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Research article

"History in a bottle": tipping dynamics in packaging systems – the case of how a bottle reuse system was established and then undone

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Abstract. In this paper, we investigate the initially successful transition from regional bottle reuse for mineral water to a widespread bottle reuse system in Germany, along with its subsequent destabilisation into a single-use recycling paradigm, and what this teaches us about tipping dynamics in packaging systems. Our aim is to understand how tipping happens, focusing on destabilising (of the previous system), tipping (towards the new system), and stabilising (of the new system) dynamics and the agency of business and policy to bring this about. Building on current research on positive tipping points (PTPs), our case study demonstrates opportunities to create an environment for change, the role of reinforcing feedback loops in accelerating sustainable transitions, and successful interventions. However, the case also demonstrates the threat of negative social tipping points: the destabilisation of newly created systems as a result of the emergence of competing technologies, in this case, single-use plastic bottles and recycling. Unsuccessful efforts to stop this included the introduction of a reusable plastic bottle and a failed policy intervention that rushed into a solution that instead accelerated the change it was designed to prevent. We close by examining what lessons can be learned from this historical case for current ongoing efforts to accelerate the transition towards a circular economy. Furthermore, based on our insights, we propose prescriptive steps based on the lens of positive tipping points to operationalise it to support the development of new solutions and interventions.

1 Introduction

> The bottle of history holds the elixir of wisdom, but only those who pour from it cautiously can avoid the intoxication of repeating past mistakes.
> (Doris Kearns Goodwin)

As part of a transformation towards sustainability, resilience, and competitiveness, the shift to a more circular economy (CE) is a widely stated desire on many levels, such as companies and nations (see Barrie et al., 2024, for an overview) and the EC (2020). However, efforts to achieve this have highlighted the systemic nature of the challenge (Raworth, 2017; Webster, 2017), with many barriers, lock-ins, and path dependencies helping to maintain the status quo of the linear take–make–waste paradigm. As such, the transition to circularity seems an appropriate candidate for considering whether there are positive tipping points (PTPs) at which the shift to circular solutions can become self-propelling (Lenton et al., 2022).

History also provides examples of tipping points both towards and away from circularity, and here we examine one such case and ask what lessons can be learned from the rapid rise, persistence, and then quick undoing of the German pool bottle reuse system. This saw the onset of extensive bottle reuse between 1950–1985, with positive tipping happening between 1969–1970, and its persistence for over 15 years (over 90 % market share), followed by a gradual decline and then abrupt negative social tipping to the recycling of single-use plastic bottles in the early 2000s. One aim is to contribute to a better understanding of how to accomplish socio-technical paradigm shifts within relatively short time frames, for which the traditionally reserved time spans are unhelpfully long in the light of the pressing nature of many societal challenges: with estimates ranging from 40–60 years for technological revolutions (Perez, 2011) up to 70 years for transitions to sustainable development and innovation (Grin et al., 2010; Gross et al., 2018).

This apparent contradiction of timescales has sparked interest in how change can be brought about faster. Socio-technical transition research (Geels et al., 2017; Meckling et al., 2015; Rosenbloom et al., 2020; Turnheim and Geels, 2013) has already highlighted the potential for rapid and non-linear system change. One such example is the reduction in coal use from 38 % to 6 % of UK electricity production in a mere 5 years (2012–2017) (Sharpe and Lenton, 2021). Another is Norway's battery EV share of car sales soaring from 20 % to 78 % in 5 years (2017–2022) (Bjerkan et al., 2016).

Knowledge creation to support such rapid change ranges from understanding how agency can be exercised by speeding up product innovation cycles through purposeful learning (Antikainen et al., 2017; Weissbrod and Bocken, 2017) to reconceptualising innovation systems for deliberately accelerating the pace of change (Blomsma et al., 2022) and to understanding how relatively small interventions can lead to big changes through self-propelling feedback (Lenton et al., 2022). Despite these efforts, the dynamics of rapid socio-technical change, path dependency, and how a new stable state is created remain poorly understood. Comprehensive frameworks for empirically evaluating respective enabling conditions and triggers, which include deliberate intervention, have only recently become a focus (Fesenfeld et al., 2022; Lenton et al., 2022; Stadelmann-Steffen et al., 2021; Winkelmann et al., 2022). Unanswered questions remain as to the interaction between systemic conditions and actor agency and learning that causes change to accelerate or *tip* to become self-sustaining. That is, whilst it is widely acknowledged that the transition towards sustainable systems is challenging (Bergek et al., 2023; Haddad et al., 2022; Kemp et al., 2022), it is still poorly understood how strategic action can accelerate the desired change and how the starting conditions influence the change trajectory. As speed alone is insufficient if the new state can be easily undone, with such failures representing a waste of time, resources, and motivation, more insight is also needed into how change can be made to endure (Sharpe and Lenton, 2021).

This knowledge gap complicates current ongoing transitions where a speedy and lasting change is desirable, such as the circularity ambitions set for key sectors within the EU (EU CEAP 2020). The packaging sector is illustrative in this regard: the goals are ambitious in terms of both scope and time. For example, according to the current proposal for the Packaging and Packaging Waste Regulation (PPWR), countries must create deposit return schemes for metal and single-use plastic beverage containers with a 90 % collection rate target by 2029 (European Commission, 2022). However, the knowledge gap means there is little guidance on how to go about these efforts and increase the chance of success. Moreover, there is a risk of repeating previous mistakes, as many so-called new solutions are reinventions or adaptations of solutions that were used in the past but which were ousted by linear alternatives (Blomsma et al., 2022). Think, for the packaging sector, of the current efforts to reintroduce reuse systems for takeaway consumption (Eunomia, 2023). With these and other alternative options for delivering goods and services with varying levels of sustainability, the question of how one system is introduced and is made to persist or perish, and how this interacts with other solutions, is more relevant than ever.

For this reason, in this research, we focus on the interplay of destabilising (of the previous system), tipping (towards the new system), and stabilising dynamics (what makes the new persist or not) and the role of business actors and policymaking in driving change. Our bottle reuse case was chosen because of the quick tipping towards a state that is similar to what is envisioned for current circular economic efforts in the domain of packaging but also because of its subsequent failure to stabilise that state. Our aim with this is to understand how to operationalise the positive tipping points (PTPs) framework as a guiding framework for such ongoing change, what guiding questions to ask, and what risks or pitfalls to be on the lookout for, so that current change efforts may be better designed.

The paper is structured as follows. Section 2 introduces the theoretical framework of temporal tipping dynamics in socio-technical transitions and our research focus. Section 3 outlines our research design. Section 4 presents our findings regarding two tipping episodes (firstly, the successful positive tipping to a widespread reuse system (1950–1985); secondly, the subsequent tipping away from the established reuse system (1985–2010)), followed by recent developments. Section 5 discusses the insights derived from this case study, and Sect. 6 sums up and concludes.

2 Theoretical framework

2.1 Socio-technical transitions and how to influence the pace of change

Sustainability transitions refer to the deliberate and systemic shifts in societies, economies, and industries towards more sustainable and environmentally responsible practices, technologies, and systems (Geels, 2011; Smith et al., 2005; Stirling, 2009). Transitions typically consist of many small, cumulative developments that culminate – over time – in the emergence of a new regime: that is, a different way in which things are done. Although this may be accompanied by phases of acceleration, the overall timeline that is the current consensus among scholars – ranging from 40 to 60 years – is too long to achieve targets such as the SDGs and the Paris

Agreement (Gross et al., 2018; Grin et al., 2010; Kondratieff and Stolper, 1935). To be on track for limiting global warming to "well below 2 °C" requires that the global economy is decarbonised (at least) 5 times faster than it has been (Sharpe, 2023).

Luckily, there is also evidence that change can be accelerated by taking strategic action (Sovacool, 2016; Victor et al., 2019) and that systems can be "tipped": change not only accelerates but becomes self-sustaining (Lenton, 2020). Different tipping mechanisms have been identified that each emphasise a different aspect of change. A well-known example of this is the diffusion of innovations theory (Rogers, 1962), or diffusion for short. This theory puts the spotlight on the user and states that a critical mass threshold exists that, when reached, makes other users more likely to adopt an innovation. An alternative model (Arthur, 1989) identifies how increasing returns, path dependency, and feedback loops create conditions where systems evolve in a self-reinforcing manner. Arthur demonstrates these effects for technology: technologies that achieve early adoption benefit from increasing returns, leading to "lock-in", despite superior options being available. Another example is the coordination game by Kandori et al. (1993), who describe how network effects lead to situations where increasing numbers of individuals adhere to a norm or behaviour and gain more by adhering to it than by deviating from it, thereby amplifying the positive effects and attractiveness of coordination. In these models, the initial change creates the conditions for amplification, which then leads to significant and often accelerating change.

Although such tipping mechanisms have explanatory capacity, their synthesis and integration into action-oriented management frameworks is still limited (Geels and Ayoub, 2023). The actions prescribed by transitions management (Loorbach, 2007), strategic niche management (Schot and Geels, 2008), and the technological innovation systems framework (Hekkert et al., 2007), for example, are (in our view) for a large part inspired by and derived from diffusion. To better understand how to bring about tipping, a richer and more comprehensive picture is needed as to the differing roles of these different dynamics, how they interact, what concrete interventions trigger them, the influence of different starting conditions, and what barriers and pitfalls exist. Whilst the first steps towards synthesis have further refined the interacting dynamics between techno-economic developments and core actor groups (Geels and Ayoub, 2023; Lenton et al., 2022), more empirical work is needed. For this reason, we undertake a historical case study looking at the agency exercised by business and policy, using one of the most comprehensive synthesis efforts of tipping mechanisms to date: the positive tipping points (PTPs) framework.

2.2 The positive tipping points framework

The positive tipping points (PTPs) framework (FOLU and GSI, 2021; Lenton, 2020; Lenton et al., 2022; Sharpe and Lenton, 2021) is the antonym of the negative climate tipping points that are driving and accelerating climate change (Lenton et al., 2019). Starting from systems thinking and Meadows' "leverage points" framework (Abson et al., 2017; Meadows, 1999), it has evolved into a framework that synthesises different tipping point models alongside interventions for different actors to trigger tipping dynamics (FOLU and GSI, 2021; Lenton et al., 2022). The PTPs framework highlights the importance of creating enabling conditions (e.g. price reductions or shifts in social norms) before a small perturbation can trigger a socio-technical tipping point. For example, the policy-supported deployment of renewable power in the UK created enabling conditions for a positive tipping point away from coal power that was triggered by a small perturbation in the "floor" price of carbon emissions imposed on the power sector (Sharpe and Lenton, 2021).

PTPs provide insight into how a system can be deliberately tipped in a more desirable direction (Lenton et al., 2022). Specific actions, behaviours, or interventions can (separately or combined) reach a critical threshold (Dakos et al., 2015; Kopp et al., 2016) that triggers transformative system-wide change (Otto et al., 2020). That is, a system "tips" from one state to another through making the previous state unstable, after which strong positive (reinforcing) feedback mechanisms take over to amplify the effects of the small change(s) resulting (in a relatively short time frame) in a fundamental shift towards a qualitatively different quasi-stable state or new dynamic equilibrium. Once initiated, these dynamics can be abrupt and sometimes, but not always, be difficult to reverse; see Fig. 1 (top). In this figure, the depth of the valley and the height of the hill represent the stability of the current system and, consequently, the difficulty to bring about a new system state. Note that this diagram is a state-space diagram: it represents the transition from one state to the next and is not indicative of time or desirability, and the direction can be from left to right or vice versa.

In some cases, tipping in one domain may trigger a further chain reaction of change across sectors and scales, in a *positive tipping cascade* (Geels and Ayoub, 2023; Sharpe and Lenton, 2021). Lenton et al. (2022) advance the operationalisation of this framework in a non-exhaustive list that links system conditions, reinforcing feedback mechanisms and interventions or actions that can be taken to trigger PTPs, based on FOLU and GSI (2021) and further elaborated in GSI (2023). Figure 1 (bottom) represents a synthesis of these efforts.

Thus far, the framework has been applied to energy, mobility, food, and land use systems, with a focus on guiding actors in triggering tipping points across a limited number of transitions (FOLU and GSI, 2021; Meldrum et al., 2023; Lenton et al., 2022). This has provided initial insights into the adoption of renewable energy and electric vehicles, developing a socio-technical transition perspective that highlights significant actor reorientations (Sharpe and Lenton, 2021; Geels and Ayoub, 2023) and policy changes that prioritise environmental protection, providing a procedural synthesis to streamline the identification and coordination of agent capacities required to implement transformative solutions (Tàbara et al., 2018; Fesenfeld et al., 2022). Other previous work, through expert elicitation, also identified potential social tipping interventions in subsystems such as human settlements, financial markets, and education (Otto et al., 2020). Here, social tipping elements (STEs) represent specific subdomains of the planetary social–economic system where disruptive changes can lead to a fast reduction in greenhouse gas emissions, making them a crucial component of positive tipping points in the transition to carbon-neutral societies.

In this current research, we take up two areas for further development for the PTPs framework with the aim to operationalise it for better understanding – and steering of – current developments: (1) a focus on the set of destabilising, tipping, and stabilising dynamics in order to create insights into path dependency and (2) a more explicit focus on the role of and actions taken by business and policymakers in tipping dynamics. More information on these is given in the following sections.

2.3 Destabilising, tipping, and stabilising dynamics: on path dependency and (in)stability

There are three phases of system dynamics surrounding a positive tipping point: destabilising of the original system state, the tipping itself, and stabilising a new system state. The overall change happens because of "forcing" of the system, which can come from deliberate action and/or inadvertent changes in the system's sociocultural and technological "landscape" (boundary conditions). In each phase, the overall balance of damping (negative) and reinforcing (positive) feedback loops shifts. In the *destabilisation* phase, damping feedbacks that maintain the stability of the old state get weaker, and reinforcing or amplifying feedbacks that can propel change get stronger. The net effect of all the feedbacks is still dampening (negative) but less and less so. This is captured visually by the shallowing of the valley that represents the initial state. At the tipping point, the net balance of feedback becomes reinforcing (positive) and is sufficiently strong to support a self-propelling change, meaning that change will continue under its own self-amplifying momentum, without needing further forcing of the system – the ball rolls into the other valley. This *tipping* is where the system "transitions" from one state to another. It is necessarily a transient state of affairs – the reinforcing feedback will ultimately weaken as, for example, everyone comes to adopt the new state of doing things. Lastly, there may be a phase of *stabilising* dynamics, where the net balance of feedback in the system becomes damping (negative) again as new damping feedbacks arise that stabilise the new state.

As such, both damping (negative) and reinforcing (positive) feedback loops are usually present throughout, but their relative strength varies. Reinforcing feedback is the key focus at the tipping point and in the ensuing tipping dynamics. However, beforehand, a mix of weakening of damping feedback and strengthening of reinforcing feedback can play a role in destabilising the initial state. Afterwards, in the stabilising phase, there is a strengthening of damping feedback, but these may be different damping feedbacks to ones that stabilised the initial state.

Changes in the (sociocultural) "landscape" and deliberate actions can both force the system towards or move it away from a tipping point. The term "enabling conditions" was introduced to describe those factors that may be deliberately changed in a direction that helps bring the system closer to a tipping point. This phase of destabilising dynamics warrants further elaboration in the PTPs framework.

The phenomenon of destabilisation or decline has received attention elsewhere (Turnheim and Geels, 2013), but this body of work also remains small. Examples are frameworks such as Panarchy (Gunderson and Holling, 2002), which conceptualises how established solutions need to decline to "make space" for the new within ecology and socio-ecological change. Other work explores this idea within social transformation and organisational change, e.g. the Two Loops change (Wheatley and Frieze, 2011) and the x curve (Loorbach et al., 2017), and paradigm change, e.g. the waveS model (Blomsma et al., 2022). What these frameworks have in common is that they feature a downward curve or trend in an established solution, which may involve repurposing and exaptation (that is, reusing the old in new ways).

The final phase of stabilising dynamics also warrants more attention in the PTPs framework. In particular, how strong the damping feedbacks that stabilise the new state become is an important determinant of how persistent (or resilient) that state will be to ongoing changes in the system landscape or actions within the system. If they are weak, the new state is more vulnerable to being tipped away from.

The overall interplay of destabilising dynamics (weakening of balancing loops, strengthening of reinforcing loops), tipping dynamics (strongly reinforcing feedback that brings about the new system state), and stabilising dynamics (balancing loops re-establish control post-tipping) could benefit from additional cases and insights. Hence we explore this here, asking the following: how can we better understand the dynamics of destabilisation, tipping, and stabilisation within the PTPs framework?

2.4 The role of business and policymakers as key actor groups in success and failure

As existing PTPs case studies tend to focus on significant changes in socio-technological systems from a macro-social perspective, there remains a need to better understand agency from the perspective of specific societal actors and how failure to make a new system state endure arises from their interactions. Specifically, we focus on the interplay of policy and business. Unlike past transitions that were primarily

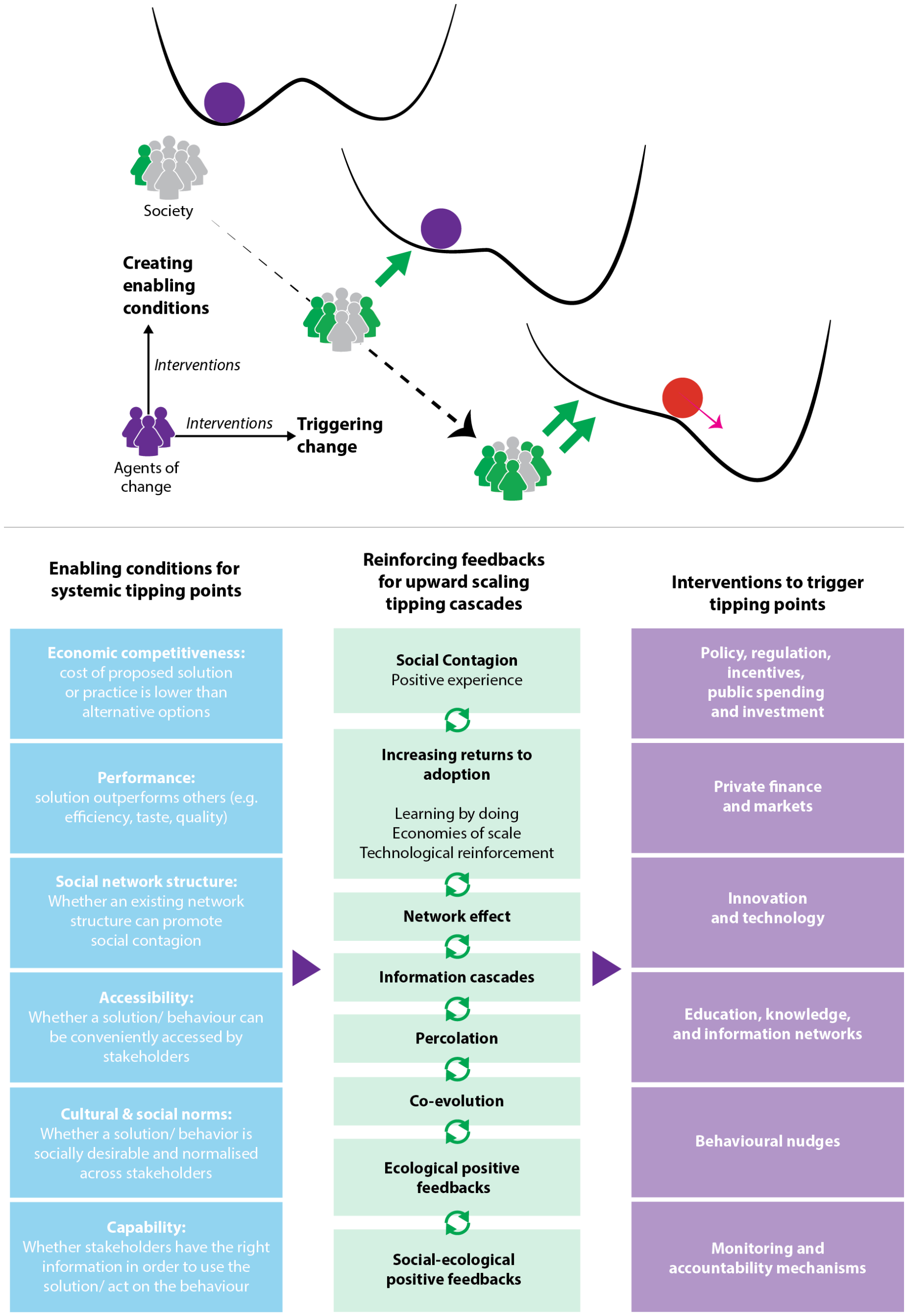

Figure 1. Top: a dynamical systems conceptualisation of positive tipping points (Lenton et al., 2022). Bottom: summary of framework for triggering positive tipping points, adapted from Lenton et al. (2022) and FOLU and GSI (2021).

driven by emergent commercial opportunities, sustainability-oriented transitions are aimed at addressing persistent environmental and societal issues (Geels, 2011). This requires changes in, for example, taxes, subsidies, regulations, and infrastructure – often the domain of policy. However, it also requires changes in innovation practices, such as embracing and embedding sustainable principles in production and consumption practices, ranging from design to sourcing, from production to marketing, and from retail to revalorisation – often the domain of business (Fischer and Newig, 2016). It is therefore necessary to both navigate politics and involve and reorient firms to accomplish a qualitative change in systems.

This can be challenging for a number of reasons. For one, as different stakeholders control different parts of the system that will need to be aligned, there is a coordination cost. Successful collaboration, for example, means that organisations exhibit proactive, solution-oriented cooperation and adaptability, supporting and strengthening the transition, whilst a lack of alignment means that entities pursue conflicting agendas and resist change, resulting in a waste of resources and potentially putting up a barrier for future efforts.

Secondly, tensions will need to be resolved that arise from varying and sometimes conflicting interests and perspectives on the directionality of sustainability transitions (Stirling, 2009), the merits or drawbacks of specific solutions, and how to arrive at goals. Such tensions can be resolved when, for example, stakeholders engage in constructive dialogue and consensus-building processes, enabling change, or they can cause inertia or failure when, for example, parties insist on rigid positions and prioritise short-term gains over long-term solutions. In other words, in both enabling and obstructing change, business actors and policymakers are pivotal agents of change, and their interactions can significantly impact the scope and speed of transformative change.

In order to accelerate systemic change, an improved understanding of the interplay of the actions of policy and business in the context of systems is needed. That is, how these agents act to create the forces to propel or inhibit change within systems, or what to do and what *not* to do. Specifically, with this work, we improve the resolution of PTPs by understanding how actions of policy and business set positive feedback loops in motion or how they inhibit them. For this reason, we analyse the role of these actors in creating enabling and destabilising dynamics.

In the following historical case study, we thus ask the following sub-questions: what were the destabilising dynamics? Which tipping dynamics can be identified that triggered the acceleration of change? What stabilising dynamics can be seen? How can business and policy influence these destabilising, tipping, and stabilising dynamics?

Next, we explain the case that was selected and our method for analysing it.

3 Research design

3.1 The case study

Mineral water has long since had a prominent place in German culture, resulting in a robust industry with numerous companies vying for consumer preference. Whilst this includes soft drinks, the focus here is on mineral water: carbonated and noncarbonated. Our focus lies on the developments in West Germany.

The use of the industry's key asset – its bottles – forms an important part of how it operates. Organised as a reuse pool system, the reuse of the bottles is – to date, as measured by fillings per year (6 billion) and circulating reusable packaging units (1.2 billion) (UBA, 2022b) – the biggest reuse system in Europe and is unique in its effectiveness and comprehensive scope according to the Genossenschaft Deutscher Brunnen (GDB, 2023b), the business cooperative which organises and manages it. This system became successful with the introduction of a 0.7 L standardised pool bottle in 1969 called the "pearl bottle", which has remained unchanged since (see insert in Fig. 2). Although other reusable bottles did exist, this bottle was adopted nearly industry-wide initially (Bielenstein, 2019) and currently still makes up 70 % of all reusable mineral water bottles (GDB, 2023a).

This system is characterised by a high circulation rate: the bottles can be reused 40–50 times with average transportation distances of 260 km (DUH, 2014a, b; UBA, 2016). It can therefore be expected that this system has less environmental impact than single-use alternatives: the sustainable break-even point (in terms of GHG emissions, water use, material use, and waste generation) is estimated to be reached within 3–10 circulations (Coelho et al., 2020; DUH, 2014b) and a transport distance of less than 500 km (Coelho et al., 2020; EMF, 2023; UBA, 2016). As such, the pool reuse system well exceeds these limits. The short transport distance is accomplished by transporting the bottles to the closest participating mineral water company where possible, as opposed to returning them to the original bottling company. The bottles are owned by the cooperative and lent to their business customers, the vast majority of which hold an ownership stake as members of the cooperative (GDB, 2023c).

This case was selected for generating insight into how actors influence PTPs because of the rapid changes it has seen over the years and the prominent role of both business and policy. When pool reuse was introduced, there was an almost industry-wide adoption within 1 year with a relatively stable market share of over 80 % for the following 3 decades (1970–2000). Later, however, with the advent of mass production and consumption, the necessity of reuse gave way to single-use (König, 2019). This meant that single-use plastic bottles were introduced which rapidly destabilised the reuse system: its market share fell from over 80 % to around 40 % in the decade from 2000–2010 (Fig. 2). Today, the bottle reuse system coexists alongside the dominant single-use plastic bottle and recycling system.

3.2 Data collection and analysis

To assess this case study, we used qualitative content analysis (Gioia, 2021). The basis for our analysis is a comprehensive timeline of events that was constructed using secondary data, incorporating relevant information from the political and economic context and developments within the mineral water industry, with a focus on how policy and business shaped the outcomes. Industry information was sourced from historical reports of a leading mineral water company Gerolsteiner (Lippert et al., 2012; Schuck, 2015) and the industry cooperative GDB (Bielenstein, 2019), supported by an expert interview. Additional insights were drawn from existing literature on the history of the mineral water industry (Eisenbach, 2004) and from complementary literature on the German history of waste (Kleinschmidt and Loge-

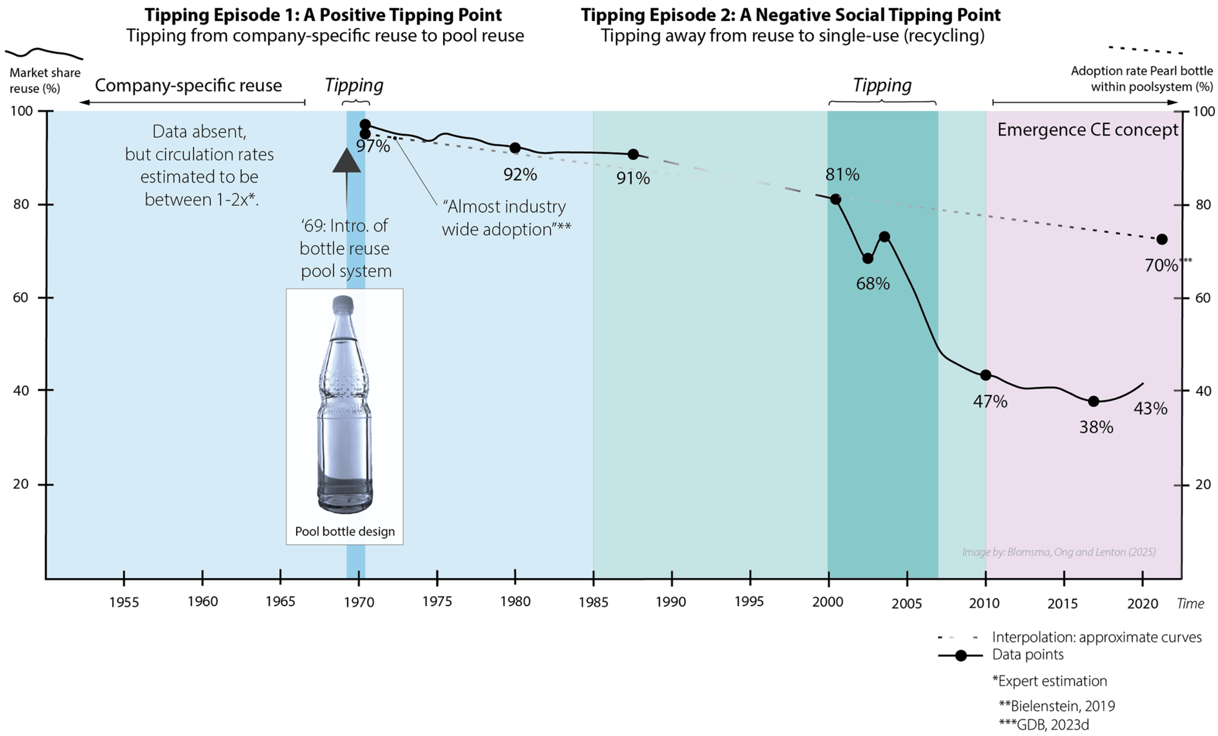

Figure 2. Market share of reusable mineral water bottles (UBA, 1983, 2022a) and the (approximated) adoption rate of the pearl bottle (Bielenstein, 2019). Image insert: the reusable glass pool bottle. Two rings (in the middle and at the bottom) function as "shock absorbers" to prevent breakage in the filling and cleaning process. The pearl-like patterns at the neck of the bottle express freshness while enabling a good grip (Bielenstein, 2019).

mann, 2021; König, 2019). To enrich the analysis, archival documents from the Federal Archive in Germany, specifically those relating to the beverage industry from 1980–1990, were consulted. Key performance indicators such as market shares and circulation rates were extracted from reports issued by the German Federal Environmental Agency (UBA, 1983, 2010, 2016, 2022a).

Based on this timeline, two tipping episodes were identified: (1) a positive tipping point, tipping towards the pool bottle system covering the period between 1950–1985, with tipping happening between 1969–1970, and (2) a negative social tipping point, tipping towards the single-use and recycling system between 1985–2010, with tipping between 2000–2007.[1] For these two periods, an overview was created that covers the enabling conditions, feedback mechanisms, and relevant interventions by both business and policymakers using deductive qualitative content analysis (Gioia, 2021). Text segments from the various sources were coded according to the enabling conditions, the feedback mechanism categories as identified within the PTPs framework (Lenton et al., 2022), and the presence of dampening mechanisms; see Table 1. An example of a feedback loop is the *network effect* that reinforced tipping towards a new system as the attractiveness of participating in the new system increased the more other companies joined.

Additionally, the feedback mechanisms are assigned as part of the destabilising dynamics (magenta), tipping dynamics (green), or stabilising dynamics (blue), accepting that the same feedback may play a part across more than one phase, in particular, reinforcing feedback that is part of both destabilising and tipping dynamics. The feedbacks are also assigned to (or in between) the curve(s) dedicated to the time frame upon which they exerted influence (indicative times indicated in the purple balls); see Figs. 4 and 5. In this way, the overview emphasises the dynamics and their interactions. Specifically, *destabilising* dynamics refer to those forces or drivers and shifting feedbacks that undermine the validity of current practices and solutions: what is "tipped away" from. For example, the economic inefficiency of company-specific bottle reuse and material and energy shortages meant this solution was no longer fit for purpose in tipping episode 1.

Tipping dynamics are those that propel a system towards the next paradigm as opposed to another: what is "tipped towards". For example, in tipping episode 1, the existing reliance on reuse practices and the promising increasing returns

[1] In reality, there exists some overlap between these two periods in the sense that the conditions that enabled the second episode already started to change towards the end of the first period. For reasons of simplicity and brevity, we strictly separate the two episodes.

of adopting a centrally organised solution enabled tipping to a pool reuse system.

Stabilising dynamics are those that stabilise the new state of a system. These, for example, could be recognised in the high costs of switching to a new technology.

Lastly, the interventions that enabled the change, where agency was exercised, are furthermore assigned to either business and policy.

4 Results: the historical development of the German bottle reuse system

Before discussing the two tipping episodes, we briefly discuss the case context and the starting conditions. Abbreviations mentioned below refer to *enabling conditions* (EC), *reinforcing feedback loops* (R), *balancing feedback loops* (B), and *interventions* (I). Numbering of these elements is continuous across both episodes to create a clear distinction between them. Numbering follows the images (Figs. 4 and 5), which may differ from where developments are featured in the text for clarity and brevity. Additionally, interventions are assigned to an actor group: e.g. *business* (b) or *policy* (p).

4.1 The case context: the starting situation

Germany's rich geological diversity provides access to various natural springs, allowing mineral water to gain a prominent place in German daily life as a staple beverage. Additionally, the country's strict regulations ensure high quality standards for the production of mineral water, fostering a competitive market. In this industry, like in many others, reuse had long been the standard before the "throwaway mentality" emerged. This was due to scarcity-driven economies, which made it necessary to maximise the exploitation of available resources and goods by reusing, reutilising, and repurposing them for as long as possible (Denton and Weber, 2022). Consequently, bottle reuse was a common procedure, i.e. *social norm* (EC1), to save costs for mineral water companies. However, large-scale reuse systems did not exist due to a lack of infrastructure. Before the first tipping episode, every mineral water company used its individually shaped, company-specific bottles for reuse – leading to long, laborious, and expensive exchange and return processes – or directly discarded them through costly glass recycling (Eisenbach, 2004).

Earlier efforts to change this had failed: already in 1875 and again in 1950, efforts were made to implement a more efficient solution in the form of a standardised bottle design. The first effort suffered from a lack of leadership and difficulties in aligning prospective partners, whilst the second effort stumbled over unsurmountable technical difficulties, and both efforts were abandoned (Eisenbach, 2004). However, after the end of WWII, enabling conditions changed, which paved the way for a crucial business intervention that led to near-industry-wide adoption of the pool reuse system and which set the sequence of tipping episodes in motion; see Fig. 3.

4.2 Tipping episode 1 (1950s–1985): a positive tipping point from company-specific reuse to pool reuse

In the following, we first discuss the enabling conditions. Next, we discuss both the developments that led to the destabilisation of the company-specific reuse systems that existed before the pool bottle and the developments that allowed the tipping towards this new state specifically, and we highlight the relevant strategic interventions that triggered the tipping. See also the overview in Fig. 4.

4.2.1 Enabling conditions: setting the scene for systemic change

Firstly, because of historic reasons, bottle reuse was already a common practice, i.e. *social norm* (EC1; see above), ensuring the capability (EC6) for reuse behaviour. Secondly, a special *network structure* (EC2) emerged, in the form of cooperatives, that allowed the mineral water companies to tackle shared challenges. This was partly driven by the strong regional focus of the companies and partly driven by economic growth. The former limited the competitive overlap in the operating areas (GDB, 2023b) and aided collaboration. The latter, while interrupted by WWII, was rebooted with the economic upswing after the war and influenced by currency reform and the Marshall Plan. This had the effect of the industry as a whole growing rapidly. Consequently, the GDB also grew to 133 members by the early 1960s, which represented about three-quarters of West Germany's mineral water companies. All this set the stage for the introduction of the pearl bottle (see *Intervention* (I1(b)) below), whilst the systematised procurement and logistics provided by the GDB made bottle reuse much more *accessible* (EC3). Moreover, promising lower costs through reducing the need for the production of new bottles contributed to the better *economic competitiveness* (EC4) of reuse at scale in particular. At the same time, advances in manufacturing technologies and more efficient logistics, in the form of more return points in supermarkets and the purchasing of replacement bottles and empties exchange by the GDB, meant that the *performance* (EC5) of reusable bottles (their handling and circulation rate) could now be significantly improved. That is, six of six enabling conditions of the PTPs framework were present (see Fig. 1), although they are interconnected and themselves driven by both global and local enablers.

4.2.2 Tipping (1969–1970): tipping from individual company reuse to pool reuse

The first tipping episode took only a single year: from 1969–1970. After an initial near-industry-wide adoption, a stable

Table 1. Example of data coding.

Data	First-order code (paraphrase)	Second-order code (generalisation)	Aggregate dimensions		
			Enabling conditions	Reinforcing feedback loops	Intervention (policy or business)
"The success of the standardised bottle and the standardised crates are clear evidence that the mineral water companies, despite all the competition among themselves, developed a sense of the common interests that was channelled by the VDM and the GDB." (Eisenbach, 2004, p. 265)	The success of the standardised bottle and crates prove that the cooperatives enabled working together towards shared interests, despite the competition among the mineral water companies.	The profit from working together towards shared interests in the cooperative outweighed the competitive nature between the companies.	Network structure		
"The large bottle losses during the war and the shortage of glass bottles in the post-war years had made it painfully clear to those in charge that bottle ownership was one of the most important assets of a mineral water company." (Eisenbach, 2004, p. 259) VDM makes efforts for a regulated deposit scheme and stresses the efficiency of a standardised bottle that is used by the whole industry: "a big chunk of the capital of mineral water companies is bound to the empty bottles." (Eisenbach, 2004, p. 259)	Realisation of the mineral water industry that bottle ownership is one of the most important assets of a mineral water company, increasing efforts for a regulated deposit scheme with a standardised bottle.	Packaging as an important asset for beverage companies.	Economic competitiveness, accessibility, desirability	The more important reliable material supply is for a product, the higher the necessity for a functioning deposit system.	
While, until 1933, the activities of the RDM were essentially limited to traditional lobbying because of the different interests of its members on many issues, after its re-establishment in 1949, the VDM worked successfully in close cooperation with the GDM in a variety of fields. This was made possible by the mineral water companies' realisation that many pressing problems could only be solved together and with the help of a strong cooperative. The members were even ready to pay a substantially higher fee, since they profited from the work of the cooperative (industry community advertising, the development of standardised bottles and crates, education and training opportunities, and coordinated development of production machinery), which undoubtedly had a considerable share in the upswing of the industry (Eisenbach, 2004, p. 267).	Successful collaboration of the cooperatives VDM and GDB, due to the realisation that many pressing problems could only be solved together and with the help of a strong cooperative.	Realisation of the importance of collaboration between companies for a higher resilience of the industry and therefore also their own companies.	Economic competitiveness	Network effects, social contagion	
In 2006, the decree on packaging was tightened, making it mandatory for all retailers to take back all single-use bottles. Retail therefore introduces vending machines that collect the single-use bottles and return the deposit to the customers (König, 2019, p. 38).	Tightening of the law leads to complementing technological innovation and higher return rates of single-use bottles and their recycling but contributes to reuse market shares continuously decreasing.	Tightening of the mandatory deposit regulation contributes to new complementing technological innovation, making the deposit system for single-use bottles more efficient.		Technological reinforcement	Policy

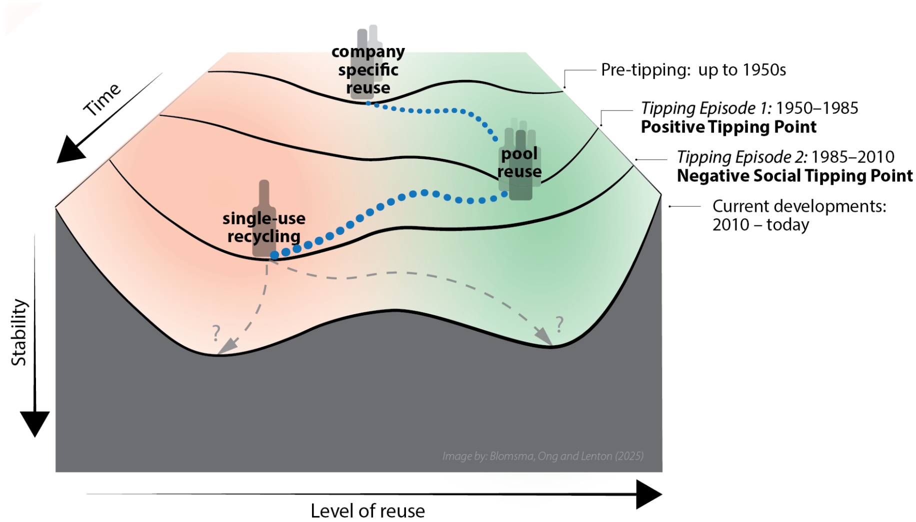

Figure 3. Illustrative visualisation of the development of bottle management systems using the tipping points state-space format. It depicts the progression of the case in Germany from individual company reuse to a widespread reuse system to a single-use recycling system and potential future pathways. The valleys represent alternative stable states of the system, which differ in their level of reuse and are evolving over time. The bottle icons represent the actual state of the system at a particular time. The dashed line shows the historical trajectory of the system, and the dashed arrows show the possible trajectories unfolding now and into the future.

state followed between 1970–1985, where the market share continued to be > 90 %; see Fig. 4.

Destabilisation: regional reuse no longer fit for purpose.

Fig. 4 shows the weakening of two damping feedback loops (B1 and B2 in magenta) that made the company-specific reuse system less fit for purpose. Firstly, approximately 150–210 million bottles and 3 million crates were lost during World War II. Obtaining replacements was highly challenging due to post-war material supply shortages and frequent energy shortages in glass factories (Eisenbach, 2004). As bottles are an essential asset, there was an economic necessity to ensure the return and reusability of bottles. However, this was hindered by the inefficiency, e.g. the low circulation rate and costly sorting and exchange, of the regional reuse systems, *weakening their performance (B1)*. Also, in the meantime, global soft drink brands, such as Coca-Cola, had successfully entered the beverage market as strong competitors, thus *weakening the economic competitiveness of regional reuse (B2)*, and the mineral companies recognised this (Eisenbach, 2004). As a result of these two developments, there was a need to stand together and the GDB was formed.

Tipping: actions to trigger tipping towards pool reuse – the (in)active role of policy and business.

In Fig. 4, the strengthening of two reinforcing feedback loops helps lower the "hilltop' and generate the next "valley", representing the next system state that is to follow, as indicated by the downward arrows (R1–R2 in green). In our case, the main triggering intervention (I1) was the introduction of the pearl bottle and related services provided by the GDB. The pearl bottle provided both *economies of scale* and *economies of reuse*, thus *increasing the returns of adoption (R1)* of the system. That is, it used both increases in the scale of production, lowering the per-unit cost, and at the same time spread the initial cost of production, lowering the cost per use. Due to the new network structure (the formation of the GDB), *contagion (R2a)* enabled a near-industry-wide adoption (Bielenstein, 2019), further reinforcing benefits gained from *increasing returns of adoption (R1)*.

Here, the role of the enabling conditions can be clearly recognised. Previously, in 1950, the GDB had commissioned the development of a uniform bottle shape, resulting in a standardised design guideline for a bottle with a lever cap. However, this remained a niche experimentation and was not widely adopted: the bottles still needed to be closed manually and were therefore unsuitable for machine handling. Additionally, the breakage rate of the caps and bottles was still high (Eisenbach, 2004). Approximately 2 decades later, however, due to technological advances, bottles with external screw caps were possible with significantly lower costs (EC4 and EC5). This led to the investment of the cooperative GDB and the trade association VDM to develop a new standardised bottle together in 1969.

A wide range of actors was involved in this effort, including designers, market researchers, experts for glass works, and representatives of the mineral water companies and cooperatives. The outlook of the actors was to create a system that would serve them in the long term, or what would now be called a product–service system design or whole systems design. That is, the focus was not only on the bottle, but also on creating a well-organised mechanism for the return and refill process through the GDB (Bielenstein, 2019). A relatively quick iterative process (a mere 5 months) was used to optimise both technical and aesthetic requirements so that the bottle would be lighter and more elegant and modern looking, as suggested in several market research feedback cycles. This resulted in the final pearl bottle design (see insert in Fig. 2) (Bielenstein, 2019). The complementary technological development of stackable and palletised crates (which can be reused over 100 times) also played a pivotal role in enabling smooth logistics for a more efficient *performance* (EC5) of the system (Eisenbach, 2004).

After the design of the bottle was finalised, a vote followed (where, again, a wide range of stakeholders was included), and a decision made with unity led to a quick and almost industry-wide adoption of the pool bottle. Previously, during the 1875 effort, there was no one to take responsibility and leadership of a pool system, but now, with the GDB, this was no longer a barrier. Moreover, the *network effect – contagion* (R2b) reinforced the functioning of the reuse system as it became more efficient the more companies participated (Bielenstein, 2019) thus further increasing its *performance* (EC5). Additionally, the central responsibility and management of the pool system by the GDB enabled the streamlining of the bottle procurement process. This facilitated easier and more reliable *access* (EC5) to the necessary bottles and favourable pricing agreements that were leveraged by the cooperative's purchasing power (GDB, 2023b). This made participation in the GDB system even more attractive and beneficial for the mineral water companies, leading to strong social contagion effects: still, to this day, around 95 % of all mineral water companies are members of the GDB (GDB, 2023c).

In sum, there were strong forces that destabilised the company-specific reuse system and strong (but largely unconnected) forces to enable the pool reuse system. Crucial, also, was that the solution (the pool reuse system) leveraged the new enabling conditions (the possibility to make improvements in *performance* (EC5) and *economic competitiveness* (EC4)) to address shortcomings of the company-specific reuse (e.g. weakening *performance* (B1) and *economic competitiveness* (B2)) whilst leveraging existing practices (e.g. to consumers, there was not much change).

Stabilisation of the pool reuse system.

Two factors contributed to its initial period of stability. Firstly, investing in alternative technologies was perceived as having *high switching costs and risks* (B3) by individual companies (Eisenbach, 2004) – more so, given that consumer acceptance of these alternatives was still low: PET, for example, was not yet accepted as a packaging material for water (Eisenbach, 2004). However, efforts were already underway to change this: the single-use tin and aluminium can industry (greater competition to reusable glass than single-use plastics at the time) initiated campaigns that endorsed convenient use-and-dispose behaviour from the late 1960s onwards (Köster, 2021) (*information cascades – R3*)).

Secondly, to reinforce glass as the material of choice, the industry therefore wielded its joint communication power to continue to *emphasise the benefits of the system* (B4). Already, before the tipping, the industry actively shaped the perception of the high quality of natural mineral water compared to table water (Eisenbach, 2004), so, when other alternatives emerged, the industry responded with initiatives such as the *PRO MEHRWEG* (in English: pro-reuse) campaigns through radio and television features and numerous press publications, and public awareness around the environmental impact of single-use packaging was raised (PRO MEHRWEG, 1984). This continued effort ensured that reuse was seen in a positive light, reinforcing the *social norm* of reuse (EC1) and contributing to the preservation of the *capability* (EC6) of consumers to make an environmentally beneficial choice.

The pool reuse system had adoption rates above 90 % up to the 1990s, after which adoption slowly started to decline – early signs of the second tipping episode drawing closer. All the developments during the first tipping episode solely included businesses, and no (additional) policy interventions were involved, which was about to change during the second tipping episode.

4.3 Tipping episode 2 (1985–2010s): a negative social tipping point away from the reuse regime

Following the logic of the previous section (see also Fig. 5), we depict the change as a reversal to indicate a change that is deemed undesirable from a sustainability perspective.

4.3.1 Enabling conditions: setting the scene for systemic change – yet again

Some of these developments already started in the background of the previous tipping episode, but, during this period, their influence became so pronounced as to decrease the stability of the pool bottle reuse system as a solution.[2] For one, the post-World War II landscape changed *social norms* (EC7a). The economic boom, fuelled by liberal policies, shifted spending towards convenience and individuality as product choices grew (Fabian, 2021; Köhler, 2021), which increased the demand for disposable products. This sparked a related change in *business norms* (EC7b): with market saturation came fierce competition for customer loyalty (Köhler, 2021). It became important for businesses to pursue tailored marketing strategies and personalised products (Beyering, 1987; Fabian, 2021), challenging the legitimacy of standardised packaging. Additionally, the retail landscape diversified with large chain stores and discounters based on the self-service principle (Köster, 2021), which offered lower prices by simplifying store layouts and selling their own brands.

[2]Here, we continue to use "enabling conditions" as a technical term to mean the conditions that set the scene for tipping towards the single-use recycling system, irrespective of the desirability of the direction or nature of the change.

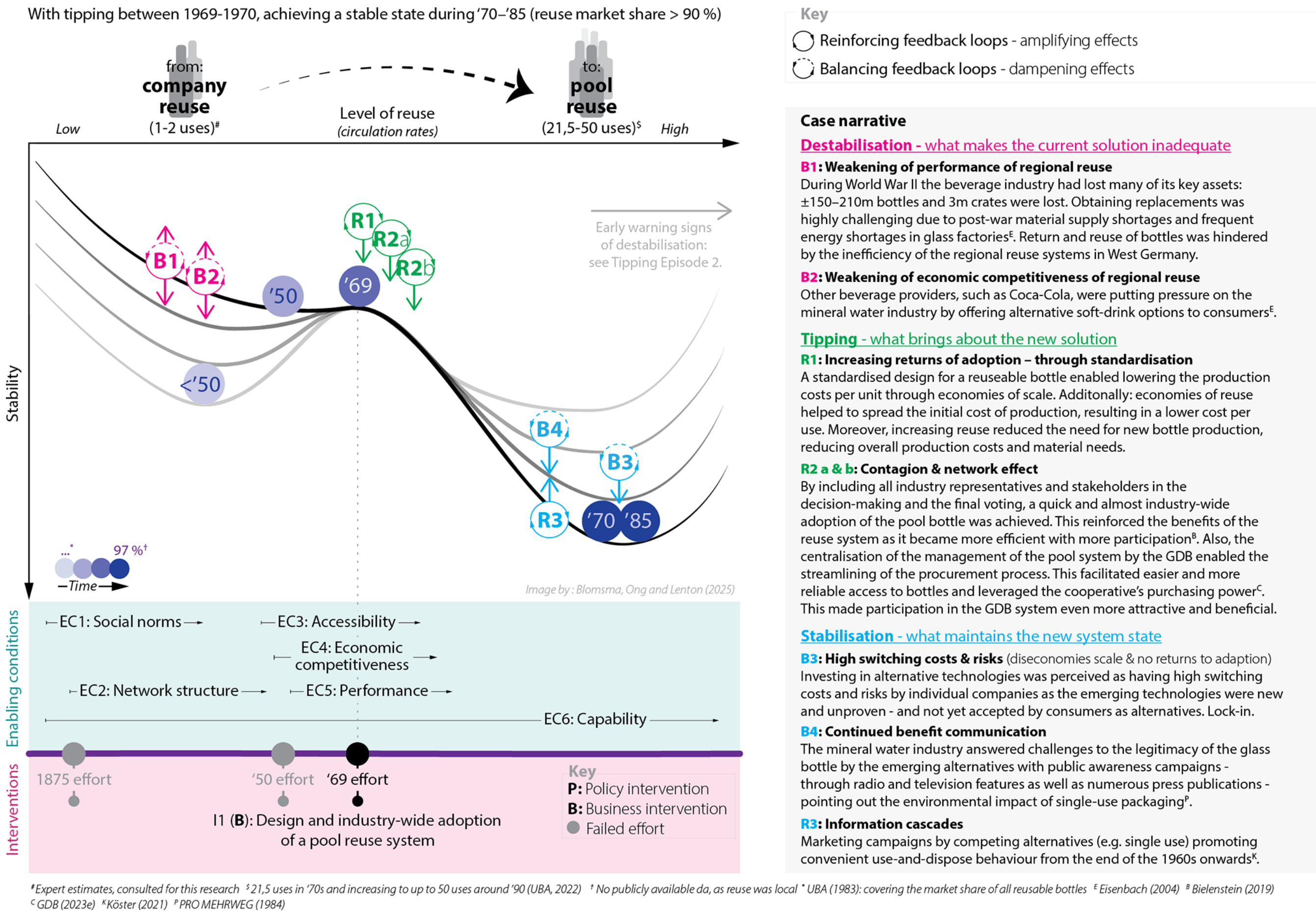

Figure 4. Tipping episode 1 (1950–1985): a positive tipping point.

This pressured traditional retailers to adjust pricing strategies.

At the same time, advancements in plastic manufacturing technology significantly reduced production costs with promising economies of scale, leading companies to invest in this new technology. This meant that single-use packaging was not only becoming more available and *accessible* (EC8), it was also swiftly becoming a cost-effective alternative, thus challenging the *economic competitiveness* (EC9) of reusable packaging. Moreover, the single-use system did not need a supporting *network structure* (EC10) in the same manner that the pool reuse required, thus reducing the need for participation in the GDB and the benefits it offered and reducing the *accessibility* (EC8) of the pool reuse system. Shifting investments also had the effect that the financial and innovative capacity of reuse pools declined, making it difficult for the reuse system to keep up with the *performance* (EC11) of the single-use system: not only was single-use becoming cheaper for companies, it was also more convenient for both consumers and companies and offered more possibilities for differentiation.

Although the resulting waste from single-use was seen as a problem and recognised by policymakers as such, the complexity of waste management and recycling systems made them difficult to understand for consumers. This made it difficult to know what constituted environmentally friendly behaviour, thus reducing the *capability* (EC12) of consumers to make informed decisions about this. Moreover, there was a belief – among consumers and policymakers alike – that the newly emerging recycling technologies would be able to solve many of the waste issues, establishing a new *norm – belief in eco-optimism (EC13)* (Köster, 2021). In short, during this period, many of the forces that had previously enabled the tipping towards pool bottle reuse now reversed direction or stopped being relevant, and the door was now open to single-use.

4.3.2 Tipping (1985–2000): tipping from pool reuse to single-use and recycling

The second tipping episode took place over 7 years: from 2000–2007. During this period, after already having declined somewhat from its success days of over 90 % to > 80 %, the reuse levels declined further to levels around 40 % and stayed there between 2010–2020, to the benefit of single-use and recycling. Tipping episode 2 differs from tipping episode 1 in one important aspect: the presence of forces that both destabilised the pool system *and* simultaneously enabled the single-use system. We will first describe the destabilising aspects, before linking them to the enabling feedbacks in this section. In Fig. 5, these linkages are indicated by the arches connecting the destabilising dynamics on the right with their respective enabling dynamics on the left.

Destabilisation: competing solutions start to undermine pool reuse.

In Fig. 5, destabilisation happens because of B5 and B6 no longer being sufficient to counterbalance R4 to R7. These latter feedbacks are the result of competing solutions undermining the pool reuse system. That is, the general increased competition for market share and the resulting need for product differentiation (EC7 and EC9) affected the packaging for mineral water in particular because the product has inherent limited marketing options. To stand out, distinctive packaging designs became the focus, either serving a low-price market or aiming for a luxurious and modern look for settings such as restaurants. Companies responded to this in one of two ways: to revive earlier company-specific reuse solutions and/or to develop single-use bottles.

These two developments had the combined effect that the pool system as a whole became less efficient (Lippert et al., 2012): the pool reuse system started to struggle with rising transportation costs, increasing losses and costs for replacement bottles due to lower return rates, and higher costs due to high storage space and staff costs for handling empties (compared to single-use) (UBA, 2010). This started to be problematic due to EC6–10 and favoured the new solutions even more. Being a member of and participating in the GDB bottle reuse system was not needed any longer; therefore companies exited the GDB and its pool system (ibid). Pool membership became less appealing: it was acceptable for a business to have its own solution (*contagion – business* – R4), and this further compounded the shortcomings of the pool system (*network effect* – R7). At the same time, the emergence of these competing solutions, and the redirected investments towards single-use this entailed, undermined the financial and innovative capacity of pool reuse (*co-evolution* – R6).

As reuse rates declined (see Fig. 2), something needed to change. In an effort to preserve the reuse system, policymakers issued an ultimatum to the industry: if reuse rates were to drop below 72 %, a mandatory deposit would be introduced on single-use packaging (B5). The aim of this was to make single-use more expensive, thereby tilting the playing field towards reuse. To this end, a conditional law was included in the Packaging Regulation[3] that was passed in 1991: *Intervention* (I2(P)). However, several studies had already predicted it would fail (Sprenger, 1997; Golding, 1999; Baum et al., 2000; UBA, 2010; Hoffmann, 2011): amongst other reasons, the mandatory deposit–refund system was likely to lead to "windfall profits" for participating companies due to unreturned bottle deposits and the fact that single-use bottle collection would be exempt from the general EPR[4] scheme for all packaging (Peters and Czymmek, 2002; BMU and BMWi, 2002). Still, the deposit was adhered to, although the result was characterised as an "obligatory consensus" rather than a "joint agreement" (Hoffmann, 2011: p. 144). Then, in 1999, the reuse market share had fallen below 72 %,[5] which put the conditional mandate into effect if the market share was breached again in the subsequent 1-year review period. Eventually the mandatory deposit was introduced in 2003: I5(P). However, instead of reversing the downward trend[6], as predicted, it provided an advantage to single-use (Jungbauer, 2000; Sachse, 1998); see more in the following text.

This policy failure can be attributed to a lack of leadership to correct course and steer towards a better solution (Hoffmann, 2011). A subsequent government inherited the Packaging Regulation (policy legacy) and, with reuse rates still falling, was now faced with having to enforce the conditional law that would introduce the mandatory deposit. As a way of reducing the time pressure somewhat, though, the industry was given the opportunity to find its own solution. How-

[3]From the 1970s, growing environmental movements, including the Green Party's rise, highlighted waste as a major environmental issue in Germany. This led to the introduction of new waste management laws. After German reunification in 1990, the West and East German waste systems were merged. Although East Germany's SERO system was more efficient, it collapsed due to the influx of West German waste and credit fraud post-privatisation (UBA, 1992). In response, the recently established Ministry of Environment passed the German Packaging Regulation of 1991 (I2: *policy intervention*), including an Extended Producer Responsibility (EPR), making producers accountable for managing the waste they generate (Quoden, 2010). In response to the EPR and to avoid further regulation, the private sector in Germany established a comprehensive second collection system for packaging (I3 (B): *market intervention*), funded by licensing fees of companies that produce packaging (Quoden, 2010). This is known today as the yellow bin or bag, which exists alongside the public waste system funded by taxes and fees. This dual system, primarily financed by industry licensing and fees (Seifert, 2011), improved the organisation of packaging recycling and enabled the collection and recycling of single-use PET bottles with relatively high rates (80 % collection, 66 % recycling) (IFEU, 2004). However, recycling rates for other packaging types remained low (Bünemann et al., 2011).

[4]See previous footnote.

[5]Retrospective reporting: actually, already in 1997, the share was at 71.35 %.

[6]The introduction of the mandatory deposit for single-use bottles in 2003 (I5: *policy intervention*) initially led to a new (albeit modest) peak in reusable bottles, while single-use bottles temporarily lost market share because retailers had not prepared appropriate infrastructure, as they had not anticipated the mandate's actual implementation. However, this was short-lived.

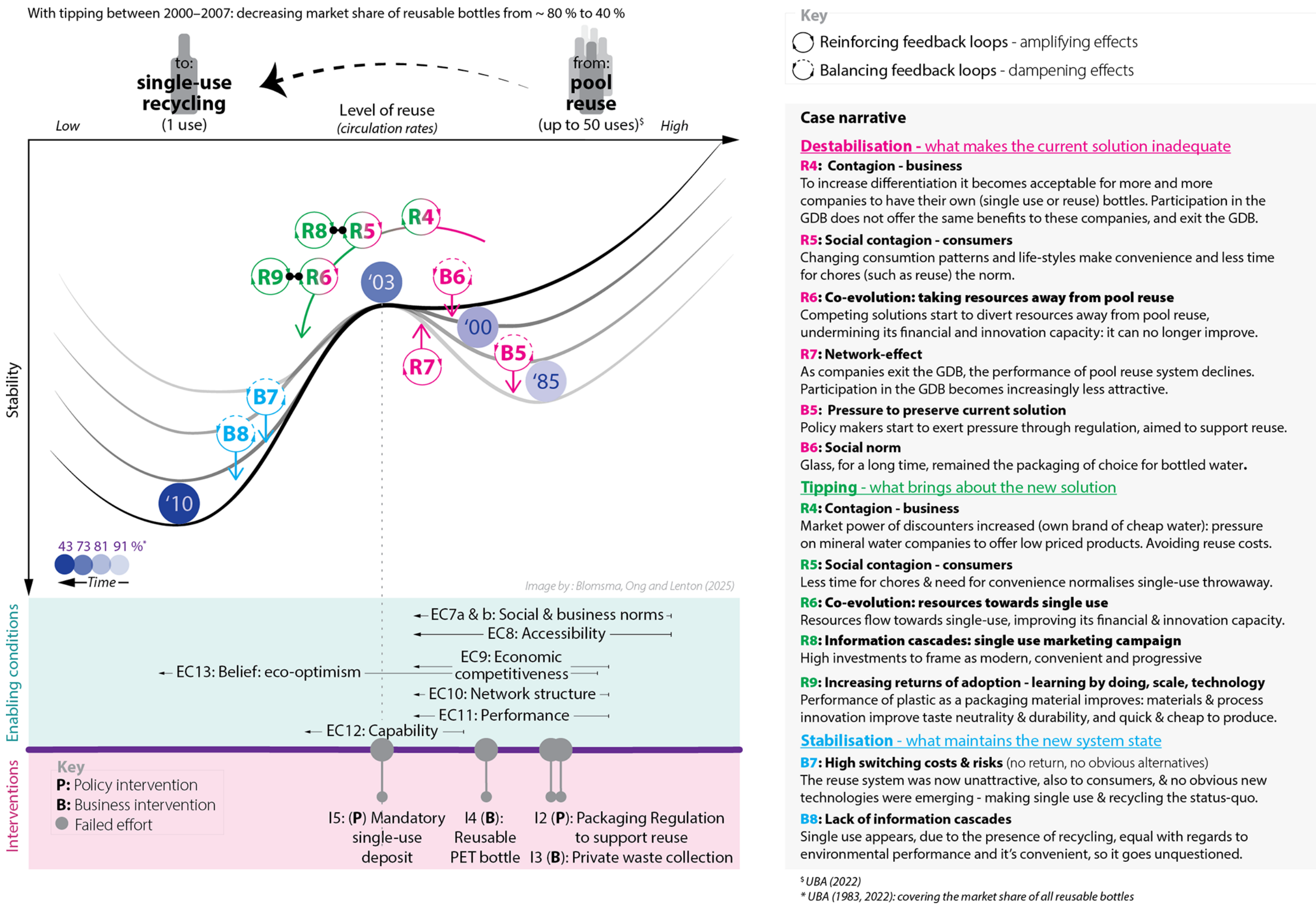

Figure 5. Tipping episode 2 (1985–2010): a negative social tipping point.

ever, given the lack of political consensus, industry did not make use of this opportunity but rather waited. As a consequence of industry not taking the political pressure seriously and policymakers needing to show decisive action, an alternative could be neither efficiently designed by its proponents nor fully prevented by the opponents. Ultimately this led to a "solution" that was not desired by anyone involved (Hoffmann, 2011).

A business intervention was similarly unsuccessful: efforts were made to adjust to the new PET bottle material. A leading mineral water company introduced individual reusable PET bottles in 1998 (Lippert et al., 2012), followed by the GDB cooperative's reusable pool PET bottle and matching crate in 1999 (Eisenbach, 2004) (*I4(B): reusable PET*). Although these bottles, with an average circulation rate of 25 times and lighter weight, are considered a good eco-efficient packaging option (UBA, 2016), surpassing reusable glass bottles, they could not prevent the rise of single-use bottles.

Simultaneously, the increasing need for convenience, driven by factors such as rising employment, smaller households, an ageing population, increased out-of-home consumption, and decreasing time for chores (such as returning bottles) (Fabian, 2021), resulted in a decline in reuse practices (*social contagion – consumers – R5*). Even though, for a long time, glass was considered the material of choice (B6), this balancing loop was insufficient to preserve the glass reuse pool system.

As destabilising feedbacks undermine the pool reuse system and interventions aimed at preserving it instead stimulate single-use, "tipping" towards this seems inevitable.

Tipping towards single-use.

A number of the previous feedback loops not only destabilised the pool reuse system, but also – at the same time – enabled single-use. Such a strong linkage is seen, for example, for *R4 contagion – business*. That is, the aggressive low-price strategies employed by discount stores for mineral water (UBA, 2010) forced mineral water companies to adapt. Discounters deliberately used cheap mineral water in single-use bottles to create customer loyalty, avoiding the costs of reusable bottle infrastructure. Their market power and refusal to participate in the reuse system weakened its effectiveness. The dominance of discounters led the mineral water companies to also adopt single-use packaging for low-priced channels (Stracke and Homann, 2017; UBA, 2010). As such, R4 describes both the decline of the reuse pool and the rise of single-use as a result of the same developments.

Similarly, *social contagion – consumers* (R5) on diminishing reuse practices has as its counterpart normalising single-use. That is, the increasing need for convenience has the direct effect of both destabilising reuse and enabling single-use and throwaway practices. Single-use is the automatic and only logical alternative to the cleaning, sorting, storing, and returning of bottles. This is further reinforced by *information cascades* (R8), where, following the significant investments in transitioning to single-use bottle production, companies heavily invested in marketing single-use bottles as modern, convenient, and progressive, reinforcing their appeal.

R6 involving *co-evolution* is mirrored in much the same way: because finite resources are being rerouted towards (a.o.) single-use, these are not available for improving, or continuing to improve, the pool reuse system. This also sets in motion *increasing returns of adoption (R9)* for single-use as this system improves, driven by technological improvements in plastic bottles, including enhanced taste neutrality, durability, and functionality (Eisenbach, 2004). These advancements, combined with *economies of scale* from quick and inexpensive mass production, reinforced the widespread adoption of plastic bottles.

A key intervention in triggering tipping, as discussed previously, was the introduction of the mandatory deposit, *intervention* (I5(P)): after 2003, when it was first introduced, the reuse market share continued to decline sharply, whilst single-use rose equally quickly. Much of this can be attributed to the way in which the scheme was designed. For example, the recently introduced EPR scheme, which made companies responsible for their waste, had an underpinning assumption that the bottle reuse system could be preserved and that recycling could be stimulated. An important factor in this was the promise of and trust in the new recycling technologies; see (EC13). However, where the EPR scheme applied to packaging in general, only bottles were singled out for reuse, and, as already anticipated by experts at the time, since the recycling infrastructure did not incorporate reuse infrastructure, this favoured the single-use regime in general, making the reuse option for bottles unattractive. Also, the mandate required retailers to accept returns of all deposited single-use bottles, but this did not apply to reusable bottles. What is more, technologies such as vending machines improved the efficiency of the single-use system but did not accommodate reusables at that time. Additionally, the higher deposit for single-use bottles (25 ct) compared to reusables (8–15 ct) provided consumers with stronger incentives to choose single-use, contrary to the intended goal of making it less attractive (UBA, 2010). Single-use was thus both a simpler option for producers and more convenient and more worthwhile financially for consumers, whilst also appearing the most modern (EC7a).

In sum, the dual forces of R4, R5, and R6 conspire to undermine pool reuse and simultaneously enable single-use, whilst the intervention, which intended to preserve reuse, inadvertently triggered tipping to single-use.

Stabilisation of the single-use system.

The introduction of Germany's mandatory deposit system for single-use bottles created three parallel collection systems: the household dual system for recycling (for all packaging waste), the mandatory deposit–return system for single-use bottles, and the voluntary deposit–return system for reusables. This complexity led to confusion and frustration among consumers and businesses, making it difficult to navigate the various processes and understand the differences between single-use and reusable options. The varying deposit amounts and lack of clear information on environmental impacts further compounded the issue, giving consumers the false impression that all collection methods were equally environmentally friendly, which further stabilised the new regime (a lack of *informational cascades – B8*). Moreover, similarly to the previous tipping episode, as considerable efforts and investments had been spent, changing it back or finding yet another solution was associated with *high switching costs and risks* (B7) for individual companies.

4.4 2010s–today: current developments and looking ahead – continued interaction of reuse and recycling

The market share for reusable bottles seems to have stabilised at around 40 % from 2010 to 2020. In the meantime, the GDB has responded to current trends by introducing additional bottle sizes and designs. Currently, more than 70 % of all reusable bottles are GDB pool bottles (glass and PET) (GDB, 2023a); the rest are individual reusable bottles. Many established mineral water companies and retailers offer water in several packaging types, aiming at different consumer segments, while most discounters still exclusively offer single-use packaging. However, while LIDL relies on the alleged eco-efficiency of the bottle-to-bottle recycling system (Kolf, 2023), ALDI recently announced it would restart testing a reusable bottle system from 2024 in light of the strongly increasing political interest in promoting circular strategies (Bender, 2023).

With the increasing pressure exerted by policymakers to create a more circular economy (with ambitious targets for both reuse and recycling) and to do so swiftly, the question of how to bring about this change away from the linear economy and with interacting circular strategies – within the domain of packaging and elsewhere – is still highly relevant today. That is, how do we effectively design a circular configuration – a situation where two or more circular strategies interact (Blomsma and Brenna, 2017; Blomsma et al., 2023) – so that both business and environmental benefits are optimised? In the next section, we derive insights and guidance from this historical case both for academics aiming to understand and support the transition towards a circular economy and for change agents within policy and business involved in this transition.

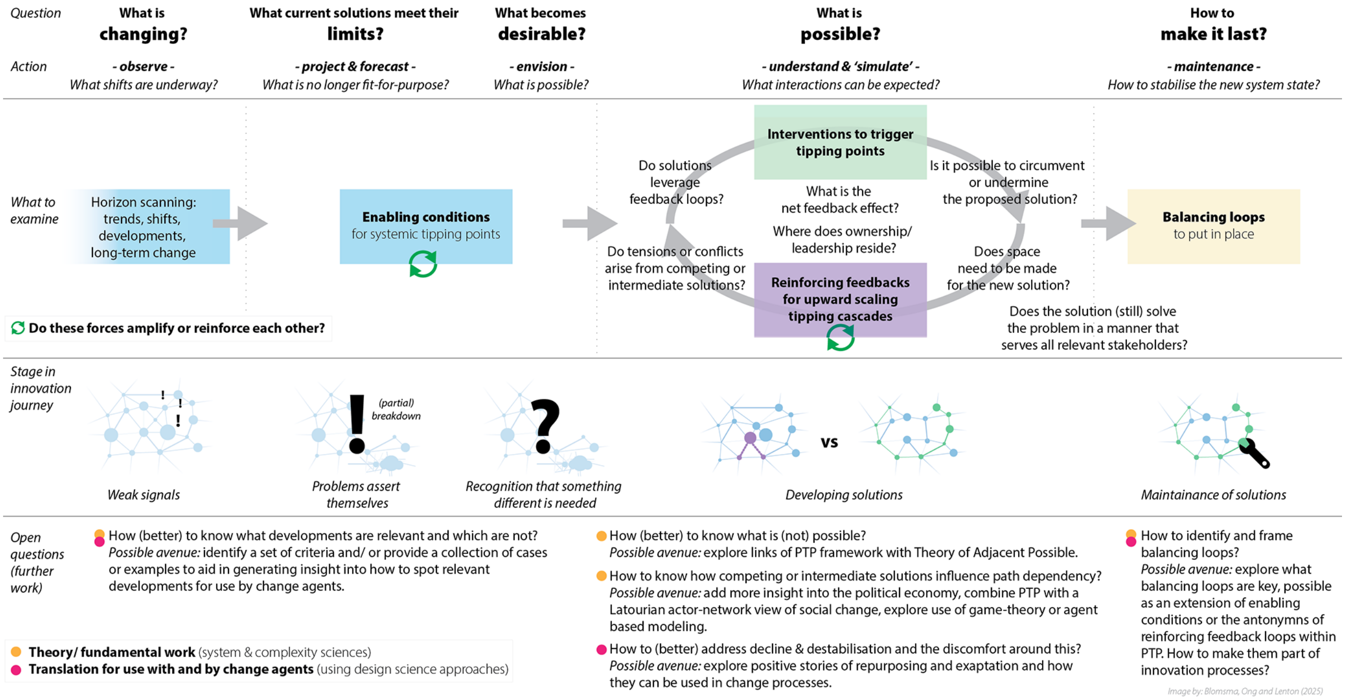

Figure 6. An overview of PTPs as a method: the steps that need to be taken and the key questions that need to be answered in order to gain insight into what interventions may bring about tipping for use in analysing current problems and designing suitable solutions.

5 Discussion

The unfolding of the two tipping episodes could be interrogated in an insightful manner through applying the PTPs framework. It has allowed the identification of what enabling conditions emerged, how this problematised current solutions, and what interventions set in motion which feedback loops. Figures 4 and 5 show how applying PTPs allows the richness in dynamics that played a role to be drawn out and show the importance of new solutions leveraging feedback loops to become established quickly. Alongside showing the analytical value of the PTPs framework, the case illustrated other change dynamics that are in line with established knowledge about decline and destabilisation, such as the repurposing of existing elements (reframing the reuse behaviour consumers already exhibited in tipping episode 1) or the possibility of a period of confusion and contention (the competing solutions in tipping episode 2).

5.1 Shifting balance of feedback loops

Distinguishing how the net balance of damping and reinforcing feedback loops shifted through three phases of destabilisation, tipping, and (re)stabilisation in each episode provides additional insight into PTPs. Notably, episode 2 shows how both a weakening of dampening feedbacks and a strengthening of reinforcing feedbacks played a role in the destabilisation phase. Then, the same reinforcing feedbacks augmented by additional ones were key to the tipping phase. Afterwards, in the stabilising phase, different dampening feedback to the ones that had stabilised the pool reuse state established stability of the single-use recycling state. An illustration of how the same reinforcing feedback can work in either direction is also seen across the two episodes. In episode 1, a network effect propelled the uptake of the pool bottle reuse system, whereas, in episode 2, it helped propel its demise. That is, the possibility of circumventing the GDB pool system – the possibility of not being part of the existing network structure – started to undermine and weaken it, and, the more the network was left, the less effective it became.

In addition, in episode 2, (part of) what destabilised the current system (pool reuse) at the same time enabled the new system to emerge (single-use combined with recycling) (e.g. R4–6). This (strong) dual force effect was not seen in episode 1. The linking of destabilising and tipping dynamics implies that this dynamic may indicate path dependency as a factor in tipping. That is, in episode 1, there was no pre-existing central solution: the circular strategy was only different in its execution (from company-specific reuse to pool reuse) and relied largely on different practices within business within the sector (thus limited in the number of actors involved and no change for consumers). As such, only limited destabilisation of the pre-existing solution was needed. This was not so for episode 2: there was a pre-existing central solution, the change was to a different circular strategy (recycling), and the change involved both packaging in general and consumers. Therefore, how to "make space for the new" seems an important phenomenon to pay attention to in tipping, and both the nature of the pre-existing system and the nature of the proposed change (how (dis)similar they are) are relevant factors, but how exactly this can or should happen – dismantling, repurposing, exaptation, etc. – with regard to sustainable transitions requires further work.

Possible fruitful avenues to further investigate these phenomena could be linking and extending the PTPs framework with work, for example, on path dependency (e.g. Arthur, 1989; Mahoney and Thelen, 2009) and the Theory of the Adjacent Possible (Kauffman, 1996, 2000). Moreover, and specific to a circular economy, there is scope to design (economic) experiments to examine the conditions controlling the tipping between reuse and recycling systems. Approaches based on existing experimental economics studies on tipping into or out of coordination and tipping of social norms (e.g. Barrett and Dannenberg, 2014) could serve as examples, that is, experiments where a large number of groups "play the game" under different conditions in order to build up statistical learning that is then used for modelling. "Natural experiments", such as those taking place in the Netherlands and Germany at the moment, where attempts are being made to reintroduce reuse and improve recycling rates, could also be used to gain insight into relevant dynamics and to inform the further rollout of similar interventions in other countries.

5.2 Wicked solutions: leadership, ownership, and actor networks

Another key takeaway from the bottle reuse case is that the solution introduced in episode 2 is not desired by those involved. Although it is difficult to speculate what would have been the "best" solution, it is clear that, compared to episode 1, episode 2 shows failure when it comes to leadership and ownership of the solution. In episode 1, the GDB, in which members also hold an ownership stake, plays a key role in bringing together stakeholders in the design phase and managing the resulting pool reuse system. Compare this to episode 2, where a simplistic view involving wishful thinking of policymakers when it comes to the impact of the Packaging Regulation and a wait-and-see approach by both business and policy result in a wicked solution (Rittel and Weber, 1973). What this points to is that PTPs could benefit from more insight into the political economy (lobbying, formation of interest groups, etc.), as these dynamics are not currently explicitly included in the framework. One fruitful avenue is to further explore both social tipping points (Smith et al., 2020) and linkages with other work on cross-sectoral collaboration (Dentoni et al., 2021; Stadtler et al., 2024). (Elements of) game theory and agent-based modelling can also be included as part of the method to think through the responses of various actors and understand how the behaviour of the system as a whole is influenced by this.

5.3 Balancing loops and why slower can be faster (or better)

A last takeaway is the influence of balancing loops post-tipping that we observed in the two tipping episodes. These are important in two ways. Firstly, if tipping results in a system that is undesirable, there is a certain lock-in effect as resources are spent (finance, attention, motivation, etc.), and the new solution is likely to be stable for at least some time, as both tipping episodes were. This is an important argument for proceeding with caution. In fact, it may be why "slower = faster": pursuing speed for the sake of speed risks a loss of momentum.

Secondly, when the change is indeed desirable, there may be a need for maintenance or after-care to stabilise the new system in order to actively maintain balancing feedback loops, that is, to not become complacent and take the solution for granted. Whilst, in episode 1, these efforts were eventually not sufficient to stop the second tipping episode, they may have delayed its onset. This does not necessarily mean that the solutions need to be rigidly adhered to, but, as with the pool reuse system in episode 2, it requires continuous improvement to keep up its fitness and to ensure it is resourced independently of other developments, otherwise it will deteriorate. In other words, how can maintaining balancing loops be made resilient? One fruitful avenue to gain further insight into this could be to explore additional cases of balancing dynamics and how these lessons could be used to extend the PTPs framework.

5.4 PTPs as a method for designing interventions

Working with the PTPs framework and the insights it generated have led us to compose a process model of PTPs, describing the steps and the key questions that need to be answered when using PTPs as a method to develop solutions and innovations for current problems, that is, how to use PTPs as a method; see Fig. 6. Along with extending it with steps at the beginning and end to form a process, the centre contains an iterative loop, where the interventions and the reinforcing feedback loops are considered in turn, whilst key questions are answered along the way. In this manner, the PTPs framework facilitates a focus on the dynamics and interaction of various forces and enables those using the framework to consider different scenarios and interactions. The key questions, based on this current work, force a critical perspective on the proposed solutions and force us to test the viability and robustness of proposed solutions.

6 Conclusions

Through a historical case study consisting of two tipping episodes examined through the positive tipping points (PTPs) framework (Lenton et al., 2023a, b), we gained insight into the dynamics of tipping and, in particular, on how destabilising and enabling feedback loops are related. That is, if the proposed change involves a pre-existing central solution, a qualitatively different solution, and a large number of actors, destabilisation may be an integral part of tipping. As such, there is a need for interventions that steer both *towards* what is desired and *away* from what is not wanted simultaneously, whilst considering how different solutions may influence each other.

In light of this, Buckminster Fuller's famous quote, "you never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete", whilst it may have been true in his time, now has to be adapted to say "to change something, you have to fight the existing reality, whilst *also* building a new model that makes the existing model obsolete". For a circular economy, this means that it needs to be understood how the linear economy can be outcompeted and how different circular strategies may interact. Whilst these are not necessarily new insights separately, this study shows the relevance of both simultaneously.

A key implication of the insights on destabilisation and wicked solutions – for both knowledge creation and impact-driven work – is that whole system or systemic design is needed, combined with a human-centred perspective on change and change management. Solutions cannot be designed in isolation without considering both what is being replaced and the dynamic that competing and intermediate solutions bring to the table and what competing and conflicting interests are involved. In this sense, our work offers support for the emergent domain of translational systems sciences, specifically systemic design (e.g. Jones and Kijima, 2018; Jones and van Ael, 2022), which seeks to understand and influence complex, interconnected systems by considering all their components, relationships, and potential futures by combining holistic, interdisciplinary approaches with creative design thinking and rigorous systems analysis. Our study provides an example of how design science approaches can be used for further developing PTPs: through a case study, insights are derived that are then codified in a first version of a prescriptive tool and method. These are the first steps in design science approaches, such as DRM (Blessing and Chakrabarti, 2009) or eDSR (Tuunanen et al., 2024), where insights are translated into a prescriptive framework or method, which are then further refined through additional cases and field work. We encourage and welcome such further work.

Data availability. All source data are provided in the text and associated references.

Author contributions. MKCFO designed the study and conducted the data collection. FB and MKCFO structured the data. MKCFO wrote an initial draft of the paper with input from FB and TML. FB led the preparation of subsequent submissions. FB and MKCFO prepared the figures with input from TML. TML contributed the theoretical framework and edited the paper in each submission round.

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