited to the receipts from SWF, the model contains the structure that

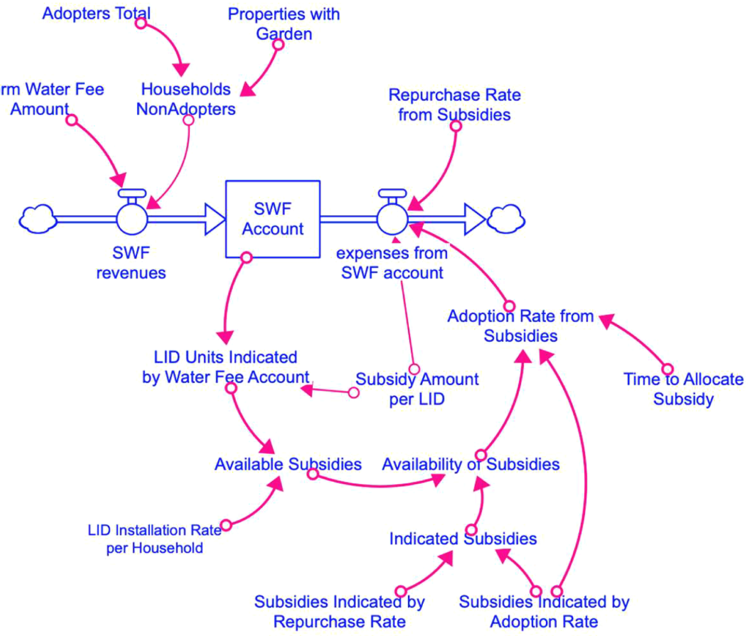


Fig. A7. Simplified stock and flow diagram of SF account sub-model integrates the two policies through monetary flows (Fig. A.7).

The stormwater fee from non-adopters is tracked through the flow of **Stormwater Fee Revenues** and is accumulated in the stock of **Stormwater Fee Account**. The total of LID subsidies paid out to households comprises **Expenses from Stormwater Fee Account** that depletes the Stormwater Fee Account stock. The subsidies that are paid out of stormwater fee account are of two types: subsidies for first-time LID installations are associated with the adoption rate and subsidies for repurchases are associated with indicated repurchase rate. Both types of subsidies are subject to financial availability constraint (**Availability of Subsidies**), calculated as **Available Subsidies** relative to **Indicated Subsidies**. The former is determined by the funds available in Stormwater Fee account, given the policy-determined amount of subsidy and **LID Installation per Household**. The latter is the sum of **Subsidies Indicated by Adoption Rate** and **Subsidies Indicated by Repurchase Rate**.

References

Abebe, Y., Adey, B. T., & Tesfamariam, S. (2021). Sustainable funding strategies for stormwater infrastructure management: A system dynamics model. *Sustainable Cities and Society, 64*, Article 102485. https://doi.org/10.1016/j.scs.2020.102485

Akers, J. F., & Yasué, M. (2019). Motivational Crowding in Payments for Ecosystem Service Schemes a Global Systematic Review. *Conservation & Society, 17*(4), 377–389.

Ando, A. W., & Freitas, L. P. C. (2011). Consumer demand for green stormwater management technology in an urban setting: The case of Chicago rain barrels. *Water Resources Research, 47*(12). https://doi.org/10.1029/2011WR011070

Barton, D., Ring, I., & Rusch, G. (2017). Policy Mixes: Aligning instruments for biodiversity conservation and ecosystem service provision. *Environmental Policy and Governance, 27*, 397–403. https://doi.org/10.1002/eet.1779

Barton, D. N., Venter, Z. S., Sælthun, N. R., Furuseth, I. S., & Seifert-Dähnn, I. (2021). Brukerfinansiert klimaberedskap? En beregningsmodell for overvannsgebyr i Oslo. *Vann, 56*(4).

Cote, S. A., & Wolfe, S. E. (2014). Research Article: Assessing the Social and Economic Barriers to Permeable Surface Utilization for Residential Driveways in Kitchener, Canada. *Environmental Practice, 16*(1), 6–18. https://doi.org/10.1017/S1466046613000641

de Gooyert, V. (2019). Developing dynamic organizational theories; three system dynamics based research strategies. *Quality & Quantity, 53*(2), 653–666. https://doi.org/10.1007/s11135-018-0781-y

Dhakal, K. P., & Chevalier, L. R. (2017). Managing urban stormwater for urban sustainability: Barriers and policy solutions for green infrastructure application. *Journal of Environmental Management, 203*, 171–181. https://doi.org/10.1016/j.jenvman.2017.07.065

Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution, 186*(1), 351–363. https://doi.org/10.1007/s11270-007-9484-z

DNB. (2021). Gjennomsnitts-kurser mot NOK. Retrieved from https://www.dnb.no/bedrift/markets/valuta-renter/valutakurser-og-renter/HistoriskeValutakurser/Hovedvalutaer-mndogor/Hovedvalutaer-mndogor.html.

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A review. *Science of The Total Environment, 607-608*, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

Elliott, R. M., Motzny, A. E., Majd, S., Chavez, F. J. V., Laimer, D., Orlove, B. S., & Culligan, P. J. (2020). Identifying linkages between urban green infrastructure and ecosystem services using an expert opinion methodology. *Ambio, 49*(2), 569–583. https://doi.org/10.1007/s13280-019-01223-9

Ezzine-de-Blas, D., Corbera, E., & Lapeyre, R. (2019). Payments for Environmental Services and Motivation Crowding: Towards a Conceptual Framework. *Ecological Economics, 156*, 434–443. https://doi.org/10.1016/j.ecolecon.2018.07.026

Forrester, J. W. (1970). Urban Dynamics. *IMR; Industrial Management Review (pre-1986), 11*(3), 67.

Furuseth, I. S., Seifert-Dähnn, I., Azhar, S. Q., & Braskerud, B. C. (2018). Overvann i bebygde strøk - tid for å involvere innbyggerne. *Vann, 53*(4).

Gerber, A. (2017). Why do some Food Availability Policies Fail? A Simulation Approach to Understanding Food Production Systems in South-east Africa. *Systems Research and Behavioral Science, 34*(4), 386–400. https://doi.org/10.1002/sres.2462

Goonetilleke, A., Thomas, E., Ginn, S., & Gilbert, D. (2005). Understanding the role of land use in urban stormwater quality management. *Journal of Environmental Management, 74*(1), 31–42. https://doi.org/10.1016/j.jenvman.2004.08.006

Hoover, F.-A., Meerow, S., Grabowski, Z. J., & McPhearson, T. (2021). Environmental justice implications of siting criteria in urban green infrastructure planning. *Journal of Environmental Policy & Planning, 23*(5), 665–682. https://doi.org/10.1080/1523908X.2021.1945916

Horvat, A., Fogliano, V., & Luning, P. A. (2020). Modifying the Bass diffusion model to study adoption of radical new foods–The case of edible insects in the Netherlands. *PLOS ONE, 15*(6), Article e0234538. https://doi.org/10.1371/journal.pone.0234538

Kea, K., Dymond, R., & Campbell, W. (2016). An Analysis of Patterns and Trends in United States Stormwater Utility Systems. *JAWRA Journal of the American Water Resources Association, 52*(6), 1433–1449. https://doi.org/10.1111/1752-1688.12462

Kukadia, J., Lundholm, M., & Russell, I. (2018). Designing Rain Gardens: A Practical Guide. In U. D. London (Ed.), (pp. 43). London.

Lekkerkerk, W. (2020). *Opportunities to make Grefsen stormwater proof: developing adaptation pathways for the Grefsen district in Oslo, Norway*. (Masters of science). Wageningen University.

Li, H., Gao, H., Zhou, Y., Xu, C.-Y., Ortega, MR. Z., & Sælthun, N. R (2020). Usage of SIMWE model to model urban overland flood: a case study in Oslo. *Hydrology Research, 51*(2), 366–380. https://doi.org/10.2166/nh.2020.068

Lieberherr, E., & Green, O. O. (2018). Green Infrastructure through Citizen Stormwater Management: Policy Instruments, Participation and Engagement. *Sustainability, 10*(6). https://doi.org/10.3390/su10062099

Londoño Cadavid, C., & Ando, A. W. (2013). Valuing preferences over stormwater management outcomes including improved hydrologic function. *Water Resources Research, 49*(7), 4114–4125. https://doi.org/10.1002/wrcr.20317

Luan, B., Yin, R., Xu, P., Wang, X., Yang, X., Zhang, L., & Tang, X. (2019). Evaluating Green Stormwater Infrastructure strategies efficiencies in a rapidly urbanizing catchment using SWMM-based TOPSIS. *Journal of Cleaner Production, 223*, 680–691. https://doi.org/10.1016/j.jclepro.2019.03.028

Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., …, & Chang, H. (2018). Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience. *Earth's Future, 6*(12), 1638–1659. https://doi.org/10.1029/2018EF000926

Montalto, F. A., Bartrand, T. A., Waldman, A. M., Travaline, K. A., Loomis, C. H., McAfee, C., …, & Boles, L. M. (2013). Decentralised green infrastructure: the importance of stakeholder behaviour in determining spatial and temporal outcomes. *Structure and Infrastructure Engineering, 9*(12), 1187–1205. https://doi.org/10.1080/15732479.2012.671834

Norges Bank. (2020). Interest rates. Retrieved from https://www.norges-bank.no/en/topics/Statistics/Interest-rates/.

Oslo kommune. (2013). *Strategi for overvannhåndtering i Oslo*.

Oslo kommune. (2018). *Norm for blågrønn faktor i boligprosjekter i Oslo*.

Oslo kommune. (2019). *Handlingsplan for overvannshåndtering i Oslo kommune*.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences, 104*(39), 15181. https://doi.org/10.1073/pnas.0702288104

Rahmandad, H., & Sterman, J. (2008). Heterogeneity and Network Structure in the Dynamics of Diffusion: Comparing Agent-Based and Differential Equation Models. *Management Science, 54*(5), 998–1014. https://doi.org/10.1287/mnsc.1070.0787

Richardson, G. P. (1991). System Dynamics: Simulation for Policy Analysis from a Feedback Perspective. In P. A. Fishwick, & P. A. Luker (Eds.), *Qualitative Simulation Modeling and Analysis* (pp. 144–169). New York, NY: Springer New York.

Ring, I., & Barton, D. (2015a). Economic instruments in policy mixes for biodiversity conservation and ecosystem governance. In J. Martinez-Alier, & R. Muradian (Eds.), *Handbook of Ecological Economics* (pp. 413–449). Cheltenham: Edward Elgar.

Ring, I., & Barton, D. (2015b). Economic instruments in policy mixes for biodiversity conservation and ecosystem governance. In (pp. 413-449).

Schifman, L. A., Herrmann, D. L., Shuster, W. D., Ossola, A., Garmestani, A., & Hopton, M. E. (2017). Situating Green Infrastructure in Context: A Framework for Adaptive Socio-Hydrology in Cities. *Water Resources Research, 53*(12), 10139–10154. https://doi.org/10.1002/2017WR020926

Shaw, B. R. (2011). Predicting Intent to Install a Rain Garden to Protect a Local Lake: An Application of the Theory of Planned Behavior. *Journal of extension, 49*(4), 14–2011. v.2049 no.2014.

Shin, D. W., & McCann, L. (2018). Enhancing Adoption Studies: The Case of Residential Stormwater Management Practices in the Midwest. *Agricultural and Resource Economics Review, 47*(1), 32–65. https://doi.org/10.1017/age.2017.3

Sælthun, N. R., Barton, D. N., & Venter, A. (2021). *REO: estimering av overflateavrenning fra urbane felt. Beregningsgrunnlag for et arealdifferensiert overvannsgebyr*.

Tasca, F. A., Assunção, L. B., & Finotti, A. R. (2018). International experiences in stormwater fee. *Water Science and Technology, 2017*(1), 287–299. https://doi.org/10.2166/wst.2018.112

Thurston, H. W., Taylor, M. A., Shuster, W. D., Roy, A. H., & Morrison, M. A. (2010). Using a reverse auction to promote household level stormwater control. *Environmental Science & Policy, 13*(5), 405–414. https://doi.org/10.1016/j.envsci.2010.03.008

Ureta, J., Motallebi, M., Scaroni, A. E., Lovelace, S., & Ureta, J. C. (2021). Understanding the public's behavior in adopting green stormwater infrastructure. *Sustainable Cities and Society, 69*, Article 102815. https://doi.org/10.1016/j.scs.2021.102815

Zhao, J. Z., Fonseca, C., & Zeerak, R. (2019). Stormwater Utility Fees and Credits: A Funding Strategy for Sustainability. *Sustainability, 11*(7). https://doi.org/10.3390/su11071913

Graphic design: Communication Division, UiB / Print: Skipnes Kommunikasjon AS

uib.no

ISBN: 9788230860755 (print)
9788230842089 (PDF)