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Sustainability-oriented labs in transitions: An empirically grounded typology

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A B S T R A C T

Sustainability is high on the political agenda, with its analytical and practical importance underscored in the field of sustainability transitions. Experiments, arenas, and laboratories are frequently highlighted as real-world objects to investigate sustainability in place. Despite existing lab studies, attempts at comparison at the empirical level remain unconvincing. Here, sustainability remains oversimplified, warranting further investigation to unpack how labs compare in their orientation towards sustainability. This article presents a rigorous and transparent empirically grounded typology, intended to discern ways to engage with sustainability. We outline and elaborate upon six distinctive types entitled: 1) Fix and control, 2) (Re-)Design and optimize, 3) Make and relate, 4) Educate and engage, 5) Empower and govern, and 6) Explore and shape. This study highlights similarities and differences between labs, and across different types. These findings are discussed with reference to ongoing conceptualizations on directionality, providing a fruitful point of departure for ongoing transitions research.

1. Introduction

Sustainability is high on the political agenda, expected to guide multiple and major changes in the coming decades (European Environment Agency, 2017; United Nations, 2015). In 2015, the necessity of fundamental societal change was outlined in the universal, transnational agreement, Agenda 2030, under the headline of “transforming our world”. Together, Agenda 2030 expresses an ambition to grapple with persistent challenges faced by society. As part of this agenda, the term sustainability carries aspirations to guide complex change into the future. Although its importance is underscored in policy (United Nations 2015) and research (Bai et al., 2016; Köhler et al., 2019), sustainability remains a concept capable of polarizing and mobilizing in equal measure, particularly when practiced concretely in context (Jacobs, 1999).

In socio-technical transitions research, the term sustainability is gaining traction, where it is considered to be of analytical and practical importance in systems change (Meadowcroft, 2011; Raven et al., 2017; Williams & Robinson, 2020). Whilst once concerned with systematic investigation into the mechanisms of socio-technical stability and change (Geels, 2002; Schot, 1998), transitions are now underpinned by a multitude of frameworks, perspectives and disciplines (Sovacool & Hess, 2017). As such, sustainability constitutes a broad normative or value-based layer of transitions, establishing purpose as well as direction (Köhler et al., 2019; Meadowcroft, 2009; Smith et al., 2005).

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A growing set of approaches are concerned with the governance of transitions towards sustainability (Grin et al., 2010; Loorbach, 2007; Rotmans et al., 2001). These multi-, inter- and transdisciplinary modes of research (Loorbach et al., 2017) hold that transitions are not only historical processes to be analyzed and described. Rather, coordinated and directed systems changes, based on an understanding of transitional dynamics, are deemed necessary in the present and near future to, for example, avert catastrophic changes expected on a warming planet (Meadowcroft, 2009; Stirling, 2016). The task of transitions governance may therefore be understood as twofold: to 1) orchestrate the governance of complex socio-technical-ecological systems towards sustainability, and to 2) assume a continuously reflexive stance that acknowledges the high ambivalence and uncertainty inherent in transitions. Complementary approaches do bring sustainability to the fore, but remain open to the breadth of such change processes, ranging from rethinking science-society relationships to those in pursuit of socially robust knowledge for a particular issue in context (Biermann et al., 2017; Miller et al., 2014).

Studies on transition experiments, arenas and laboratories (hereafter referred to as sustainability-oriented labs) claim sustainability to be embedded into shared ideas and visions as a basis for experimentation (Loorbach, 2010; Nevens et al., 2013; Torrens et al., 2019; von Wirth et al., 2019; Williams & Doyon, 2020). Some labs, such as Urban Transition Labs (Nevens et al., 2013), Challenge Labs (Larsson & Holmberg, 2018) and Real-World Labs (Schäpke et al., 2018; Bergmann et al., 2021) articulate explicit relations to sustainability. This collection of labs embraces the view that *"there is an inevitably experimental, and experiential, nature to sustainability"* (Robinson, 2004, p. 379).

This study is motivated by the realisation that at the empirical level, sustainability orientations of labs remain oversimplified in comparative studies, warranting further investigation. As part of a recent review of sustainability-oriented labs in real world contexts, McCrory et al. (2020) contend that *"for some, sustainability was treated as an exogenous environmental challenge to be solved through particular technological systems. For others, it was treated as a contingent manifestation of a complex, multi-dimensional phenomenon"* (p. 12). They highlight that there are a multitude of ways that labs describe, interpret, and negotiate what sustainability is. Understandings of sustainability have performative consequences for how labs are designed, evaluated (Cf Williams & Robinson, 2020), and positioned in relation to transitions towards sustainability[1]. Moreover, understanding sustainability cannot be separated from the transition process itself. It guides choice and action, shaping how decisions are made in practice (Meadowcroft, 2011; Stirling, 2009).

Existing attempts to synthesize the relation between lab approaches and sustainability fall short. Sengers et al. (2016) reviewed experiments, but limited sustainability in types of experiments to a level of desired change and success factor. Caniglia et al. (2017) developed "*a definition and a typology for scientific experimentation in sustainability science*" (p. 2), but focused on types of intervention and evidence, rather than understandings of sustainability. Schäpke et al. (2018) provide a comparison of ideal-type labs derived from common conceptualizations, but lack empirical grounding beyond the ideal case. When considering the situated nature of sustainability-oriented labs in relation to broader calls in the sustainability transitions community to take sustainability seriously (Köhler et al., 2019; Susur & Karakaya, 2021), sustainability-oriented labs are apt study objects and real-world initiatives to investigate sustainability in place. In response to the research gap above, we aim to describe and classify the particularities of sustainability in sustainability-oriented labs and discuss their relevance for transitions. We do this by addressing the following research questions:

1 In what ways do sustainability-oriented labs engage with sustainability in practice?
2 What similarities and differences can be observed amongst sustainability-oriented labs in how they engage with sustainability?

Our contribution takes the form of an empirically grounded typology, intended to highlight distinctive ways that labs engage with sustainability, as well as similarities and differences between them. In this article, we also provide a methodologically rigorous and transparent typology-development process, a contribution that is under-articulated or absent in studies with such an output. We maintain a descriptive and classificatory character, ensuring that focus remains on the role of types in making sense of variance surrounding sustainability in labs. The collection of labs within this typology is therefore cross-sectional, moving away from pre-established conceptual labels associated with particular labs on a level of design.

2. Sustainability and transitions

In this section, we point towards the development of sustainability as a concept for approaching, understanding, and guiding transitions. We situate sustainability within the field of sustainability transitions, drawing upon contemporary understandings. We elaborate on the inclusion of sustainability in transitions governance as a relevant form of research and practice, emphasizing directionality in the context of sustainability-oriented labs.

2.1. Sustainability in transitions research–Historical development

There has been an expansion in the use and focus of sustainability in sustainability transitions research. Initially, sustainability was

[1] Living labs serve as an illustrative example here as central contributors to current knowledge on labs in transitions. They informed the development of urban living labs and urban transition labs and appear in debates around urban governance and government by experiment (Bulkeley et al., 2016). Yet, sustainability remains largely absent from many of the aims, methods used, and the effects of living labs. When explicitly touched upon, there is an acknowledgement that sustainability is often reduced to environmental impact (Ståhlbröst, 2012), or a stock that can increase or decrease through efficient management (Hossain et al., 2019).

tangential to analytical-descriptive perspectives on socio-technical change (Geels, 2002; Sengers et al., 2016). Seminal transition studies referred to environmental consequences for socio-technical systems of provision such as mobility, waste, and energy (Geels, 2010). The fixed environmental conditions of a socio-technical system were often used interchangeably with environmental sustainability and motivated from a European/Western perspective. Radical change was claimed to require strong improvements of the eco-efficiency (the societal value/environmental harm creation ratio) of production and consumption systems by a factor between 4-10, suggesting innovation on a level of systems rather than incremental adjustments in existing systems (Elzen et al., 2004; Grin et al., 2010). Within dominant descriptive-analytical frameworks, such as the multi-level perspective, "*the notion of 'niche' was already present in the innovation literature but was not focused on inducing sustainable development*" (Schot & Geels, 2008, p. 399).

Gradually, the emergence of broader conceptions of sustainability began to direct attention towards transformative change at a level of systems and structures (Loorbach et al., 2017). Sustainability acquired a distinctively normative quality, reflecting the desirable features of innovations or technological configurations (Voss & Kemp, 2005). This development was motivated by the view that, as a phenomenon of interest, sustainability transitions were not reducible to socio-technical change of an environmentally friendly nature (Stirling, 2009). Rather, embedded in new approaches was a multifaceted view of change and the role of sustainability that was qualitatively different in nature to those that preceded (Geels, 2019; Loorbach et al., 2017; Scoones et al., 2020).

In transitions research, ambitions now exist to 1) describe and analyze historical processes of socio-technical change assumed to be desirable (Tziva et al., 2019), 2) analytically inform future socio-technical trajectories with an overtly normative stance (Rosenbloom et al., 2018), and 3) simultaneously understand and induce desirable socio-technical change (Loorbach, 2007; Meadowcroft, 2011; Stirling, 2016; Williams & Robinson, 2020).

2.2. Contemporary areas of engaging with sustainability

There is an interpretative flexibility (Waas et al., 2011) when engaging with sustainability. Here, a scale exists between sustainability as a precise, unified, and objective target, or as social, plural, and principled aspiration. On the one hand, techno-managerial forms of top-down governance regularly define sustainability as a quantifiably set threshold or property, subject to accumulation or depletion over time (Dryzek, 2013; Leach et al., 2010). This framing aligns with narratives previously concerned with the depletion and substitutability of capital stocks (Solow, 1995), and recently with bio-physical thresholds mirrored in grand scientific frameworks such as "planetary boundaries" (Rockström et al., 2009). On the other hand, sustainability takes an egalitarian and contextual view of the environmental, social and challenges faced by society in particular places at particular times (Sneddon et al., 2006). Rather than relying on universal indicators and expert views, sustainability here appears as a socially constructed and lived matter of concern, graspable in context through the perspectives of affected actors in their context.

In sustainability transitions the content of sustainability differs according to social, technical, political, environmental, and cultural contexts. This contextuality is illustrated by Raven et al. (2017), who highlight the need to discern competing place-based views of sustainability when appraising different technologies. Additionally, contestedness is a property of the dynamics within transitions towards sustainability (Geels, 2010). It is pervasive in negotiations around content, causes and courses of transitions (Jacobs, 1999; Robinson, 2004). These include (but are not limited to) differences between actors on what sustainability means, problems and solutions that are deemed appropriate, feasible and why, as well as the divergent values between incumbent agendas and disruptive processes (Grin et al., 2010; Rauschmayer et al., 2015).

Place-based attempts to induce, guide and accelerate transitions to sustainability differ in their normative orientation. They resemble what Sneddon et al. (2006) consider a pragmatic middle path; a multi-faceted, dynamic approach that attempts to connect multiple realms of knowledge in a normative, purposeful and learning-oriented manner. Moreover, sustainability is 1) general, with the need to be specified, 2) emergent and interrelated, rather than reduced, 3) subject to "trade-offs", and related to new sustainability gains, and 4) subject to interpretation within an implementation context (cf Waas et al., 2011). Such approaches are common in modes of reflexive governance and transdisciplinarity (Loorbach, 2007; Scholz, 2017), connected to forms of action-oriented knowledge (Caniglia et al., 2021). Here, sustainability operates procedurally as "*the emergent property of a conversation about desired futures that is informed by some understanding of the ecological, social and economic consequences of different choices*" (Robinson, 2004, p. 381).

2.3. Reflexive governance and directionality

Sustainability is tightly linked to the direction and orientation of transitions (Köhler et al., 2019; Schäpke, 2018; Stirling, 2009). It brings an explicit normative base for motivating and guiding transitions into desired pathways (Loorbach et al., 2017; Smith et al., 2005; Vergragt & Quist, 2011) in the presence of uncertainties, across time and space, and in the absence of foresight (Meadowcroft, 2009; Rotmans et al., 2001). Understanding and approaching sustainability challenges therefore require the linking of both long-term thinking (e.g., visions) and short-term actions (Collins, 2020), as well as global perspectives in local, contextualized action.

Current debates highlight the presence of multiple desirable futures compatible with properties of sustainability (Grin et al., 2010). It is suggested that transitions entail collective reflexive learning in the face of uncertainty, with the future as a starting point for filling "sustainable" and "unsustainable" with contextual meaning (Walker & Shove, 2007). This includes the kind of future state deemed desirable, as well as the (transformative) opportunities that may fill the gap between desirability and current unsustainabilities (Holmberg, 1998; Senge, 1990; Stewart, 1993). These considerations characterize some of the wickedness associated with systems change (Andersson, 2014), and resonate with the claim of Meadowcroft (2011) that sustainability transitions are inevitably and explicitly political. Stirling (2008) argues that the notion of direction is often neglected or ignored from many contemporary transition studies. This may be partly due to the challenging nature of establishing directionality in transition processes, given the divergent values that underpin such governance activities. Moreover, the approaches carry uncertainty regarding whether, how, and to what extent research could or should engage with values beyond a level of study object (Kläy et al., 2015; Leach et al., 2010; Potthast, 2015).

In addition to values, the practices of establishing direction can be seen in engagement with visions, issues, options, and uncertainties (Stirling, 2009). Analytically, directionality is commonly elicited through future scenarios or visions. Here sustainability implications are analyzed and discussed with a particular technological configuration in the centre (Geels, 2010; Hojčková et al., 2018; Schippl & Truffer, 2020; Andersson et al., 2021). Labs with an explicit orientation towards sustainability may be understood as “directionally conscious”, regardless of the particular stance they adopt in the here-and-now of purposeful strategic action (Pel et al., 2020). The incorporation of a directional perspective into labs is arguably crucial as reflexive governance processes influence transitional change by strategic action in the present (Voss & Kemp, 2005; Yang et al., 2021). These considerations are of growing concern to those investigating labs and experiments (Loorbach et al., 2017), where “*a characteristic of reflexive governance is that it is concerned with itself – its working within the context of societal development and the specific potential and limitations that result from it. It understands itself to be part of the dynamics which are governed*” (Voss & Kemp, 2005, p. 8).

The way initiatives approach and articulate sustainability has implications for the alternatives that are proposed, as well as their associated feasibility. Directionally-conscious activities include those that engage with sustainability as a latent property, existing and causally unfolding within socio-technical configurations under conditions of uncertainty. Alternatively, sustainability may function as a normative construct to externally guide unfolding systems, extending transitions from historical-causal to futures-oriented and teleological (Fischer & Riechers, 2019; Stirling, 2011). Relatedly, some scholars argue for reflexive governance to facilitate open agreement between engaged actors on normative aims of transitions in a process of directed incrementalism (e.g., sustainability, Frantzeskaki et al., 2012), while others propose ethical yardsticks to assess the normative orientations of processes (Rauschmayer et al., 2015).

We now move towards sustainability-oriented labs as a way of engaging with sustainability challenges and experimenting with alternatives, acknowledging that such initiatives likely range from the incremental to the transitional (Meadowcroft, 2011; Yang et al., 2021). We do this by exploring and classifying how various sustainability-oriented labs unfold in practice as attempts to reflexively govern in place. The diversity of sustainability-oriented labs, when seen as directionally conscious, has implications for the required width and depth of their associated change process (i.e., transition).

3. Typology development methodology

As stated in the introduction of this paper, we aim to classify sustainability-oriented labs in real world contexts according to understandings of, and approaches to, sustainability. This is based on the claim that sustainability remains oversimplified in comparative studies on labs, warranting further investigation to unpack how labs compare in their orientation towards sustainability. We adopt a qualitative case-based approach, with McCrory et al. (2020) as an initial sample of labs in real-world contexts (see Appendix 1 for a list of cases). It is a recent, demarcated, systematic sample of labs with orientations towards sustainability. This review provided a provisional descriptive understanding of a sample that crosscuts disciplines and conceptual labels. However, McCrory et al. (2020) lacks a

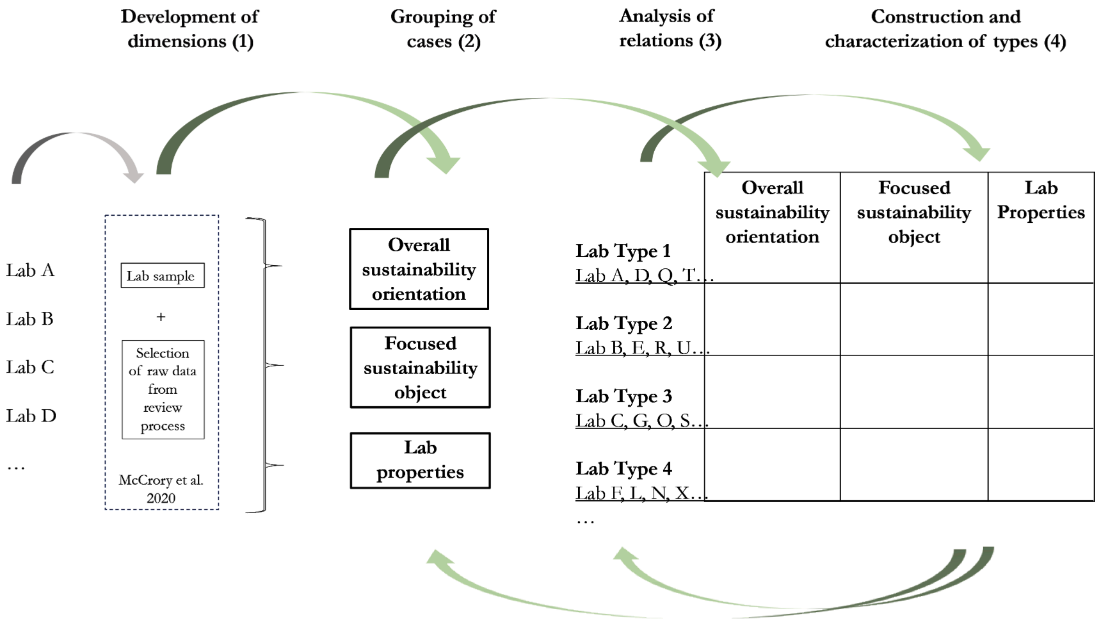

Fig. 1. Schematic of typology process adopted in this study. This figure highlights the movement from empirical labs (far-left) to empirically grounded types (far-right) This progression included the development of dimensions, grouping of cases, and analysis of relations between cases and dimensions, resulting in a type-based classification.

comparative quality, as the level of aggregation in a systematic review analytically conceals detailed understandings of sustainability. Therefore, comparing labs to one another extended beyond the scope of a descriptive and aggregative review. Building on this limitation, we engage in case-based typology development, providing a basis for comparison and analysis.

The research design for this study stems from an empirically grounded typology method proposed by Kluge (2000). Empirically grounded typologies are descriptive and/or classificatory devices, aiming to *"create an arrangement from data reduction that helps us understand complex events, processes, or constructs"* (Suter, 2012, p. 21). Such typologies are designed to explore variance via an integrative process of arrangement. The process of "typologizing" is reflexive, where one assesses and classifies material according to shared descriptors before examining to remain mutually exclusive (Berg & Lune, 2017). Furthermore, it is iterative, with a back and forth between dimensions and cases, as well as regularities and types. Typologizing of this kind occupies a middle ground between deduction and induction, favouring the latter in favour of the empirical-driven nature of the study (Järvensivu & Törnroos, 2010). Kluge suggests a 4-step process comprised of the: 1) development of dimensions, 2) grouping and analysis of cases, 3) analysis of relations and 4) construction and characterization of types. This methodological application is visualized in figure 1, and further elaborated below.

In Step 1, we determined relevant dimensions that would underpin the typology development process. We generated codes from raw data derived from an original sample of McCrory et al. (2020). This provided the basis for a continuous analysis process, where data was disassembled, reassembled and interpreted as a basis for comparison (Yin, 2011). This coding process, where understandings of sustainability emerged from and were refined through classification, generated a provisional set of dimensions[2]: a) **overall sustainability orientation**, b**) focused sustainability object**, and c) a **set of properties of sustainability in labs**. In qualitative studies, such dimensions are expected to emerge during the process of analysis, rather than before or after (Kluge, 2000).

In Step 2, the dimensions from the first step provided an explanatory basic for both describing and grouping lab cases. Each lab was compared to others by searching for patterns at the level of dimension. This ongoing process of dimensionalization (ibid) involved two parallel movements: vertically generating relations across cases, and horizontally updating dimensions according to case descriptions. Provisional groups were established by grouping lab cases according to a combination of attributes within each dimension.

In Step 3, the attribute space of this typology was adjusted with a further analysis of relations between groups. Dimensions were added, combined, or removed according to their explanatory function and in the process of establishing types that are internally coherent and externally distinguishable. The goal of dimensionalization here was to reduce this space to a size no larger than is necessary (Lazarsfeld & Barton, 1951). Thus, descriptions were considered to be mutually exhaustive, whereby new insights could no longer be generated from the empirical cases (Berg & Lune, 2017). At this point, the typology became stable.

Following the development of dimensions (Step 1), case-by-case analysis and grouping (Step 2) and reduction of the attribute space (Step 3), we gradually constructed an empirically grounded typology of labs based on their orientation towards sustainability (Step 4). This typology included the arrangement of dimensions in an attempt to further comprehend the variance among different labs (Suter, 2012). We hold that distinctions of sustainability-oriented labs can be made at two levels: 1) within each type are labs that are sufficiently alike (internal homogeneity) and, 2) similarities and differences can be elicited across different types (external heterogeneity). These levels are essential during the typology process, where cases are compared to each other to ensure internal homogeneity, and where types are compared to each other to ensure external heterogeneity (Kluge 2000).

4. Findings

This section presents our findings, organized as an empirically grounded typology alongside a description of lab types, and accompanied by illustrative lab cases. We then turn to dimensions central in the construction of types, aiming to surface similarities and differences across types.

4.1. Empirically grounded typology of sustainability-oriented labs

Through our analysis, we established six different types of sustainability-oriented labs, entitled: **1) Fix and control, 2) (Re-)Design and optimize, 3) Make and relate, 4) Educate and engage, 5) Empower and govern and 6) Explore and shape**. This typology is detailed in Table 1 and found in full in Appendix A.

4.1.1. Fix and control

Fix and control labs are exemplars whose focus is on eco-efficiency in technical systems. These labs are controlled environments for technological testing, bound at street, district or city level. A sub-group of labs exists on university campuses, where students and staff are energy users. Underpinning all **Fix and control** labs is an assumption that real-time information will increase awareness, thus reducing energy use, and increasing eco-efficiency and cost savings. Processes are driven by experts and focused on implementation.

As empirical context, consider *T-City Friedrichshafen* (Lee et al., 2011; Menny et al., 2018). Unique in the funding attracted (more

[2] Jacobs (1999) claims that layered descriptions are below the level of discourse, at a second level of meaning, where alternative ideas of sustainability co-exist and compete. Similar to Robinson (2008) and Jacobs, (1999), these represent two levels of sustainability relevant for place-based experimentation. Overall sustainability orientation can be viewed as equivalent to substantial (Robinson, 2008) or higher-level sustainability (Jacobs, 1999). Focused sustainability objects and lab properties then reflect the approach of defining sustainability through practice (Robinson, 2008), where "multiple sustainabilities in practice" and competing and alternative definitions exist (Jacobs, 1999).

Table 1
Typology of sustainability-oriented labs – detailed overview (for a complete list of labs cases attributed to types see appendix A).

Dimensions Lab types	Overall sustainability orientation	Focused sustainability object	Properties Constructed as	Ambitions	Foregrounding	Collaboration	Experimentation	Approach to innovation	Nature of process
Fix and control	Technological innovation/ change	Eco-Efficient technical systems	Research/private testbeds at city/ district level	Technical roll-out	Technology in responding to sustainability	Instrumental, citizens as receivers	Controlled, technology-centred experiments	Market-oriented innovation, technology as an end	Implementation and evaluation
	Technological innovation/ change	Eco-Efficient technical systems	Closed, research-driven experiments on uni campus	Technical scaling across buildings	Technology in responding to sustainability	Expert-driven	Controlled, technology-centred experiments	Market-oriented innovation, technology as an end	Implementation and evaluation
(Re-)Design and optimize	Consumption and user involvement in production	Sustainable lifestyles and behaviors	1) real-time controlled, or 2) real-world uncontrolled environment	Changing user-consumption and speed to market	Technology as an enabler	User-focused with hybrid research involvement	User-centred experimenting, prototyping and evaluation	User-driven, with tech challenge as starting point	Design-thinking and ideation techniques
Make and relate	Participation and cultural development	Practices and relations in local communities	Hubs, constructed and bound at the local level	Space in local setting	Communities, practices, and relations	Voluntary and driven by locals	Material and social learning-by-doing	Social innovation	Informal and self-organizing
Educate and engage	Education (for sustainable development)	University-society relations, students as change agents	Educational learning environment	Multi-stakeholder real-world education using transdisciplinary tools	New ways of educating	Student-stakeholder-society; researchers as teachers	Curriculum and learning	Curriculum innovation	Formal and sequenced, bound to curriculum
Empower and govern	Interconnected and multi-facetted (urban) challenges	Governance and urban regeneration	Urban, partnership-based, and inclusive	New ways of governing and organizing around community challenges	Partnerships and governance	Driven by communities/ researchers	Relational and institutional	Technology as means; innovation as participatory	Varying formality
Explore and shape	Complex and contested (social-ecological) systems	Diverse–Systemic and collective interventions in local context	A shared exploration	Grasping complexity	Methods and process	A pre-condition, with researchers as process designers	Systemic, value and challenge-driven	Systemic - opening boundaries within which innovation may occur	Formal, rigorous, and sequenced

than €100m), this lab attempted to strategically realize the smart city at city level. T-City aimed towards improving: (1) quality of life for citizens; (2) locational advantages for businesses; and (3) networking between participating partners (Lee et al., 2011). *T-City* was supported by private interests and organized around learning, mobility, tourism, citizens, business, and health sectors. Citizens provided information to public/private stakeholders through smart city technologies under the label of participation and co-creation. A second example of a **Fix and control** lab is *Pecan Street PSP*, situated at street level (Levenda, 2018). As a top-down approach, smart-grid technologies are foregrounded in the development of a residential area in Austin, Texas. Since 2008, *Pecan Street* exists as a living testbed where technologies are continuously prototyped and tested in households. This lab supports entry to market for immature technical solutions and bounded socio-technical configurations. *Pecan Street* is governed through multiple public and private actors, with numerous private and commercial interests central to its inception and development.

4.1.2. (Re-)Design and optimize

(Re-)Design and optimize labs focus on user experimentation in lifestyles and behaviors. Their interest lies in understanding and influencing individual consumption patterns at the household level. They exist as either permanent research infrastructures for technological testing, or user-innovation methodologies applied in less-controlled environments. **(Re-)Design and optimize** labs are developed to co-create technologies and services through experimentation. User engagement is framed as a win-win, where the testing of technological artefacts in naturalistic environments accelerates their adoption in real-world settings. Participation is regularly limited to trusted networks, stakeholders, or partners, especially during the formative stages of the innovation process.

Home Energy Management Systems (HEMS) (Schwartz et al., 2015) is an example of a **(Re-)Design and optimize** lab. For 3 years from 2009-2012, this lab aimed to reduce household energy use through the development, testing and evaluation of new home information systems. A user innovation testing approach was adopted, with involvement through the sensing, prototyping, and refining of various technological solutions in homes in the North Rhine-Westfhalia region in Germany. *HSB Living Lab* represents a **(Re-)Design and optimize** lab with similar ambitions, but longer-term sources of funding (Andersson & Rahe, 2017; Burbridge et al., 2017). As a flexible built environment to combine interdisciplinary research and permanent living, it emphasises the way in which labs can accommodate more sustainable lifestyles through design. At the level of process, HSB living lab is a research-heavy design intervention, underpinned by an aim to optimize lifestyles through the everyday use of smart technologies in conjunction with the testing of innovative products and services.

4.1.3. Make and relate

Make and relate labs are a collection of civic initiatives that focus on local practices and relations. These labs are locally created, owned, and practiced, often taking the form of makerspaces and do-it-yourself hubs. They are driven by the enthusiasm of voluntary residents, start-ups, and entrepreneurs; interactions are self-organizing and organic, supported by the sharing of resources and knowledge. **Make and relate** labs are therefore fragile in their setup and ability to attract funding. By responding to local challenges and practices, these labs are unique in material, geographical and institutional scope. They experiment with new social and or material constellations in a learning-by-doing fashion.

Trial and Error is an example of a **Make and relate** lab (Hector, 2018). It functions as a space for learning-by-doing through material experimentation. This lab responds to broader concerns about cultural participation, focusing on consumption and production practices in the city of Berlin. It is dependent on self-organized, local involvement and a mix of funding streams. Despite moving location multiple times, *Trial and error* has maintained a focus on sharing of space, resources, and knowledge since 2010. *Blue City Lab* is another example of a **Make and relate** lab (Puerari et al., 2018). Situated in Rotterdam, Netherlands, it emerged as a grassroots urban circular food initiative. The lab reclaimed an abandoned swimming complex in 2015 and attempted to shift its symbolic meaning. Through a combination of network building, increased visibility and local actor commitment, Blue City Lab has developed into an enabling platform for local co-creation processes.

4.1.4. Educate and engage

Educate and engage labs include real-world university approaches to teaching and learning sustainability. These educational environments, located at university campuses, focus on rethinking university-society relations by engaging students in experiential, action-oriented learning. Institutionally, they frequently counter conventional approaches to education for sustainable development that are teacher-centred, lecture-based and disconnected from real-world application. **Educate and engage** labs experiment with new forms of collaboration, material constellations, learning environments and curriculum designs. One shared goal is to support students in engaging with situated challenges, often around a specific thematic or topical focus, where educational curricula are woven into real world situations.

The University of Wisconsin lab (Lindstrom et al., 2015) is one such **Educate and engage** lab. The university exploited a lighting retrofit to recast how students, teachers and staff connect sustainability to campus. It did this with the belief that *"bridging academics and campus operations can equip students with new eyes to view sustainability as a previously unrecognized facet of campus life, allowing them to make connections between the campus and the bigger picture"* (Lindstrom et al., 2015, pg. 67). The staff leveraged organizational restructuring at the university to demonstrate its relevance as a multi-stakeholder collaboration. Additionally, *Seychelles Sustainability Learning Lab* is a real-world learning space where students collaborate around sustainability challenges in a transdisciplinary manner (Krütli et al., 2018). Their curriculum is organized as part of ETH Zurich and continuously linked with real-world waste management challenges in the Seychelles. Through a combination of transdisciplinary research and collaborative problem framing, this lab anchors itself within a local (and international) context as a part of university education.

4.1.5. Empower and govern

Empower and govern labs are partnership-based labs, whose focus is to understand, intervene in, and respond to, multifaceted sustainability challenges often located at "the urban" level. Novel partnerships and organisations commonly emerge from **Empower and govern** labs to enable interactions that were previously challenging. Experimentation is therefore broader than technical, with little emphasis on the commercialisation of products, and services. Rather, labs catalyze relational or institutional forms of experimentation. The former includes organizational experimentation with neighbourhood healthcare provisions, whereas the latter includes land for new relations and ownership.

Mooi Mooier Middelland represents an **Empower and govern** lab (Puerari et al., 2018) with a focus on sustainability as urban regeneration, well-being and quality of life. Between 2016 and 2018, financial investments were made in a district in Rotterdam to co-develop public policy through co-creation processes. Civil society partners and residents were central in founding this lab. They surfaced the institutional need for a lab through resistance to local decision making, creating conditions for partnership-based experimentation (Puerari et al., 2018). Another example of an **Empower and govern** lab is *Manor House PACT* (Astbury & Bulkeley, 2018). This lab was established to respond to cross-cutting urban challenges. It focused on the community level, where local citizens could develop ownership and benefit from their efforts. With experimentation related to housing, growing, green economy and open spaces, Manor House PACT organized efforts in London around two forms of engagement: (1) ways of knowing the local urban areas, and (2) ways to empower, engage and enrol participants in regeneration activities.

4.1.6. Explore and shape

Explore and shape labs are process-based initiatives, whose focus lies in generating a collective and systemic understanding of sustainability in context. These labs begin by orienting around a complex and contested challenge, which may require alternative perspectives and new framings. Inherent in the challenge is a significant degree of uncertainty, and a systemic quality to be engaged with. **Explore and shape** labs develop processes to create this understanding at the level of system, to surface multiple perspectives, and to embrace complexity.

Thus, **Explore and shape labs**, such as *Xochimilco Transformation Lab* (Charli-Joseph et al., 2018), operate in response to traditional or linear approaches to problem solving. As an emergent space for reflection, reframing, and the formation of new pathways for change, this lab frames sustainability as a complex interplay between urbanization and wetland degradation in Xochimilco, Mexico City. Time was dedicated towards agency recognition, systems understandings, and shared values. Stakeholders included civil society, diverse local agricultural producers, municipal actors, and academics. Involved researchers assumed the role of process orchestrators and facilitators. *Zimbabwe Change Lab* (Mukute et al., 2018) is another example of an **Explore and shape** lab. Here, sustainability was focused on the nexus between climate change, water, food, and solidarity. The *Zimbabwe Change Lab* process was structured to support multiple stakeholders in making progress on a problematic situation, by ascending from the abstract to the concrete through an expansive learning cycle. This approach included a collective framing of challenges that should be addressed in the system of activity, as well as measures to surface and resolve contradictions within this system.

4.2. Analytical differences across types

Analytical dimensions were central in developing an empirically grounded typology. They emerged from Step 1 of the typology development process and were refined in an ongoing process of analysis between cases and types. This typology includes the following dimensions: (i) focused sustainability object, and overall sustainability orientations, (ii) construction, ambitions, and foregrounded aspects within labs, (iii) the form of collaboration, (iv) experimentation (v) approach to innovation, and (vi) and the nature of process in labs. These dimensions highlight the similarities, differences, and relations between types.

4.2.1. Sustainability object and orientation

Types display a combination of overall sustainability orientations within which they are embedded, as well as the specific objects of sustainability. *Overall sustainability orientation* outlines broader domains of engagement that establish the significance for sustainability-oriented labs within each type (e.g., social cohesion, climate change). *Focused sustainability object* zooms in on the specific objects (e.g., trust within a neighbourhood) that motivate each lab type. It represents the meaning and substance of sustainability in place. Lab types differ in their overall sustainability orientations, as a matter of technology, consumption, participation, education, the urban or essentially complex challenges. They focus on objects of sustainability from technical eco-efficiency, lifestyles and practices to university-society relations, governance, and the local contexts where definitions emerge out of science-society collaboration. As an example, **Fix and control** labs share a broader area of interest, where technological change is both pursued and prioritized to generally advance sustainability. Within this broad orientation, labs focus on increasing the eco-efficiency of specific technical systems as a key enabler of sustainability. **Make and relate** labs share a broader interest in cultural development and social participation as an overall contribution to sustainability. This broad interest manifests in a focus on local practices and relations.

4.2.2. Lab properties

Lab properties aim to capture the ambitions and qualities in responding to objects of sustainability. These properties also reflect at which stage, by whom and how sustainability has been defined and practiced in the labs.

4.2.2.1. Construction, ambitions, and foregrounded aspects. Types can be compared by exploring how labs are constructed and motivated. These properties offer an insight into what Leach et al. (2010) refer to as a "*politicized, normative perspective on sustainability*" (p. 41). In combination, they illuminate the normative stances taken in labs, as well as the dominant ideas that appear within certain types. Lab types show characteristic differences in these foundational orientations. For example, **(Re-)Design and optimize** labs are constructed as bounded co-creation environments and framed at the level of user with a focus on technological challenges and needs. Technology is foregrounded as an enabler in achieving lab ambitions, often through the iterative testing of products and services. **Fix and control** labs share this emphasis on technology in ambition and foregrounding. In contrast, **Explore and shape** labs are constructed as shared explorations to grasp complexity at the level of systems. Here, methods and processes are foregrounded in these labs. **Educate and engage** labs expose a different orientation as educational learning environments, focusing on new forms of multi-stakeholder, transdisciplinary education.

4.2.2.2. Forms of collaboration. Emphasis is placed on the collaborative qualities of labs and place-based experiments (Ofei-Manu et al., 2018; Puerari et al., 2018). Various models of participation unfold amongst lab types. We can see differences in the ownership of the lab, involvement of actors, and perceived and actual roles of researchers. For example, both **Fix and control** and **(Re-)Design and optimize** labs rely on participation of citizens when developing technologies, products, and services. **Explore and shape** labs, however, integrate technologies, products, and services only if they foster diverse and deep forms of participation, as a normative element of sustainability. A range of stakeholders are invited into the problem space, differing from most other types. As one moves from **Fix and control** towards **Explore and shape**, there lies a spectrum along which singular actor interests are gradually replaced with multiple actor interests and concerns. Some types see the function of participation to be instrumental, to gain acceptance or as central to technology development **(Re-)Design and optimize** labs**)**. For others, participation is central in facilitating social innovation **(Make and relate)**, enabling processes of governance **(Empower and govern)** and education **(Educate and engage),** generating problems, including different voices, and developing individual and collective agency **(Explore and shape)**.

4.2.2.3. Experimentation. Experimentation is broadly understood as a landmark-practice of labs. Labs provide space, resources, and demarcation for experiments to test new ideas, material or social configurations, as potential solutions to sustainability challenges in practice (Caniglia et al., 2017; Bergmann et al., 2021). Experiments can take various forms, and lab types here illustrate both rigorous as well as emergent forms of experimentation. **Fix and control** labs typically host technocentric experiments such as of new smart city technologies and often make use of rigorous, sensor-driven monitoring and evaluation. Conversely, **Make and relate** labs are based on learning-by-doing oriented, emergent, and collaborative experimentation with new material and social constellations. **Explore and shape** labs apply experiments with a systemic and challenge-driven orientation, aiming for transformative impulses to the system in question.

4.2.2.4. Approach to innovation. Similar differences exist in the forms of innovation conceived across lab types. These forms of innovation range from technological **(Fix and control)** and service-centred **(Re-)Design and optimize),** towards innovation that is of a more learning-oriented nature **(Educate and engage).** In addition, certain types include innovation processes that extend significantly beyond products and services, towards alternative forms of governance and collaboration, embedded within complex systems. In contrast to market or technologically-oriented forms of innovation, the latter lab types are predominantly social **(Empower and govern)** or systemic in character **(Explore and shape). Explore and shape** labs extend the boundaries within which innovation occurs; **Empower and govern** labs de-centre the role of technology, which operates as a means within partnership-based approaches.

4.2.2.5. Nature of process. In sustainability-oriented labs, the nature of processes relates to the structuring and sequencing of certain tools in labs. The importance of process has grown alongside the development of prescriptive attempts to intervene in, guide, or steer, sustainability transitions (Loorbach et al., 2017). The salience of process is evident in recent calls for the acceleration of transitions (Markard et al., 2020) and rapid transformations (Ehnert et al., 2018; Grandin et al., 2018). Our typology highlights that lab types introduce, formalise and structure their processes to differing degrees. For example, **Fix and control** labs are implementation and evaluation-focused, displaying little, to no, evidence of engaging at the level of complex systems or futures. Systems are perceived to be technical and complicated, and implementation is largely consigned to technological installation, testing and measurement. **Make and relate** labs are self-organizing at the level of process, reliant on organic interactions across stakeholders with a shared intrinsic motivation. **Explore and shape** labs have rigorous methodological approaches around complex sustainability challenges. Processes and methods are prioritized to foster the engagement of multiple stakeholders. Tools are oriented towards understanding the complexity of present systems, as well as widening the perspective involved in shaping these understandings. Tools for engaging with the future are also present, including envisioning (Frantzeskaki et al., 2018) and future scenarios (Davies et al., 2012). Additionally, there are examples of overarching futures-oriented approaches such as backcasting, seeking to envision sustainable futures followed by systems analysis, intervention development and strategic experimentation (Larsson & Holmberg, 2018).

5. Categorizing labs in sustainability transitions–A discussion

The aim of this study was to describe and classify the particularities of sustainability in sustainability-oriented labs. In fulfilling our research questions, we developed an empirically grounded typology of labs (RQ1) based on their engagement with sustainability. We iteratively analyzed both lab cases and analytical dimensions to generate types that are internally related yet externally separable. The six distinctive types – **1) Fix and control, 2) (Re-)Design and optimize, 3) Make and relate, 4) Educate and engage, 5) Empower and govern, and 6) Explore and shape** – illustrate a plurality of labs according to the objects of sustainability in focus, their overall orientations, as well as their core properties (RQ2). We further discuss our typology in three ways. Firstly, we expand upon the contribution of this typology for research and practice. Secondly, we situate our results within existing debates around directionality in sustainability transitions. Thirdly, we consider the methodological implications of typology development.

5.1. Implications of an empirically grounded typology

Our study and approach was motivated by the view that there are a multitude of ways to describe, interpret and negotiate what sustainability is (Köhler et al., 2019; Raven et al., 2017; Williams & Robinson, 2020). We depart from preliminary insights of McCrory et al. (2020), holding sustainability to be a plural term that differs according to context. The empirically grounded typology in this study carries a twofold contribution to the conversation on labs in the context of sustainability transitions.

Firstly, this typology functions as a heuristic for situating and comparing labs as a rich set of transitions initiatives. Our findings contribute to debates around the content, cause, and courses of sustainability in place-based transition initiatives. With a six-type distinction, it advances understanding of how labs compare to each other in practice. This typology maintains a classificatory quality; by categorizing labs according to their dimensions, we endeavour to provide a structure for surfacing differences and similarities. For example, we elicit similarities between labs such as *T-City* and *Pecan Street* **(Fix and control)**, as well as how they differ to labs such as *Xochimilco T-Lab* **(Explore and shape)**. By delineating types according to key dimensions (RQ2, Section 4.2), our findings highlight how labs might share a commitment to sustainability discursively, yet in practice can contrast vastly in their entry points, understandings of sustainability, processes, and the nature of their collaboration. These differences are not trivial in what they may mean for sustainability transitions. Whether monitoring electricity consumption through smart meters, repairing and remaking socio-technical artefacts, or attempting to identify leverage points for real-world sustainability challenges and experimentation, embedded in each lab are implicit framing choices. These choices affect the boundaries of systems, associated problems, and solution certainty (Voss & Kemp, 2005). Here, this case-based typology supports reflection and comparison beyond abundant, yet often inconsistently used labels. Furthermore, it facilitates the identification and in-depth analytical comparison of analogous approaches, as a basis for cross-case learning and refinement of sustainability-oriented labs (cf Caniglia et al., 2017.).

Secondly, this typology provides a frame for reflexive lab design and praxis. We believe that it is not solely of conceptual relevance, but also of a practical nature. Our study maintains a focus on labs that engage with sustainability, claimed to align with the broad normative character of transitions towards sustainability. We are mindful of the recent urgency associated with transitions towards sustainability, driven by the need to deliberately induce, guide and accelerate systems change at a pace not previously experienced (Ehnert et al., 2018; Markard et al., 2020; Roberts et al., 2018). Given this momentum, the typology offers a practical point of comparison for new and burgeoning labs. Due to the empirically grounded nature of this typology and this methodology (outlined in section 3), we provide a frame that we believe may support stakeholders involved in future lab design, orchestration, or participation, to reflexively explore, adjust, or challenge the direction of change implied by the properties of labs. The typology may support the informed choice of specific lab designs according to present interests and opportunities of engaging with sustainability, not by providing blueprints, but by showing the broad options available (Caniglia et al., 2017). For instance, although **Make and relate** and **(Re-)Design and optimize** labs both relate to consumption practices, they follow different logics and procedural designs of contributing to sustainability, by empowering local sustainability practices or co-designing marketable sustainable products and services. Rather than a dogmatic approach where classification schemes are uncompromising in form, we consider this typology a living classification device, capable of adapting to changing circumstances, with the goal of aiding understanding for a given study (Berg & Lune, 2017). We therefore invite others to adapt, extend and critique the typology developed in this study. In addition, there is a need to test and validate this typology in the context of emerging endeavours. We anticipate that types and descriptions will stretch accordingly, potentially bringing new constellations to accommodate new case understandings or engagements with sustainability.

5.2. Labs and sustainability transitions–Considering directionality

As highlighted above, the contribution from this study is predominantly comparative. We therefore refrain from making strong evaluative judgements regarding the transformative potential or impact of labs. The reason for this is that the implications of a lab, or type, depend on a range of forces, conditions and dynamics that cannot necessarily be captured from within this study and resultant typology. These include, but are not limited to, the enabling or constraining conditions of context (Collins, 2020; Torrens et al., 2019), the socio-spatial characteristics specific to a place (Hansen & Coenen, 2015) and the degree of value divergence and controversy associated with matters of concern (Roberts et al., 2018). We recognize the ongoing challenges with the evaluation of transition initiatives, as well as the efforts being made from within the field to discern transition impacts through evaluative frameworks (Luederitz et al., 2017; Williams & Robinson, 2020). At the same time, there are possible disparities in how labs may influence ongoing processes of change. We revisit the notion of directionality to discuss lab types, exploring markers that may support in understanding labs as directionally-conscious activities.

This typology distinguishes lab types that: assign instrumental **(Fix and control)** or fundamental value **(Make and relate)** to participation; that limit **(Fix and control)** or create methodological space **(Empower and govern; Explore and shape)** for engaging with futures**;** and that conceal **(Fix and control)** or support **(Explore and shape)** the role of framing and reframing in understanding challenges in context. Connected to participation, the work of Stirling (2009) highlights that directionality cannot be neatly distinguished from diversity in transitions. Rather, diversity crosscuts processes of establishing direction in place, implicit in the decisions around values, interests, priorities, and perspectives. Viewing participation as a link between diversity and the development of direction is therefore of importance for three reasons when critically comparing labs: 1) it broadens value bases, 2) it elicits conflicting values in the development of direction, and 3) it produces robust forms of innovation (Rosenberg, 1982). There is a consequential nature to labs concerning the voices that are included, the views and interests that are expressed and the outcomes that are decided upon. This is due to the realization that transitions, within which labs and other initiates are embedded, are matters of justice, as ethical as they are technical (Williams & Doyon, 2019).

In this typology, engagement with the future is most visible in **Explore and shape** labs, and **Empower and govern**, to a lesser extent. **Make and relate** labs engage through processes of prefiguration. Here, they do this through ways of organizing that may attempt to live the future within existing institutional configurations (Törnberg, 2021). Such type distinctions resonate with the view of Feola (2020) that engagement with directionality in place is underpinned by engagement with futures at the level of the process. Explicit, process-based engagement with futures therefore arguably resembles more conscious directional work; implementation-focused activities, such as those present in **Fix and control** labs, methodologically and epistemologically restrict the space for futures and arguably represent weak directional work.

If regarded as the capacity for continuous societal reflection (Meadowcroft, 2009), labs can be viewed as sites where "battles for meaning" (Jacobs, 1999) take place in the framing of sustainability. In our typology, **Fix and control** labs mobilize extensive infrastructures and resources around pre-determined issues, to be eventually "solved" via technological implementation. This can be contrasted with **Explore and shape** labs, where deeper forms of participation underpin their ambitions in developing a collective sense of direction to internally guide lab activities and outcomes. Yang et al. (2021), building on Smith & Raven (2012), highlight two broad directional orientations of relevance. The authors identify both incremental and radical directions, which are dependent on the way in which actors engage in institutional shaping. Incremental directions are shaped by optimization of existing systems and the preservation of existing institutions, whereas radical directions emerge through disruption of existing systems in search of new institutional forms. This plane – between incrementalism and radicalism, highlights an important difference between types that broaden, unfix, and open-up sustainability, and those who narrow, rigidly define and close down conversations about what sustainability is, could be and should be.

The ability to locate and unpack the above markers – such as the relation between diversity and directionality, the role of the future as well as the plane between incrementalism and radicalism – remains an important task for further designing and understanding labs and related transitions initiatives (Loorbach et al., 2017; Stirling, 2009). Furthermore, lab types can function as examples for future dialectical interaction between different strands of sustainability engagement in transitions research, ranging from preconfigurative understandings of green technologies (Tziva et al., 2019), procedural understandings of directed incrementalism (Franzeskaki et al., 2012) to justice-based ethical assessments of transition alternatives (Rauschmayer et al., 2015).

5.3. Methodological reflections

When arriving at empirically grounded types, the methodological considerations of this study should be underlined. Firstly, empirically grounded typologies maintain a reciprocal link to empirics and theory (Kluge, 2000). In practice, this involves managing the movement between abstract constructs and concrete empirics. Rather than an explicit choice before analysis, there is a continuous tension between these two interconnected poles. Overemphasis on former results in development of ideal types (Weber, 1949); stylized abstractions, whose function is to shape theoretically conceivable groups according to constructs. The latter results in inductively grounded classifications, purely reflecting empirical properties (Kluge, 2000). In this study, the use of an empirically grounded typology represents a methodological middle ground in classification, benefitting from, and driven by, engagement between case, construct, and eventual type. Underpinned by an interplay between empirics, cases and theory, the typology aims to function as a heuristic that can represent an empirical phenomenon via classification. Presented types were formed when the analysis showed stabilizing results (see methods). Importantly, this classification is provisionally dependent on the availability of empirical cases, with other lab configurations possible (e.g. Empower and govern labs in rural spaces). As mentioned, critique of the types is invited and further development of types is hoped for and anticipated.

Secondly, within each internal type lies a group of labs that exhibits high diversity and contextual difference. We have classified labs according to currently held knowledge and the dimensions that emerge from typologizing. Therefore *"although typologies may seem like oversimplification of social life, this is actually their beauty. They permit the researcher to present data in an organized and simple fashion, allowing the reader to better understand the explanations offered as interpretation and analysis of the typology scheme*" (Berg & Lune, 2017, p. 127). For example, this typology captures, at least partially, the temporal development of labs through their own dynamic process.

Each lab may have progressed across different types at various stages of maturity. Whilst beyond the scope of this study, we welcome attempts to further trace and account for such developments within and across types.

As an interpretive and analytical act, simplification in typology development can produce anomalies and exceptions. Kluge (2000) highlights that these appear through deviating cases. Whilst limited to a few examples, labs on the boundary of types can be viewed as deviating cases. Examples include *Challenge Lab* (Larsson & Holmberg, 2018), a transformative educational intervention exhibiting Explore and shape-style processes; *Concept Village House* (Burbridge et al., 2017), an experimental district that combines education with planning; *UTL Ghent* (Nevens & Roorda, 2014), a rigorous transition approach that is embedded within an urban setting; and *CISR*, a built environment intervention that blends user-interaction, experimental collaboration and optimized working environments (Coleman & Robinson, 2018). The reason for such blurry cases lies in the complexity of each lab, as well as the level of detail within each type. This is more marked when the phenomenon under study is both diverse and contingent, and when the data at hand is of a qualitative nature.

6. Conclusion and future research

The purpose of this study stems from interest in understanding how labs with explicit orientations towards sustainability can relate and differ in practice. We attempt to take sustainability seriously as a socially motivating entry point, of relevance for the analytical and practical transitional pursuits of labs, transition experiments, and transition arenas. In fulfilling research questions 1 and 2, we derive three core insights:

1 **We identify six different types of sustainability-oriented labs (RQ1)**: 1) Fix and control, 2) (Re-)Design and optimize, 3) Make and relate, 4) Educate and engage, 5) Empower and govern, and 6) Explore and shape. Collectively, these types take the form of an empirically grounded typology.
2 **We organize according to three dimensions of sustainability (RQ2):** Focused sustainability object, overall sustainability orientation, and lab properties.
3 **We discuss labs in relation to notions of directionality in transitions, exploring** implications of different lab types in directionally-conscious action.

This typology functions as a living classification device that may be of relevance for lab design and reflexive governance. It provides a fruitful starting point for understanding sustainability-oriented labs in various contexts, including the implications of six distinctive types. We encourage the further development of these types, as well as extensions and integrated studies that can help to discern potential for transitions towards sustainability, viewed as qualitatively different in nature to previous socio-technical change research.

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CRediT authorship contribution statement

Gavin McCrory: Conceptualization, Methodology, Project administration, Data curation, Writing – original draft, Formal analysis, Writing – original draft, Writing – review & editing. **Johan Holmén:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Niko Schäpke:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **John Holmberg:** Conceptualization, Methodology, Writing – original draft.

Declaration of Competing Interest

None.

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Appendix A

Appendix A

Expanded lab typology

Dimensions / Lab types	Overall sustainability orientation	Focused sustainability object	Properties Constructed as	Ambitions	Foregrounding	Collaboration	Experimentation	Approach to innovation	Nature of process	Illustrative lab case
Fix and control	Technological innovation/ change	Eco-Efficient technical systems	Research/private testbeds at city/ district level	Technical roll-out	Technology in responding to sustainability	Instrumental, citizens as receivers	Controlled, technology-centred experiments	Market-oriented innovation, technology as an end	Implementation and evaluation	T-City Friedrichshafen (Lee et al., 2011; Menny et al., 2018)
	Technological innovation/ change	Eco-Efficient technical systems	Closed, research-driven experiments on uni campus	Technical scaling across buildings	Technology in responding to sustainability	Expert-driven	Controlled, technology-centred experiments	Market-oriented innovation, technology as an end	Implementation and evaluation	University Cape Town (McGibbon et al., 2014)
(Re-)Design and optimize	Consumption and user involvement in production	Sustainable lifestyles and behaviors	1) real-time controlled, or 2) real-world uncontrolled environment	Changing user-consumption and speed to market	Technology as an enabler	User-focused with hybrid research involvement	User-centred experimenting, prototyping and valuation	User-driven, with tech challenge at starting point	Design-thinking and ideation techniques	SustLabNRW (Baedeker et al., 2017)
Make and relate	Participation and cultural development	Practices and relations in local communities	Hubs, constructed and bound at the local level	Space in local setting	Communities, practices, and relations	Voluntary and driven by locals	Material and social learning-by-doing	Social innovation	Informal and self-organizing	Trial and Error (Hector, 2018)
Educate and engage	Education (for sustainable development)	University-society relations, students as change agents	Educational learning environment	Multi-stakeholder real-world education using transdisciplinary tools	New ways of educating	Student-stakeholder-society; researchers as teachers	Curriculum and learning	Curriculum innovation	Formal and sequenced, bound to curriculum	University of Wisconsin Lab (Lindstrom et al., 2015)
Empower and govern	Interconnected and multi-facetted (urban) challenges	Governance and urban regeneration	Urban, partnership-based, and inclusive	New ways of governing and organizing around community challenges	Partnerships and governance	Driven by communities/ researchers	Relational and institutional	Technology as means; innovation as participatory	Varying formality	Mooi Mooier Middelland (Puerari et al., 2018)
Explore and shape	Complex and contested (social-ecological) systems	Diverse–Systemic and collective interventions in local context	A shared exploration	Grasping complexity	Methods and process	A pre-condition, with researchers as process designers	Systemic, value and challenge-driven	Systemic - opening boundaries within which innovation may occur	Formal, rigorous, and sequenced	Xochimilco T-Lab (Charli-Joseph et al., 2018)

Appendix B

Appendix B
Attribution table of empirically grounded typology, according to cases and types. Labs in **bold** indicate **deviating cases**, which overlap with one or more lab types

Lab type	Number of cases	Case attribution
Fix and control	5	Pecan Street, T-City Friedrichshafen, Canton Basel-Stadt, Smart Nasha, Oxford Corridor
	2	Lancaster University Lab, University of Cape Town
(Re-) Design and Optimize	11	HSB Living Lab, SABER, Ubigo, Washing Home Lab, **CISR**, Cahors Living Lab, Berlin Tegel Airport UTR, SustLabRWE Bottrop, Carbon Generalized System of Preferences scheme, HEMS, SubLab North-Rhine Westfalia
Make and relate	5	Blue City Lab, Sewing Cafe Dietenheim, Temporary, Trial and Error, Green Source Environmental Volunteer Association
Educate and engage	4	Seychelles SLL, University of Wisconson, **Challenge Lab**, Lab Course BU Egypt
Empower and govern	16	RWL Mirke, New Light on Alby Hill, Peltosaari together more, Resilience Carnisse, Nexthamburg, RWL Arrenberg, R131, Kenniswerkplaats LeefbareWijken, Marconia, Mooi Mooier Middelland, Zorgvrijstaat, RLL Karditsa, **Concept Village House**, Green Source Environmental Volunteer Association, Manor House PACT, Livewell Yarra
Explore and shape	10	Xochimilco T-Lab, ELL Vietnam, Ghana ELL, Accra Region ELL, Zimbabwe Change Lab, Cat Ba Biosphere Reserve Learning Lab, WINO, RWL Oberbarmen, **UTL Ghent**

Appendix C

Appendix C
List of lab sample included in development of empirically grounded typology

Case names	Description of specific lab (*From source*)	Source text
Concept House Village Lab	"Concept House Village Lab operates as a test-bed for sustainable building technologies and innovative approaches to building retrofitting in the area of Heijplaat in Rotterdam. This Lab is a place where innovative houses, products, and systems are tested together with and by the (temporary) occupants, while experimenting with new approaches of urban development."	Burbridge et al., 2017
Kenniswerkplaats LeefbareWijken	"The lab acts as a knowledge broker between municipality and university and works through the co-creation of knowledge with real-life problems as a starting point."	Puerari et al., 2018
Marconia	"Marconia is a cooperative that is located on a 30,000 m2 old marshalling yard close to a harbour area of Rotterdam."	Puerari et al., 2018
Mooi Mooier Middelland	"An experiment with co-creation between citizens and the municipality, financed with seven million euros for a period of three years."	Puerari et al., 2018
Zorgvrijstaat	Zorgvrijstaat is an association that aims to give health assistance, mainly psychological and psychiatric, based on neighbourhood structures.	Puerari et al., 2018
Berlin Tegel Airport - UTR	"The TU Urban Lab served as a platform for incorporating the user perspective as well as furthering the development of specifications for the spatial energy model through dialogue between all involved stakeholders."	Bahu et al., 2015
Blue City Lab	"Blue City Lab is a Lab located at an iconic site, an abandoned swimming pool in the city of Rotterdam, since 2015. The building now functions as a platform for co-creation, events, and experiments with blue and circular economy initiatives."	Puerari et al., 2018
Cahors Living Lab	In the framework of the ENERPAT Project, an EU Interreg SUDOE has now been funded. Three European cities (Cahors, France; Vittoria, Spain and Porto, Portugal) are working on three different demonstrator buildings in typical ancient centres and will include several Living Labs at the different stages of the project (before, during and after refurbishment) and when the buildings are occupied.	Claude et al., 2017
Canton Basel-Stadt ULL	Since 2001, this lab has united scientists with government and industry practitioners to exploit the Canton Basel-Stadt as a testing arena for emerging built environment, mobility, and energy technologies to advance progress towards a "2,000-Watt Society"	Marvin et al., 2018
Carbon Generalized System of Preferences scheme (GSP)	By policy design, registered citizens in the scheme can trade personalized Carbon Coins on social media platforms, official website or an App. Carbon coins are earned by performing carbon saving behavior and used as vouchers to redeem commercial services and products.	Marvin et al., 2018

(*continued on next page*)

Appendix C (*continued*)

Case names	Description of specific lab (*From source*)	Source text
Cat Ba Biosphere Reserve Learning Lab	"Learning laboratory for sustainable development–The learning laboratory is a process as well as a setting and place in which a group of stakeholders can think and learn together. It is an environment where policy makers, managers, local people, and researchers collaborate and learn together to understand and address complex problems of common interests in a systemic way. The goal is to achieve coherent actions towards sustainable outcomes."	Nguyen, Bosch and Maani, 2011
Centre for Interactive research on Sustainability, Vancouver	"CIRS is a Living Lab on the University of British Columbia (UBC) campus (the term 'regenerative' here is used interchangeably with 'net positive')"	Coleman & Robinson, 2018
Challenge Lab	"In the Challenge Lab, students take on complex societal sustainability challenges in collaboration with others associated with the five regional knowledge clusters in West Sweden"	Larsson & Holmberg. 2018
Change Laboratory Zimbabwe	"Livelihood Security in a Changing Environment–Organic Conservation Agriculture (title of project)"	Mukute et al., 2018
Evolutionary Learning Lab, Haiphong, Vietnam	"The ultimate goal is to achieve coherent actions directed towards sustainable outcomes."	Nguyen, Bosch and Nguyen, 2014
Ghana Evolutionary Learning Lab	"The Evolutionary Learning Lab a methodology for creating informal learning spaces or platforms for managing complex issues"	Banson, Nguyen & Bosch, 2016
Ghent Urban Transition Lab	No definition	Nevens & Roorda, 2014
Greater Accra Region of Ghana	"Uses systems thinking tools, including causal loop diagrams and Bayesian belief network modelling, to develop new structural systems models whereby stakeholders can determine the components and interactions between the structure, conduct and performance (SCP) of the agricultural sector in Ghana"	Banson et al., 2018
Green Office UTM Campus Sustainability	"Living lab framework applied in UTM CS (Universiti Teknologi Malaysia Campus Sustainability). running a green office with student involvement. Hence, campus as–"Responsible and optimized resource management, innovative environmental and ecosystem management, efficient energy management and leadership commitment and campus-wide participation"	Zen et al., 2016
Green Source Environmental Volunteer Association	"The green source houses urban environmental protection activities based on grassroots activism. It operates on new ways of citizen engagement and other grassroots organisations, innovative lobbying techniques and local agenda setting and self-sustained financing."	Marvin et al., 2018
Home Energy Management System (HEMS), North-Rhine Westfhalia	No definition	Schwartz et al., 2015
HSB Living Lab	"A unique international facility on the Chalmers University of Technology campus in Gothenburg, where researchers and societal actors can co-create ideas and initiatives for products and services which will enable sustainable living. "The building is home to 33 residents, as a research and demonstration area. It is equipped with 2,000 sensors measuring, for example, electricity, heating, and water flows as well as the indoor climate, the location of residents inside the building and the weather conditions outside the building."	Andersson & Rahe, 2017; Burbridge et al., 2017
Knowledge Dialogue Northern Black Forest (WiNo)	No definition	Parodi et al., 2018; Pregernig, Rhodius & Winkel, 2018
Lab course, British University of Egypt	"The methodology applied in this pilot course is learning by experimentation in an urban living lab environment"	Dabaieh, El Mahdy & Maguid, 2018
Lancaster University	"Using existing IoT infrastructure to create a campus scale "living laboratory" for promoting energy savings and environmental sustainability."	Bates & Friday, 2017
Livewell Yarra	Livewell Yarra was an urban living lab that enabled community participation to trial experiments in low carbon living with an emphasis on carbon reduction and wellbeing.	Sharp & Salter, 2017
Manor House PACT (Prepare, Adapt, Connect, Thrive)	"Manor House PACT has functioned explicitly as a laboratory for learning, a space within which "trial and error" approaches have been welcomes, with processes of translation, learning, scaling and empowering given space to flourish from the grassroots. At the same time, it has relied on the strategic intervention of national funding, as well as the involvement of municipal actors."	Astbury & Bulkeley, 2018
New light on Alby Hill	"Testing of new LED lighting technologies and co-design of light installations."	Buhr et al., 2016; Menny, Palgan & McCormick, 2018
Nexthamburg	"Creating a virtual and physical space to discuss ideas." Crowdsourcing platform	Menny, Palgan & McCormick, 2018
Oxford corridor, Manchester	"The corridor is a bounded space where a public-private partnership comprised of the City Council, two universities and other large property owners is redeveloping the physical infrastructure and installing monitoring equipment to create a recursive feedback loop intended to facilitate adaptive learning"	Evans & Karvonen, 2014
Pecan Street Project PSP	Pecan street in Mueller area was selected because of the uniformity of the houses and the standards requiring energy efficient buildings. Here, various smart grid and smart home technologies got implemented in an urban neighbourhood as a test bed, monitoring and analysing energy consumption data.	Levenda, 2018
Peltosaari - "Together more"	"Together More" launched processes for co-creating a more attractive neighbourhood that would appeal to residents, visitors, and other stakeholders.	Buhr et al., 2016

(continued on next page)

Appendix C (*continued*)

Case names	Description of specific lab (*From source*)	Source text
Resilience Lab Carnisse	Veerkracht Carnisse (an urban living lab) which is an urban regeneration experiment that focused on empowering local communities and fostering urban sustainability and resilience with a place-making orientation in mind.	Frantzeskaki, van Steenbergen & Stedman, 2018
RLL Karditsa	"Is a “local partnership” that focuses on projects of social interest and environmental protection."	Giannouli et al., 2018
RWL Arrenberg	"Essbarer Arrenberg promotes sustainable, local nutrition for the Arrenberg district through urban farming, food-sharing and restaurant days."	Rose, Schleicher & Maibaum, 2017
RWL Mirke	"In the Mirke RWL, a forum that aims to integrate all relevant civil and municipal stakeholders of district development for the purpose of local well-being transformation is supported"	Rose, Schleicher & Maibaum, 2017; Wanner et al., 2018
RWL Oberbarmen & Wichlinghausen	"The Oberharmen & Wichlinghausen RWL focuses on vacant apartments in this area and aims to create solutions to care for them with the help of tenants who pay below standard but maintain the facility"	Rose, Schleicher & Maibaum, 2017
SABER	In the SABER project, a Living Lab approach was applied and used to support the innovation and development process of the SABER concept. Saber is a product and a service concept aiming to support energy saving in buildings. In this project, the focus was on development of a high-fidelity prototype and of the final system.	Ståhlbröst, 2012
Sewing Cafe Dietenheim	"A living lab research project by the University of Ulm and the University of Applied Arts Reutlingen, initiated for research on textile industries".	Hector, 2018
Seychelles Sustainability learning Lab	"A prototype of a sustainability learning lab (SLL) that we offer in the global South. We use the term “lab” metaphorically in the broad sense of an inspiring and creative learning space where people (e.g., from university, civil society, government) meet, share ideas, and create new knowledge in the context of sustainability."	Krütli, Pohl & Stauffacher, 2018
Smart Nasha	“An Industrial-Academic-Research alliance based on tight policy statutory basis led by a governance organised NGO to perform smart city experiments in special economy district”	Marvin et al., 2018
SustLabRWE Bottrop	“SustLabNRW–A real-life experiment on user-centred development of sustainability innovations around the home, located in the Ruhr area in North Rhine Westphalia (NRW). Part of larger SustLabNWE project.”	Baedeker, Liedtke & Wlefens, 2017
T-City Friedrichshafen	"Building a test bed for smart city technologies and projects"	Lee et al., 2011; Menny, Palgan & McCormick, 2018
Temporary	"Temporary (https://temporary.fi/) was a one-year hybrid project between a culture lab and co-working space in Helsinki, funded through cultural grants given to the two organizers and free for anyone to attend"	Hector, 2018
The Future City Lab	"To achieve such change, the University of Stuttgart established an interdisciplinary team working closely together with institutional practice partners, such as the Municipality of Stuttgart"	Parodi et al., 2018; Pregernig, Rhodius & Winkel, 2018
The SubLab North-Rhine Westfalia	"Consists of a Smart Home Lab, real home environments and showcase apartments in the city of Bottrop"	Burbridge et al., 2017
Trial and Error	"Trial & Error (https://www.trial error.org/) is a Berlin- based culture lab that wants to enable various DIY initiatives by providing a space for them."	Hector, 2018
Ubigo	"Piloting of a travel broker service."	Marvin et al., 2018
University of Cape Town Lab	“A living laboratory to iteratively test database models, with all the challenges of managing people as well as technology.”	McGibbon, Ophoff & Van Belle, 2014
University of Wisconsin	“Lighting upgrades to concepts of sustainability. "UW-Madison campus as a living-learning laboratory where these concepts were brought to life for students"	Lindstrom, Vakilizadeh & Middlecamp, 2015
Urban Transition Lab 131 (R131)	“The lab, and in particular the R131 location Zukunftsraum (Future Space for Sustainability and Science), serves as a networking platform and infrastructure, enabling sustainability experiments arising from the district’s needs and interests.”	Parodi et al., 2018; Singer-Brodowski, Beecroft & Parodi, 2018
Washing home labs	“Home Labs are collaborative, transdisciplinary experiments focusing on disrupting domestic water consumption based on a research led-exploratory living lab approach”	Davies, Doyle and Pape, 2012
Xochimilco T-Lab	"The T-lab aims to be an emergent space for reflection, reframing, and the formation of new pathways for change."	Charli-Joseph et al., 2018

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