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## CATALYSTS FOR URBAN CIRCULARITY

### Reasoning by analogy approach

*Ari Jokinen, Pekka Jokinen, Leena Aarikka-Stenroos, Marika Kokko, Johanna Kujala, Hanna Lehtimäki, and Jere Nieminen*

#### Introduction

In sustainability research, it is important to know the forces that can drive systems and processes to sustainable paths. Research of urban sustainability transitions (Frantzeskaki et al., 2017) studies nonlinear and structural changes to identify pathways and solutions for desirable environmental and societal change. This chapter provides exploratory research to find dynamic features from chemical catalysis that have analogical similarities with urban systems transitioning toward sustainability. The purpose is to recognise the most relevant dynamic similarities for building an analogy model that can be used as a research tool for catalyst-based sustainability research. Thus, the analogy model utilises the well-known source domain, chemical catalysis, to provide new research perspectives to study the less known target domain, urban sustainability transition and its catalytic forces.

This research task has two parts. First, we make a systematic conceptual analysis between chemistry and sustainability transitions to identify the most potential analogies. Second, we conduct an empirical case study focusing on urban circular economy (CE) transition to demonstrate the selected analogies to find out their relevance, empirical credibility, and ability to bring out fruitful insights for sustainability research. The case study site is Hiedanranta, which serves as a district-level urban laboratory for CE transition in Tampere, Finland. In this case study, we focus on key catalysts and two research questions:

- 1 What kind of mechanisms give power to the catalysts promoting urban CE transitions?
- 2 How do the dynamic features of a transitioning urban system explain the systemic effect of catalysts?

The following choices make the case suitable for our empirical analysis. First, the studied key catalysts are policy, technology, and business. They carry the historical development of the idea of CE and frame the state-of-the-art research of CE transitions together with several other factors (e.g., de Jesus & Mendonca, 2018; Geissdoerfer et al., 2017; Kirchherr et al., 2018). While sustainability transitions are complex, multidimensional, multilevel, and multitemporal societal changes and should be studied from multiple perspectives (Frantzeskaki et al., 2017; Rotmans

et al., 2001), the research focusing on these three key catalysts is particularly important in the initiation and acceleration of CE transitions. Second, the system studied is a case of urban regeneration. Urban regeneration is the core generator of sustainability transitions in cities (Wolfram, 2019). The experimental sites of urban regeneration are often conceptualised as urban living labs and can be studied, for instance, as urban CE ecosystems (Aarikka-Stenroos et al., 2021; Engez et al., 2021b). Thus, urban regeneration is a natural host for a multicausal systemic transition from a take-off phase (see Rotmans et al., 2001) towards urban circularity. During the process, the key catalysts of policy, technology, and business mutually shape one another and interact with other trajectories of change (Figure 2.1).

We utilise sustainability transitions research focusing on urban living labs as instigators of sustainability transitions (e.g., Florez Ayala et al., 2022; Frantzeskaki et al., 2017; Fuenfschilling et al., 2019; von Wirth et al., 2019) to recognise dynamic similarities between chemical catalysis and urban transitions. Context is essential: it makes no sense to study catalysts, system change, or urban regeneration without context. For urban sustainability, the defined place is a central contextual factor (Ghavampour & Vale, 2019), and we primarily conceptualise it as an evolving system property (Peris-Blanes et al., 2022).

Our research contributes to sustainability transitions research, particularly the research of urban CE transitions. We provide new insights of CE transitions by uncovering the mechanisms by which catalysts become influential both individually and in concerted ways to run urban systems towards transition. Moreover, our research provides inspiration for researchers to use catalyst-based approaches for sustainability research and to make these approaches more methodological. Thus far, the catalyst as a research term is in metaphoric use, and this use is basically communicative and expressive (Cornelissen & Kafourous, 2008). Accordingly, it evokes the research idea that catalysts for sustainability are increasingly important and points out the direction in which the most fruitful analysis of the catalytic mechanisms can be made. While the metaphoric use can be heuristic and generate promising inspiration for research, the catalyst itself as a research concept remains underdeveloped (for rare exceptions, see e.g., Lee & Waddock, 2021; Tozer et al., 2022). Analogy models provide one possibility to address this gap, and our research is a preliminary effort in that direction.

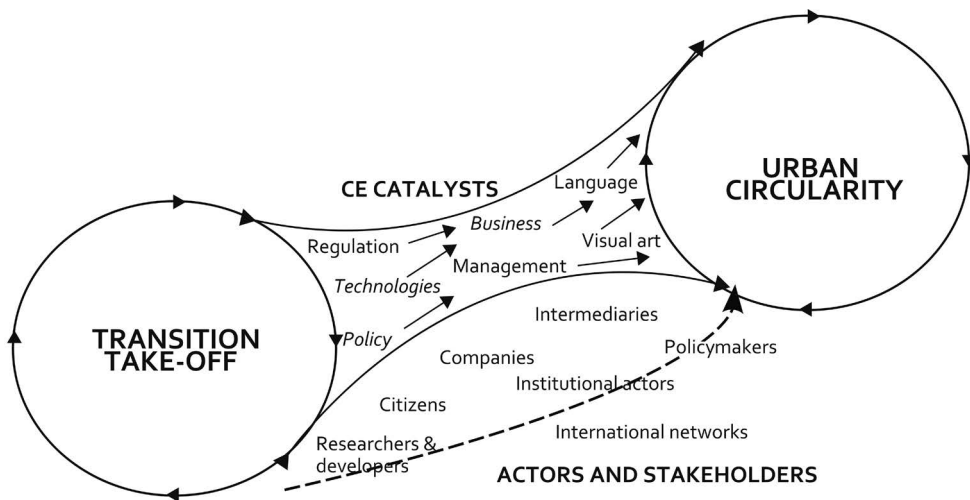


Figure 2.1 Catalysts accelerating the transition to urban circularity.

Source: CICAT2025 research project.

The structure of this chapter is as follows: in the next section, we implement our first research task by creating the theoretical basis of our approach by delving into conceptual identification, selection, and formulation of the most potential analogies between chemical catalysis and sustainability transition. This continues with a subsection in which we give some specifications of the catalytic nature of policy, technology, and business and formulate our assumption of the actualisation of this catalytic power. Then, we describe the empirical case study site of Hiedanranta, where we test the created analogies. In the results section, we uncover the catalytic mechanisms of policy, technology, and business as empirical research findings enabled by the analogy model. In the discussion section, we answer the second research question and present three dynamic features that characterised the transitioning urban system under catalytic forces. In conclusion, these results suggest that the analogy model has potential to be further developed as a research tool for sustainability research.

## **Building up the conceptual basis**

### *Analogies between chemistry and sustainability transition*

Analogies are used in research to make sense of and to produce new knowledge of complicated phenomena. Using analogies is based on the idea that there are certain aspects of the source domain similar with the target domain, which is the object of research. When the source domain is well-known, it is possible to create analogies that may significantly help understanding the unknown target domain. Analogies work if the similarities between the source and target are significant enough and provide fruitful results to increase the understanding of the target (Bailer-Jones, 2009; Haila & Dyke, 2006; Swedberg, 2014). Hence, a detailed mapping of similarities and dissimilarities is a major task in building a good analogy.

Catalysis is one of the most established areas of knowledge in chemistry. We use the chemical system of catalysis as a source domain to create an analogy model to study sustainability transitions, particularly focusing on a district-level urban system as a model case. Since numerous similarities between catalysis and transition can be found by examining these two systems, we made a systematic pre-empirical evaluation (Ketokivi et al., 2017) to identify the most relevant and helpful ones. For this purpose, we utilised our interdisciplinary knowledge, the basic textbook descriptions of chemical catalysis (e.g., Hanefeld & Lefferts, 2018; Nemeš & Longe, 2021; University of California, n.d.), and recent research of sustainability transitions in urban systems. In this iterative process, we examined chemical catalysis as a system of relations and whether these relations also hold in sustainability transition. The aim was to find the most relevant dynamic similarities between the systems because they are most helpful in analysing the real-life systems (Haila & Dyke, 2006).

After the first analogy, we constructed further analogies to get closer to our theoretical idea that system change in both domains depends on the catalytic mechanisms that push the system towards a transition state. ‘Transition state’ is a term in chemistry that describes the final stage of catalysis before the activated reactants convert into products. Throughout the chapter we also use transition state to depict the theoretical culmination point towards which an activated sustainability transition is moving during the phase of acceleration. During acceleration, change accumulates through positive feedback loops and the speed of change increases (Rotmans et al., 2001). By mechanism, we do not refer to its meaning in chemistry where it covers the whole pathway of the reaction that leads to catalysis, but as discernible factors that make the catalyst functional and keep it powerful. This means that the term ‘mechanism’ in our use covers the internal properties,

Table 2.1 Core analogies identified between the systems of chemical catalysis and sustainability transition. Grounds are the basics in catalyst thinking, and warrants refer to deeper system dynamics

<i>Core analogy</i>	<i>Potential value in model building</i>
1 Catalysts are selective and complementary.	Grounds
2 Catalysts increase the interaction of a system's entities towards a transition state.	Warrant
3 Catalytic pathways occur in a stepwise manner and overcome energy barriers.	Warrant
4 Catalytic processes are highly contextual.	Grounds

context, and trajectory of a catalyst. The focus on mechanisms helps us in our first research task to explicate the concept of catalyst but is necessary also for the second task to examine whether an analogy model is helpful in sustainability research primarily since it addresses the dynamic features of the studied system.

The following four analogies proved to be the most relevant to our research task (Table 2.1). For their tentative evaluation, we applied the idea of using the terms ‘grounds’ and ‘warrant’ presented by Ketokivi et al. (2017). We claim that the analogies 1 and 4 are necessary grounds for building an analogous model because they create the basis for catalyst thinking. They also present the novelty value of the catalyst approach, and it seems that they are at least invisibly present when the term ‘catalyst’ is used in metaphoric ways as a research concept. They become more explicit when the first ideas of an analogous model are outlined (e.g., Figure 2.1) but reach more depth only in model building. The analogies 2 and 3 can be considered warrants, because they are likely needed in model building if the goal is to develop a methodological basis for a catalyst approach. The cornerstone of all analogies is the catalyst as defined in chemistry: catalysts are substances that initiate or accelerate the speed of a particular reaction without undergoing a permanent chemical change (Hanefeld & Lefferts, 2018).

*Analogy 1. Catalysts are selective and complementary.* In chemical systems, in addition to a catalyst, the other substances participating in the reaction are called reactants, and they disappear when products appear as the result of the reaction. Chemical catalysts are usually selective, which means that they determine the product of a reaction by accelerating only one of several possible reactions that could occur. Catalysts complement each other because of complex chemical processes that require contribution by several types of catalysts. For a tentative analogy, catalysts in chemistry are selective and complement each other; this corresponds to the studied key catalysts of policy, technology, and business. Key catalysts are qualitatively different triggers, and they need to complement each other to initiate or speed up the system change towards a transition.

*Analogy 2. Catalysts increase the interaction of a system's entities towards a transition state.* Catalysts are needed in both systems to increase the interaction between the basic entities, which are molecules in chemical systems and entities like human actors, artefacts, institutions, and materials in sustainability transitions. In chemical systems, catalysts speed up the reaction by lowering the activation energy to achieve a transition state. The transition state is also changed with a catalyst, that is, the reaction goes through different pathways than without the catalyst. Transition state is an intermediate state during which the reactants are no longer reactants, nor are they yet products (Nemeh & Longe, 2021). While the time spans are different, a chemical system reaching its transition state resembles a sustainability transition approaching its turning point (Rotmans et al., 2001). In both transitions, intensive reconfiguration characterises the acceleration period during which the system becomes ready to change.

*Analogy 3. Catalytic pathways occur in a stepwise manner and overcome energy barriers.* This means that catalysts transform the system by creating stepwise pathways with lower energy demands. Chemical reactions can take place only when collisions between molecules occur with enough energy and proper orientation, and this threshold of energy is called activation energy. In chemical systems, catalysts reduce the activation energy and allow the molecules to achieve the transition state. Accordingly, it is understood in chemistry that catalysts accelerate the chemical reaction by allowing the reaction to proceed via the pathway that has a lower activation energy when compared to an uncatalysed reaction. However, catalysts do not affect the degree to which a reaction progresses but only the kinetics of the reaction. The overall change in free energy is not affected by the catalyst but is determined by the reactants and products. When catalysts decrease the activation energy and thereby accelerate the reaction, they create alternative pathways for the process. The catalytic cycle proceeds through multiple steps, from which the catalyst emerges unchanged that makes the sequence catalytic. A tentative analogy is that catalytic pathways require activation energy in both chemistry and sustainability transitions, and they are also stepwise, to avoid energy barriers of the system. Research focusing on sustainability transitions shows that steps are unavoidable in transition management (Frantzeskaki et al., 2017).

*Analogy 4. Catalytic processes are highly contextual.* Chemical catalysis requires suitable circumstances to speed up the reaction, such as temperature, pressure, energy, the presence of suitable catalyst and reactants and their dispersion and orientation, and the physical state and surface area of reactants. For instance, a higher temperature makes the particles move at a faster speed and collide with each other with more energy, and, therefore, they more likely reach the activation energy threshold needed for a chemical reaction. In systems where more than one reaction is possible, the same reactants can produce different products under different conditions. Because contextual circumstances are the necessary conditions for chemical catalysis to take place, we posit that also the mechanisms of sustainability catalysts are strictly dependent on contextual circumstances when triggering the system towards a transition.

As a result, these four analogies most faithfully respect the core dynamics of chemical catalysis and the CE transitions of urban systems and appreciate the most relevant similarities between the two domains. If this is correct, the four analogies we described can create novel ways to examine CE and other urban sustainability transitions. As we suppose, these analogies can be used for an empirical demonstration to examine how the structure of the chemical catalysis can be mapped onto the structure of the target domain. In the case study demonstration, we use the analogies to analyse the properties of policy, technology, and business as catalysts and how these key catalysts develop and interact in the studied urban system, and the mechanisms through which they run the system towards a sustainability transition. If the analogies fulfil empirical adequacy, factual validity, and structural soundness (Ketokivi et al., 2017), they give positive messages for further research to collect more empirical data for confirming, rejecting, or improving the analogy-based catalytic approach developed in this chapter.

### ***The roles of policy, technology, and business in urban circular transitions***

When we apply the analogies formulated previously to examine a transition towards urban circularity, we make the following assumptions of the key catalysts, causality, and the system under transition. Relationships, interactions, and interdependencies are crucial system properties in different approaches to transitional change. We assume that policy, technology, and business are continuously emerging catalytic triggers for urban change and thus evolve under particular circumstances. As key catalysts, policy, technology, and business are linked to the previously

mentioned system properties and, therefore, can speed up a systemic change towards transition. This assumption of causality is our firsthand methodological guideline for the analysis. The assumption allows for detecting individual catalytic mechanisms and the connections between catalysts, and identifying how the mechanisms and connections accelerate the transition. At the same time, we acknowledge that various forms of causality and uncertainties arise from complexity. We can mostly observe only first-order mechanisms and can only study the most obvious catalysts at this time. The following specifications selected from previous research illustrate the catalytic potential of policy, technology, and business.

Perhaps most notably, policy catalysts refer to political institutions such as specific policies or programs, policy-making procedures, laws, and regulations that accelerate sustainability transitions (Patterson, 2021). Policy catalysts in CE transition are needed for creating momentum and circumstances for this new branch in urban environmental policy. Multi-level policy reforms and decision-making are needed by the EU, member state bodies, and city networks. Important policy issues include regulation, financial factors, and policy integration. City institutions must create policy catalysts to promote CE transition in issues such as local strategies for CE, institutional arrangements, land use policy and planning, public procurement, and new governance models while including stakeholder collaboration and experimentation for CE transition (Predeville et al., 2017; Williams, 2021). Indications of catalyst thinking can be found from policy research. For instance, Johnson et al. (2005) have suggested that a catalytic change in policymaking employs a window of opportunity, is more intense than incremental change, and is also more fundamental in terms of implications. The concept of CE serves as a catalyst in policy processes (Nylén & Jokinen, 2022). Recent work on policy design and policy processes (Capano & Howlett, 2021) demonstrates how policy catalysts ('activators' in their terminology) trigger first- and second-order mechanisms in the studied system. Temporal issues, such as timing, sequence, and duration become important in these processes (Turku et al., 2022, 2023).

Technological evolution includes autopoietic mechanisms that lead to distinct stages in its internal development (Arthur, 2009). In our analysis, we examine these stages on a micro-level and call them as internal catalytic mechanisms of technology. Technology catalysts are crucial in urban regeneration because a fundamental infrastructural change is necessary when creating a new urban district based on CE principles (Dong et al., 2018). From a technological viewpoint, catalysts in CE transition involve, for instance, environmental, process and digital technologies that enable reduction, recycling, and reuse or sharing of resources. Novel technologies often trigger their adaptation and implementation (de Jesus & Mendonca, 2018) due to their enhanced efficiencies compared to technologies currently in use. However, to enable the transition towards a CE, technological solutions must be available, and the market, legislation, and other factors must support the implementation of the technologies (Aarikka-Stenroos et al., 2023). If these requirements are not met, a transition may be hindered. Other barriers may include the scarcity of large-scale demonstration projects and the lack of data on the impacts of technologies. However, according to Kirchherr et al. (2018), CE transition is not mainly hindered by technological barriers but by both cultural and market barriers. The technological catalysts entail innovative interaction between actors, employ material flows in the area, and thus mediate social and cultural aspects of CE transition.

The catalytic nature of business is studied indirectly by examining, for instance, the evolution of business models (e.g., Demil & Lecocq, 2010). In research on innovation ecosystems and business ecosystems, transition is understood as a dynamic change of evolution and extinction in a multi-actor network (Tsujiimoto et al., 2018). In ecosystem literature, attention is paid to entrepreneurs, customers, users, public and private investors, policymakers, and technology actors who contribute as enablers or barriers in the dynamics of ecosystems. In urban CE transitions,

the shift from innovation ecosystems to implementation ecosystems requires a value co-creating exchange between actors operating with different logics of value creation (public and private) (Aarikka-Stenroos & Ritala, 2017). The transition also requires that actors engage in the exploration of and experimentation with novel, value-creating opportunities for the different stakeholders who are involved (Tapaninaho & Heikkinen, 2022) and pay attention to the various interests that stakeholders have regarding the CE transition (Marjamaa et al., 2021). Business catalysts are needed to foster the shift from the current innovation ecosystem towards commercialisation of CE technologies, including profitable business models that can compete with current linear models, and with the practices that mitigate buyer risk when investing in novel technology (Lehtimäki et al., 2020). These catalysts employ the developing interdependences between companies and other actors. Aarikka-Stenroos and Ranta (2019) have distinguished five mechanisms of CE business catalysts: exchange, value creation, competence, business model, and collaboration mechanisms. Many of these mechanisms interact with other catalyst types.

To summarise, we assume that policy, technology, and business are intrinsically catalytic in transitions for urban circularities, but the full actualisation of this potentiality requires suitable circumstances. The context perspective is required to study the actualisation and its mechanisms. The activities of stakeholders, organisations, and institutions are essential contributors in these processes. Like catalysts in chemistry, policy, technology, and business maintain their core identity in transitions.

### **The case study for exploring catalysts in urban regeneration**

In this chapter, we examine urban regeneration by adopting the case study approach. One recognised strength of the case study approach is that it provides for analysis of the interdependencies between actors and processes within their particular social settings. As shown next, we have selected a case that can be interpreted through its characteristics and then further theoretically examined in terms of key catalysts and their mechanisms.

The case we report on is the Hiedanranta district in the city of Tampere (235,000 inhabitants), the second most rapidly growing city in Finland. Hiedanranta is an old industrial area (pulp mill) under brownfield redevelopment for up to 25,000 new inhabitants. As shown in [Figure 2.2](#), this process started in 2014, and the planning of housing for the incoming residents is ongoing at the time of publication. Enabled by the city, an entire series of experimental CE projects took place in the area between 2015 and 2020. Several companies, citizen groups, and research institutions carried out the CE projects in and outside of industrial buildings. These groups for instance, developed urban nutrient circulation by focusing on the following interlinked projects: source-separated sanitation, the cultivation of microalgae, composting, anaerobic digestion, developing methods for using urea for fertilisation, growing strawberries commercially by using LED lights and robots, experimenting with collective urban gardening, and creating waste and sanitation infrastructure for local treatment and nutrient recycling. In addition, pyrolysis and biogas plants were operated for local renewable energy. Another start-up innovation was to use overheated sand as an energy battery; the innovation raised international interest when the pilot was connected to a local district heating grid in Hiedanranta and elsewhere.

The city of Tampere's guiding strategy for the Hiedanranta area is to create a real CE city district in which residents, companies, and researchers are integrated to operate both together and separately. Hiedanranta is marked by its explicit place-based focus, and as an upcoming residential district it differs from isolated CE industrial parks commonly used for the promotion of CE in cities. The project is recognised in international city networks and is of strategic importance

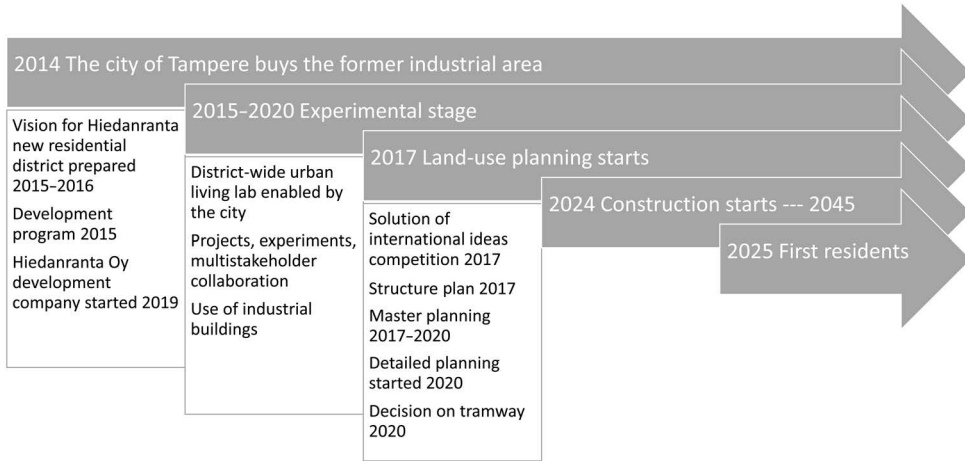


Figure 2.2 The timeline of developing Hiedanranta into a new CE district.

Source: City of Tampere, 2020, modified by the authors.

for the city. As a district-level urban living laboratory, its unique features include the intersection among the city, activist groups, businesses, and research; the generation of collective agency; the coexistence of diverse experiments; and local to transnational exchanges and connections.

The empirical case study work in 2015-2021 was based on interviews, group discussions, site visits, documents, and data created by observational and participatory methods. The primary aim of the analysis was to identify the most relevant socio-technical trajectories supporting CE practices in the area, exemplified by the ‘zero fibre project’ and the ‘nutrient cycle project’ described in the next section. The developmental path of each trajectory was followed and the mechanisms and interactions of key catalysts were specified and analysed. We made a distinction between (a) the policy catalyst creating an agenda and space for transition and keeping its momentum, (b) the technology catalyst necessary for CE innovations, and (c) the business catalyst enabling and boosting the commercial viability of CE innovations, leveraging their implementation and acceptance and thus the move of the CE transition.

While we particularly analysed technology-driven experiments for urban development following CE principles in Hiedanranta, we also considered the citizens, as they participated in many of these experiments (Engez et al., 2021a; Turku et al., 2022, 2023). Moreover, citizens were the primary actors in many other innovative projects in the area, focusing on the reuse of industrial spaces, new consumer cultures like do-it-yourself activities, and ideas for urban planning, including a new superblock implementable in the Hiedanranta area (Laine et al., 2017; Leino & Puumala, 2021; Sjöblom et al., 2021). Overall, the citizen activities significantly characterised the whole experimental stage of urban regeneration and created the spirit and preconditions for the urban CE transition in Hiedanranta.

## Results

In this section, we examine the key catalysts taking place and reinforcing CE principles in the Hiedanranta development area and thus accelerating the CE transition in urban regeneration. While analysing policy, technology, and business as key catalysts each in turn, we aim to uncover

the individual catalytic mechanisms contributing to circular urban development. In the final subsection, we analyse how the catalysts interact and accumulate, and how different catalysing forces amalgamate when enabling circular urban developments. Tables 2.2 and 2.3 summarise the empirical findings and complement the analogy model developed in this chapter.

### ***Policy catalyst***

In Hiedanranta, the policy catalyst emerged from the city's will, power, and leadership to enable a new kind of urban district and to keep momentum in its experimental development. This required a new mode of governance through which the city was able to harness multistakeholder capacities to collaborative urban development. The city's actions were decisive for the development of a CE as the guiding principle for the Hiedanranta district. The city had made a series of single decisions, but these decisions were not the only reason for the push towards the establishment of CE principles in the area. Rather, we found that the catalysing effect was evolving because of three interlinked mechanisms: the policy vision, the sequence of reflective decisions and plans, and space creation. The interaction of these catalytic mechanisms resulted in constant reorganisation of CE principles and activities in the area.

(a) *Policy vision of Hiedanranta.* In the vision, the city has launched the Hiedanranta district as the "City of the Future", referring to a district that supports "*the commercial and industrial progress, as well as the competitive strength, of the whole region, with emphasis on implementing a smart, adaptable and resource-effective city, based on a circular economy*" (City of Tampere, 2017). This vision is highly ambitious, reflecting the global inter-city competition over sustainability issues. Practically, it reflects the match between global policy models of urban sustainability and the local political and institutional receptivity, which always entails modification of global models into local circumstances (McCann, 2011). As a demonstration of global competition, the city has stated emphatically that "*the Hiedanranta district has a strong brand, because it is the first circular economy-based urban district in the world created by companies and citizens*" (City of Tampere 2018a, p. 7). This statement is a culmination of Tampere's urban development in recent years in terms of the adoption of low-carbon and other global sustainability targets in the city's strategy and strategic spatial planning (Jokinen et al., 2018). The strong position of a CE in the vision has its roots in previous works, such as the preliminary development vision for Hiedanranta made by local universities (Lehtovuori et al., 2016).

In 2018, there was an initial CE ecosystem comprising 25 operating actors (companies, associations, communities, entrepreneurs); collaboration with research and education institutes; 39 experimental research and development projects; and numerous events that annually attracted up to 40,000 visitors to the area (City of Tampere, 2018b). In short, typical of urban CE ecosystems, the collective goal was to produce sustainable urban amenities (Aarikka-Stenroos et al., 2021). Citizen activity had increased and developed diversely in the area, including many participatory elements (Laine et al., 2017; Leino & Puumala, 2021). The development in Hiedanranta shows that the vision had a quite strong catalysing power, but also required the support of technology and business catalysts and citizen activities.

(b) *Sequenced policy decisions.* Compared to ordinary urban development and the formal principles in planning and governance, the studied experimental period at Hiedanranta was quite different. The area was a free zone for actions where many formal rules had been loosened to enable attractive access to the area, interaction within and between diverse actor groups, innovation, and identity formation. The formal plans for land use only took place gradually, at the general level, and in the background. However, to support the vision, the city had to sharpen and

Table 2.2 Key catalysts along Hiedanranta urban circular developments from experimenting to implementation in the case of the urban nutrient cycle (P = Policy catalyst, T = Technology catalyst, B = Business catalyst; small letters indicate the catalytic mechanisms of each catalyst as presented in the Results section)

Components of the closed nutrient cycle	<i>Development of urban circularity</i>		
	<b>Experimenting</b> Years 2016–2018	<b>Intensification</b> Years 2018–2019	<b>Implementation</b> Years 2020–2040
Toilet	Stakeholders <i>interact</i> but experiments are mostly developed separately. Source-separating dry toilets were permanently installed for 1,000 people in the Kuivaamo cultural venue.	New <i>relationships</i> between stakeholders, experiments, and key components. New models of source-separating dry toilets were created; four vacuum toilets were installed in Kartano; systematic toilet testing.	Further development towards a system of <i>interdependencies</i> . New toilet solutions potentially implemented in the new residential district. Export potential of companies operating in Hiedanranta.
<i>Catalysts</i> → Technologies	Pabc + Tab Microthermal treatment of solid toilet waste and various treatment methods for urea were experimented to create fertilisers.	Pc + Tab + Bade Microthermal treatment technique (DTS) was formally approved for food production; developing the old and testing new technologies for urea treatment; treatment of black water from vacuum toilets with anaerobic digestion.	Pabc + Tab + Babcde Locally produced humanure products available for growing food and managing recreational green areas in Hiedanranta. Potential markets for DTS technique in Asia and Africa.
<i>Catalysts</i> → Local food production	Pabc + Tab Companies experimenting vertical farming and making soil improvers from biochar; collective gardening experiments by citizens and NGOs.	Tab + Babcde Companies creating innovations and international connections; diversification of collective gardening types; testing urea, humanure, zero fibre and biochar for soil improvement, fertilisation and food production.	Tab + Babcde Diverse communal and commercial food production in Hiedanranta supported by vertical farming techniques, biochar, biowaste recycling, and natural fertilisers and soil improvers. Export potential of participating companies.
<i>Catalysts</i> →	Pabc + Tab + Bcde	Pc + Tabcd + Babcde	Pabc + Tab + Babcde

*Table 2.3* Catalytic mechanisms breaking the system barriers and creating push towards a transition state in Hiedanranta

Key catalyst	<i>Origins of catalytic power</i>		<i>Transitional setting</i>	
	<b>Mechanisms</b>	<b>Functional logics of the mechanisms</b>	<b>Principle of management sensitising to change</b>	<b>Energy barriers to be broken</b>
Policy	Vision Decisions Space creation	Successive mechanisms	Making urban regeneration in experimental ways	Locked-in institutional rules
Technology	Internal development Incomers Experiments Scope widening	Place-induced evolutionary mechanisms	Trialling potential functions of the place	Conventional urban developments
Business	Exchange Value creation Business model Competence Collaboration	Variational fit of necessary mechanisms	Reassembling the ideas of market actions	Linear economy

revise the policy decisions also during the experimental period. The development programme of the area was divided into three functional aspects: spatial land-use planning to create a new residential district based on a CE, Temporary Hiedanranta, and the Hiedanranta Innovation Platform.

The last aspect was crucial for CE development in the area, but also debatable:

Some stakeholders were seeing this [Hiedanranta Innovation Platform] purely as a platform for accelerating business, some others as an area that resolves our sustainability challenges. In some way, these two views lead to quite distinct targets concerning processes, services, and actors they are employing. Then it was precisely outlined [in the meeting of Hiedanranta management group incorporating heads of city departments] that the innovation platform’s main priority is to support the targets we have in planning and implementing this new urban district. This means, above all, that in the innovation platform we then promote collaborative knowledge generation by harnessing diverse expertise, and one aspect of this is that we provide space for companies in the area.

(City official interview, May, 2019)

The three functional aspects of the development programme were helpful for the city because it had to make sequential policy decisions to support the vision, the principles of iterative governance and the modular ideas of urban development in the area. One of these checkpoints took place when the city shifted the name ‘Temporary Hiedanranta’ to ‘Adaptive Hiedanranta’ as a response to tensions between business-led and citizen-oriented urban sustainability (Turku et al., 2022).

(c) *Space creation*. The collaborative achievement of technological development and social innovations for urban circularity requires space for experimentation. Therefore, space creation is one of the catalytic mechanisms that can overcome barriers to circularity. In Hiedanranta, the city as the landowner was flexible in arranging space for projects, citizen groups, and companies

to experiment with CE technologies and generate co-creative knowledge for sustainability. Space creation is a political act, because allowing space for certain kinds of actors and experiments, supporting tests for some solutions instead of others, and allowing certain project continuities are political choices between alternatives and between different interests among stakeholders. Space creation becomes more demanding over time when the CE solutions experimented with will be integrated into urban structures of the new district. The applied infrastructural solutions are new and space demanding in different ways, perhaps socially acceptable only by some parties, and make the city building more complicated. These challenges may be difficult to anticipate during experimentation.

### ***Technology catalyst***

Technological progress is necessary for urban circularity, particularly for transforming infrastructures to support sustainable urban development. As a former industrial area, Hiedanranta lacked most urban infrastructures but provided multifaceted physical environments for developing new kinds of infrastructures with field experiments. Several technological solutions were piloted and implemented in the area, and this was an opportunity for us to examine the contextual emergence and on-site evolution of the technology catalyst.

(a) *Internal mechanisms.* We first found that the catalytic effect depends on the general nature of technology. We use the term ‘internal mechanisms’ to catch the evolution in which each technology fulfils a human purpose and develops intrinsically in combinatorial ways (see Arthur, 2009). In the area, there were some innovative technologies, such as pyrolysis or vertical farming, where the technology and its future possibilities catalysed the further development and implementation of the technology on site. The combinatorial development can be seen in ways some technologies piloted in Hiedanranta were realised due to requirements generated by other technologies. For example, the use of source-separating toilets called for technologies that can be used to recover nutrients from new waste streams (e.g., source-separated urine) and that are rarely used on a large scale.

Second, we found three place-dependent mechanisms that catalysed technology particularly in the context of urban regeneration so that it fulfils the goals of the policy vision of Hiedanranta. The place-dependent mechanisms are discussed next in more detail.

(b) *Novel technologies as contingent incomers.* Since the development of Hiedanranta started, the aim of the city was to attract companies with suitable CE business ideas. The incoming companies integrated their activities with other local actors and old industrial buildings with the aim of promoting CE in the area. As a result, a unique, continuous pyrolysis plant operated in Hiedanranta since 2017 by a company whose aims matched with the city’s plans for decentralised energy production. The pyrolysis plant produced carbon-neutral district heat since 2018, as well as biochar. Thus, while the technology acted as a catalyst to achieve renewable energy production with simultaneous production of biochar to be used locally (e.g., in organic food production), it crucially gained its catalytic power via the place properties. Another company started hydroponic vertical farming for strawberry cultivation in the area. The vertical farming promoted CE as it enabled the local year-round production of food as a part of urban agriculture by utilising LED lamps as the source of light. The first strawberries in the area were harvested in 2018. Both the biochar company and the strawberry company actively developed their own operations within the city’s aim towards a CE, which supported the companies in expanding their operations elsewhere. It can be seen that the technology catalyst is formed by both contingent incomers and coevolution.

(c) *Technologies emerging from core experiments.* Source-separating toilets as a part of the sanitation infrastructure were created in Hiedanranta; this technological advancement has been described as “one the most exciting developments in the area of wastewater treatment” (Larsen et al., 2013, p. xxxi). It responds to urban nutrient wastage. Urine contains approximately 50% phosphorous, 80% nitrogen, and 90% of potassium present in municipal wastewaters in a small volume of 1–1.5 L per person per day (Chang et al., 2013), compared to 150–250 L of wastewater led to the municipal wastewater treatment plant per person per day. Thus, local nutrient recovery from urine provides an interesting opportunity, but it requires the development of novel technologies.

In Hiedanranta, the implementation of source-separating toilets was catalysed by the city’s aim for closed water management cycles, and it further stimulated the piloting of other technologies on site, enabling nutrient recovery from source-separated urine or from the solid stream. Cultivation of microalgae in source-separated urine enables the algal cells to capture nutrients inside their cells, enabling nutrient recovery as a form of microalgal biomass. The cultivation of microalgae was piloted in 2017–2018 in a 2 m<sup>3</sup> raceway pond situated in a greenhouse in Hiedanranta (e.g., Chatterjee et al., 2019). Microthermal treatment of solid materials from the source-separating toilets were piloted since 2016–2017. The end material from the compost unit contains most of the nutrients present in the raw material. The plan to build a city district with specified CE targets has thus catalysed the experimentation with new technologies in ways that are compatible with place properties.

(d) *Technologies widening the scope of CE.* Hiedanranta is located on an old pulp mill site. The wastewaters from the pulp mill were piped to the nearby Lake Näsijärvi for decades, which resulted in the accumulation of circa 1.5 million m<sup>3</sup> of sedimented fibres in the closest bay. Similar areas around the world are often left untreated if there are no identified risks of environmental contamination. To improve the use of the bay area as a recreational area, the city of Tampere started to investigate the possibility of removing and treating the sedimented fibres. Three technologies were piloted for the treatment of sedimented fibres. One of these technologies was biogas process, where the fibres were biologically converted into biogas. This technology was first tested in a laboratory scale (Chatterjee et al., 2018; Kokko et al., 2018) and later piloted in Hiedanranta; this could enable decentralised energy production. In this case, a well-known technology was adapted for a new purpose. Biological conversion of the sedimented fibres into valuable chemicals with novel technological solutions and composting of the sedimented fibres were also piloted. In the pilots, the fibres as the most problematic persistent properties of the Hiedanranta brownfield made place an important constituent of technological development.

### ***Business catalyst***

When examining business aspects and commercial feasibility of circular solutions in circular development of Hiedanranta, we identified five major mechanisms of business catalyst. By ‘business catalyst’ we mean diverse business mechanisms that support commercial and business feasibility of CE transition and thus support diverse stakeholders’ efforts to realise the desired CE shift (see Aarikka-Stenroos & Ranta, 2019). From the Hiedanranta case and among its diverse actors and stakeholders comprising of diverse businesses (e.g., dry toilet company, vertical farming, biochar production) and public actors (e.g., Tampere city), we identified the following catalytic mechanisms.

(a) *Exchange mechanisms* facilitate economic transactions and change between the customers and the solution providers. They were applied by employing pilots and experiments that enabled

risk-reducing trials of technology in the actual use context. For example, regarding source-separated sanitation and zero fibre processing, the city of Tampere enabled companies to experiment with their CE technology businesses in the Hiedanranta area. Such user and customer experiences can be developed into customer references for CE innovations and solutions to nurture further sales of solutions providers and they also serve risk-reducing customer testimonials for further potential public and private customers who seek similar solutions.

(b) *Value creation mechanisms* are formed around factors that enable and particularly enhance value creation between the solution provider and the customer; they boost value or extend what is perceived as valuable. In Hiedanranta, particularly stakeholder and customer involvement in the innovation process from technology development to commercialisation were applied to gather user experiences (e.g., from toilets). User experiences by the end customers were gathered and analysed to improve the customer experience of using circular solutions, and this feedback was then used to improve the value of such solutions. For example, the customer-citizens who visited different events in Hiedanranta provided valuable feedback that enables both developing the dry toilet tech solutions and the concept further, to make it more convenient to use and maintain, and thus creating more value for the involved stakeholders from the circular solution.

(c) *Business model mechanisms* refers to conventional business model elements, namely value propositions, value delivery, and value capture. This means that companies and city and other stakeholders can identify and propose attractive circular solutions (see Ranta et al., 2020), deliver them with their supply chain partners (Aarikka-Stenroos et al., 2022), and capture economic value to make the use and implementation profitable. In Hiedanranta, examples of identified business model mechanisms included the biochar company's attractive value proposal, as it provided not only a sustainable, circular product but also its production and value delivery were sustainable. Thereby its circular value proposition and value delivery also supported Tampere city's and Hiedanranta area's "business model" as those industrial companies' were in the Hiedanranta area. The business models manifested and actualised sustainability and CE, therefore supporting also the city's and the area's value proposition on novel urban district that was sustainable and circular, thereby increasing its value and attractiveness.

(d) *Competence mechanisms* are competencies that enable public and private organisations (both the city and companies) to design businesses, scale them up and grow, and strategize. Important catalysing competencies were to sense, identify, and articulate economic and environmental customer values of the CE solutions and thus induce and increase sales. These were applied, for example, as the Hiedanranta area was branded as a CE district by the city, and many activities were promoted successfully to increase the attractiveness and awareness of the area in the eyes of multiple stakeholders like citizen-inhabitants, businesses, and public actors.

(e) *Collaboration mechanisms* refer to factors and activities relating to how firms, cities, and other stakeholders in the business networks and ecosystems organise and reorganise to enable the circular loops or reduction of resources in a profitable or otherwise value-creating way (Tapani-naho & Heikkinen, 2022). This catalytic mechanism is manifested in Hiedanranta through many means; there has been considerable collaboration between small start-ups and the city. This collaboration has enabled small start-ups to test their technology businesses in the facilities owned by the city (linking collaboration mechanisms to exchange and value creation mechanisms) and the city itself to benefit from novel CE technologies at the Hiedanranta Kuivaamo venue (see Engez et al., 2021b). Furthermore, collaboration mechanisms enabled the city to build alliances, networks, and joint projects with companies, expert organisations, universities, and other stakeholders; such networking capability is often needed for the implementation of a circular business

model (see Aarikka-Stenroos et al., 2022). These collaboration projects served, for example, knowledge-sharing platforms that allowed the city of Tampere and Hiedanranta to process their initial experiences, including lessons learned with other large cities in Finland, and thus advance CEs via public–private interactions.

### ***System changing dynamics of the catalysts***

The three key catalysts analysed previously – policy, technology, and business – were decisive in turning the development of Hiedanranta towards urban circularity. The analogy model helped us to find and specify the catalytic mechanisms that created the transitional impulse. We summarise these findings by demonstrating why the four conceptually formulated analogies between chemistry and sustainability transition were empirically relevant to increase our understanding of the transitional process in this specific case. For this purpose, we utilise the case study findings comprehensively. We also illustrate the results by focusing on the closing of the urban nutrient cycle (Table 2.2), which was one of the main CE goals of Hiedanranta during the studied period. Next, we address each analogy in turn.

#### *Catalysts are selective and complementary*

The key catalysts in Hiedanranta were selective as they induced individual pressure towards a transitional change of the system. At the same time, the catalysts complemented each other, which was the necessary condition for a CE transition in Hiedanranta. Table 2.2 illustrates that during this complementary process, the key catalysts interacted and had a cumulative effect on the transition. The catalytic mechanisms had a double role in this process: they supported selectivity by serving as a specific source of energy for individual catalysts but also complementarity by creating a boundary surface for the interplay between the catalysts. Table 2.2 shows that usually at least two catalysts contributed to a key component of the urban nutrient cycle, and each catalyst had several participating mechanisms, which increase the probability of the interaction. Thus, these mechanisms were prone to support the interplay, but this took place only in particular situations. To summarise, the key catalysts were both selective and complementary at the same time, and these dynamics were dependent on specific mechanisms of each catalyst.

#### *Catalysts increase the interaction of a system's entities towards a transition state*

Through the mechanisms and interplay described previously, the key catalysts made the system's entities move and interact in oriented ways. The entities include human actors, institutions, material and intelligence resources, technical devices, and other system components participating in the constant reorganisation resulting from the catalysing effects. The number and variance of the entities and variance between them were high enough for self-organising processes after catalytic impulses. The mechanisms of catalysts gave iterative, partly contingent direction to these processes so that the main orientation of the system was towards a transition state. We call the emergence of a transition state as a result of *synchronisation* of the key catalysts. The analogy between chemistry and sustainability transition is based on dynamic similarities and applies despite the difference that a transition state in chemistry is instantaneous and very short, whereas in Hiedanranta, the transition state will take years, and possibly remains still partly open-ended. Its emergence is important for the next processes because it uncovers the potential for multiple sustainability paths (Turku et al., 2022, 2023).

*Catalytic pathways occur in a stepwise manner and overcome energy barriers*

The catalyst accelerates the reaction by reducing the required activation energy, and this takes place via a stepwise pathway. The catalyst enables a pathway where the energy demand is lower and thereby the catalyst speeds up the reaction. Our results underpin this analogy by showing that stepwise catalytic mechanisms promoted the transitional process in Hiedanranta. The steps could be perceived, for instance, as events, emerging situations, and change of rhythms. As presented in [Table 2.3](#), each key catalyst pushed the process. First, through its single mechanisms that were essentially place-dependent; these catalyst-specific mechanisms complemented each other when giving activation energy and directionality of the process. Second, as the mechanisms worked as groupings that followed catalyst-specific functional logics and various dynamics, they gave distinct impulses for the process. Accordingly, the policy catalyst provided activation energy through sequential mechanisms that were intrinsically successive starting from the vision, but also shifting order could be recognised; the technology catalyst operated through place-induced evolutionary mechanisms that were both internally and spatially stepwise; and the business catalyst proceeded through a variational fit of necessary mechanisms that became successive at least when the change of business model required a specific order of the other mechanisms.

The functionality, directionality, and sequential order of mechanisms made the policy, technology, and business catalytic by increasing the kinetics of entities in the system. In addition, the mechanisms increased the mutual interaction and the cumulative effect of the catalysts (as described by Analogy 1), and this interaction pushed the whole transitional process into pathways with lower energy demands avoiding barriers. The progress of the whole transitional process was stepwise from experimenting to intensification to implementation because the catalysts took different complementary turns at each stage. A simultaneous part of this same process, and necessary for synchronisation, was that the mechanisms created coincident combinations across catalysts ([Table 2.2](#)). While the key catalysts of policy, technology, and business were parallel, interacting, and mutually reinforcing, they also conditioned each other in rejective ways. All these dynamic features of the transitional process break down the simplified image of linear order, in which policy creates a safety space for experimentation and innovation, technology brings content and form to renovations, and business makes them marketable.

When the key catalysts turned to reinforce each other, they sometimes accelerated change very tangibly. Digi Toilet Systems Oy (DTS) was a company established for experiments in Hiedanranta, and it finally succeeded in creating a usable product from humanure (human faecal material and urine recycled for agricultural purposes via treatment techniques). In 2019, the product gained formal approval from the Finnish Food Authority, a national regulatory body of the Finnish food chain, and now the product can be used as a fertiliser in growing food. This new technology bridges one of the gaps in the urban nutrient cycle.

*Catalytic processes are highly contextual*

The place-dependence characterised both the selectivity and complementarity of the key catalysts in Hiedanranta. As presented in [Table 2.3](#), the mechanisms and how they grouped together made the place an integral part of the transitional process. The policy catalyst gained its power from successive mechanisms enabling the circumstances for a transition in this particular place; the technology catalyst from place-induced evolutionary mechanisms (meaning that the place is mediated into internal mechanisms of technological development by other mechanisms), and the

business catalyst from the variational fit of necessary mechanisms that made the business to accelerate the transition in place-typical ways.

## **Discussion**

In the first part of our research, we used detailed knowledge of chemical catalysis to formulate an analogy model for the examination of forces accelerating sustainability transitions. This pre-examination provided four potential analogies to be empirically demonstrated in a case study analysis of urban generation focusing on a district-level CE transition. The case study confirmed that the dynamic similarities we found between chemical catalysis and sustainability transition are empirically relevant and the analogy model provides new knowledge of the central problems of urban circularity and urban sustainability transitions. For the factual validity, the studied catalysts of policy, technology, and business fulfilled the basic definition of catalyst in chemistry and allowed an empirical analysis of mechanisms through which they initiate and accelerate a transition process. The results suggest that the dynamic similarities between chemical catalysis and sustainability transition can be a fruitful starting point to develop an analogy-based catalyst approach for sustainability research.

The empirical results produced new perspectives to understand the dynamics of urban CE transitions. We summarise the findings as follows: 1) policy, technology, and business are the key catalysts of urban CE transition and their *synchronisation* leads to the emergence of a transition state, 2) synchronisation requires that the key catalysts increase their processual power and mutual interaction through *stepwise catalytic pathways*, increasing the interaction among the system's entities and the directionality of the transition process, but 3) the initial roots of the catalytic force are *place-dependent mechanisms* that actualise the intrinsic but often hidden catalytic potential of the key catalysts (see the section 'The roles of policy, technology, and business in urban circular change') by making them accelerative in a particular context when the circumstances are favourable.

The previously mentioned dynamic terms can generate new conceptual ideas for further studies. Synchronisation is the precondition of the opening of a new phase in system development, transition state, in which several possible sustainability paths become available. The examination of these choices and probabilities of their realisation is important for the future development of urban regeneration, as we have done elsewhere (Engez et al., 2021b; Turku et al., 2022, 2023). Stepwise catalytic pathways refer to events and situations in which catalyst-specific mechanisms function in ways that overcome the energy barriers of the system and thus promote the systemic change (Table 2.3). As these events and situations take place between the intentional actions of human stakeholders and the self-organising system development, they can help transition management to identify critical points and catalytic chains for a change (Tozer et al., 2022). Finally, place-dependent mechanisms are crucial as they challenge the idea that place or land can be stabilised as circumstances where a transition takes place. Rather, when a catalyst reaches its functionality through place, it 'captures' the place for its functional property, as it were. Consequently, when place becomes a constituent of catalytic force, it means that any activity in policy, technology and business is simultaneously placemaking (Ghavampour & Vale, 2019), as well. This finding emphasises place-based conditions of transitions (Peris-Blanes et al., 2022) and suggests that placemaking can be a fruitful analytic lens to study urban CE transition in relation to other ideas of urban sustainability.

The analogy model allows various systems approaches to be adopted in research of sustainability transitions. Since the real-life systems are complex and dominated by nonlinearities, it would be relevant to include system parameters in the analysis, because shifts between variables

and parameters are common during transitional processes (Haila & Dyke, 2006). For instance, the city-owned land in Hiedanranta can turn into a spontaneous catalyst or inhibitor and thereby radically change the system dynamics. Several tensions, including ‘zero fibre problem’, the limited urban space for CE solutions, potential land speculation in urban regeneration, and the dashed hopes of civic groups are creating pressures on land use since our intensive case study period.

We argue that the analogy model developed in this chapter has original value in sustainability research, including research focusing on urban CE transitions. We could illustrate only some aspects of its potential value in this chapter. The analogy model highlights the significance of catalysts in the acceleration of sustainability transitions, gives analytical depth to a catalyst approach, and can lead to novel conceptual insights in research. It also differs from two other models, the ULL and the urban CE ecosystems, that are used to study urban systems under sustainability transitions. An important point is that an analogy model works only situationally. Numerous other case studies with different ideas could be done by utilising the four-part analogy we developed in this chapter. How the analogies work and whether they provide fruitful results depends on the case. Taking this precondition into account, it may be possible to develop the analogy model as a methodological tool for a catalyst-based research approach. As presented by Ketokivi et al. (2017), this requires the accumulation of empirical evidence, critical evaluation of the results from internal and external perspectives, and a frequent emphasis on the model’s empirical adequacy, factual validity, and structural soundness.

## **Conclusions**

The analogy model developed in this chapter to support the catalyst approach in sustainability research utilises the detailed knowledge of catalysis in chemistry. The empirical demonstration of the model in the context of urban CE gave positive results for its potential in the research exploring the possibilities to accelerate sustainability transitions. The chapter encourages researchers to develop the methodological basis of catalyst-based approaches in sustainability research. The findings confirm the view that it would be difficult to understand sustainability transitions without understanding the catalytic force that makes the system change towards a transition state. Vice versa, it would be difficult to uncover how catalysts work without an empirical examination of their contextual functioning in real-life systems. The chapter presents the claim that catalytic mechanisms do not refer to mechanical features of catalysts but dynamically developing contextual properties that make them catalytic. Like in chemistry, while catalysts may have intrinsic catalytic potential, only suitable circumstances can actualise this potential to support the contextual acceleration of a sustainability transition.

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## **Educational content**

Urban sustainability transitions are diverse and are based on interconnected changes and shifting temporal scales. Due to complexity, several research approaches are needed to study them.

Analogy models can be used to study complicated research objects. In this chapter, the dynamic features of chemical catalysis were used to build an analogy model to study urban sustainability transitions and the catalysts accelerating them.

Policy, technology, and business were selected as key catalysts for empirical examination to study the emergence of urban circularities. This choice demonstrates the fact that analogy models are always unique, and they can be constructed for specified research purposes. In the studied case, the basic structure of the analogy model can be further developed by gathering more empirical evidence of its relevance and adequacy in sustainability research.

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