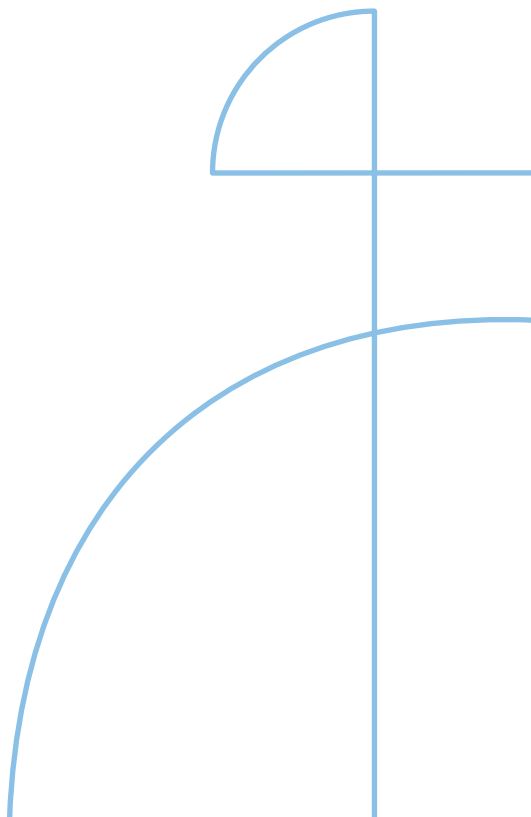
Doctoral Thesis in Industrial Economics and Management

Sorting out Circularity

Meanings, Practices and Temporal Dynamics in Industrial Recycling

BEATRIZ PÉREZ HORNO

KTH ROYAL INSTITUTE OF TECHNOLOGY



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To my parents, Jerónimo and Julia.

Abstract

In today's societies of abundance, almost anything can become waste, from worn-out possessions to newly manufactured products that were never used. This is not incidental, but a direct expression of an economic logic that treats resources as endless. Growing concerns over resource security, environmental pressure and geopolitical uncertainties surrounding access to critical resources have intensified calls to rethink these systems. Several approaches and pathways have been proposed against this background, with the Circular Economy (CE) gaining prominent attention across policy, industry and academia. Yet, despite its momentum, global circularity is in decline.

This thesis examines the gap between CE visions and their realisation, through an empirical study of industrial recycling practices. Methodologically, this thesis draws on three case studies: the well-established steel recycling systems of Sweden and Austria, the formal and informal recycling sectors in Kenya, and the emergent solar panel recycling system in Sweden. Data comprises 22 on-site observations, 47 interviews, 3 focus group discussions, document analysis and complementary workshops, analysed using thematic analysis and system dynamics modelling.

Drawing on five articles, the thesis shows that circularity is not an inherent property of so-called "circular" practices, but an emergent, multidimensional and temporally bound outcome of how they are interpreted, configured and interrelated over time. While official definitions in policy and standards legitimize almost any recirculation of material as recycling or circular, achieving circularity in practice is a context-sensitive endeavour that requires explicit consideration of trade-offs across CE objectives. Moreover, these trade-offs unfold over time, meaning that today's recycling choices can quietly

compromise future circularity. Thus, circularity requires managing not only present resource flows but also preserving future ones. With upstream decommissioning and design practices influencing the quality and quantity of materials entering recycling systems, and thereby the economic viability of investing in more specialised recovery technologies, recycling systems must remain adaptable to accommodate past, present and future material compositions and designs.

Achieving a CE thus requires more than increasing recycling rates or improving technologies; it requires rethinking the meanings, priorities and practice configurations that determine how resources are valued, managed and circulated over time, and requires metrics and interventions that account for these trade-offs and temporal effects. This thesis makes a central contribution by extending practice studies to the practices of industrial operators and by pairing it with System Dynamics to trace how present recycling shapes future circularity. Empirically, the thesis offers a grounded account of recycling across materials, institutional settings and levels of maturity; practically, it equips policy and industry actors to evaluate and prioritise circularity with a clearer understanding of its trade-offs, both across objectives and across time.

Keywords
Circular Economy, Circularity, Recycling, Practice Theory, System Dynamics, Temporality, Trade-offs.

Sammanfattning

I dagens överflödssamhälle kan nästan vad som helst bli avfall, från utslitna ägodelar till nytillverkade produkter som aldrig har använts. Detta är inte en tillfällighet, utan ett direkt uttryck för en ekonomisk logik där resurser betraktas som oändliga. Ökande oro för resursförsörjning, miljöbelastning och geopolitiska osäkerheter kring tillgången till kritiska resurser har förstärkt behovet på att tänka om kring dessa system. Mot denna bakgrund har flera angreppssätt och vägar framåt föreslagits, där den cirkulära ekonomin (CE) har fått stor uppmärksamhet inom politik, näringsliv såväl som akademi. Trots detta ökande fokus minskar den globala cirkulariteten.

Denna avhandling undersöker diskrepansen mellan visionen om en Cirkulär Ekonomi och dess realisering genom en empirisk studie av industriell återvinningspraxis. Metodologiskt bygger avhandlingen på tre fallstudier: de väletablerade systemen för stålåtervinning i Sverige och Österrike, den formella och informella återvinningssektorn i Kenya samt det framväxande systemet för återvinning av solpaneler i Sverige. Datamaterialet består av 22 observationer på plats, 47 intervjuer, 3 fokusgruppsdiskussioner, dokumentanalys samt kompletterande workshops, som har analyserats med tematisk analys och systemdynamisk modellering.

Med utgångspunkt i fem artiklar visar avhandlingen att cirkularitet inte är en självklar egenskap hos så kallade ”cirkulära” aktiviteter, utan ett framväxande, flerdimensionellt och tidsbundet resultat av hur de tolkas, konfigureras och samspelar över tid. Medan officiella definitioner i policy och standarder legitimerar nästan all återcirkulation av material som återvinning eller som cirkulär, i praktiken är cirkularitet en kontextberoende omställning som kräver

att konflikter mellan olika mål inom CE beaktas explicit. Dessa konflikter uppstår också över tid, vilket innebär att dagens val inom återvinning kan begränsa cirkularitet i framtiden. Cirkularitet kräver därmed inte bara att dagens resursflöden hanteras, utan också att framtida resursflöden bevaras. Aktiviteter uppströms, såsom avveckling och design, påverkar kvaliteten och mängden material som tillförs återvinningssystemen och därmed även den ekonomiska bärkraften i att investera i mer specialiserad återvinningsteknik. Återvinningssystem måste därför förbli anpassningsbara för att kunna hantera materialssamsättningar och design från det förflutna, nuet och framtiden.

Att uppnå en cirkulär ekonomi kräver således mer än att öka återvinningsgraden eller förbättra tekniken. Det kräver att vi omprövar de definitioner, prioriteringar och konfigurationer som avgör hur resurser värderas, hanteras och cirkuleras över tid, samt utvecklar mått och interventioner som tar hänsyn till dessa konflikter och tidsmässiga effekter. Sammanfattningsvis är avhandlingens centrala bidrag att bredda studier av praxis till att omfatta industriella operatörers praktiker samt att kombinera detta med systemdynamik för att följa hur dagens återvinning formar förutsättningarna för framtida cirkularitet. Empiriskt ger avhandlingen en förankrad beskrivning av återvinning över olika material, institutionella kontexter och grader av systemmognad. Praktiskt ger den aktörer inom politik och näringsliv bättre förutsättningar att bedöma och prioritera cirkularitet genom en tydligare förståelse av dess avvägningar, både mellan olika mål och över tid.

Nyckelord
Cirkulär ekonomi, Cirkularitet, Återvinning, Practice Theory, System Dynamics, Temporalitet, Trade-offs.

Acknowledgments

"Caminante, no hay camino, se hace camino al andar", Antonio Machado.

Little did I know when I first embarked this journey where it would take me. These four-and-a-half years have been packed with uncertain steps, frustrations, detours, good and bad decisions, and the "killing" of many darlings. The journey has eventually become bound within the covers of the thesis you now hold. Its process has been reduced to a (hopefully) coherent narrative and a single title, yet the path leading here was far from straightforward. And while, in many ways, it was a very lonely path, it was never entirely so. This thesis is shaped by encounters, conversations, disagreements and acts of generosity. It is shaped by the many people who, knowingly or unknowingly, left their traces along the way.

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Beatriz Pérez Horno

Stockholm, December 2026

List of publications

Paper A | *Pérez Horno, Blomsma* and *Feldmann (Under review). What is this thing called recycling?*

Author contribution: *I am the first author of this opinion paper and played a leading role in the conceptualization, formal analysis and writing of the original draft. All co-authors supported the conceptualization, design of methodology and revision of the paper. The main visual underpinning the paper's argument was developed collaboratively by all authors.*

Paper B | *Pérez Horno (Under review). Competing Circularities: How different socio-material practice configurations generate competing objectives in recycling systems.*

Author contribution: *I am the sole author of this paper. The data collection was conducted together with other knowledgeable interviewees for triangulation purposes: Andreas Feldmann, Peter Samuelsson, Sabine Dworak, Johanna Olofsson Behrman, Cali Nuur,* Emmanuel Yahuma and John Musyoka; each on the respective studies.

Paper C | *Pérez Horno, Feldmann and Samuelsson (2025a). Lost in the shuffle: A taxonomy for the accumulation of unwanted elements in steel recycling. Waste Management & Research. Volume 43 (12). Pp. 1962-1974. https://doi.org/10.1177/0734242X251350541.*

Author contribution: *I am the first author of this paper and played a leading role in the investigation, formal analysis, visualization and writing of the original draft. All co-authors supported the conceptualization, design of methodology and revision of the paper. The data collection was conducted together with the coauthors and RJ Compañero in Sweden, and with Sabine Dworak in the Austrian cases.*

Paper D | *Pérez Horno, Feldmann and Samuelsson (2025b). Mapping the dynamics shaping the future of steel recycling. Discover Sustainability. Volume 6 (808). https://doi.org/10.1007/s43621-025-01750-4.*

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Paper E | *Pérez Horno, Feldmann and Nuur (2025c). Shedding light on decommissioning solar panel streams: A system dynamics model for volume estimation. Resources, Conservation & Recycling Advances. Volume 26. 200252. https://doi.org/10.1016/j.rcradv.2025.200252.*

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1 INTRODUCTION

"There is only one planet Earth, yet by 2050, the world will be consuming as if there were three" (European Commission, 2020, p.1). Contemporary economies depend on the continuous extraction of resources to sustain production and consumption, while resource depletion, supply chain shocks and geopolitical tensions over raw materials increasingly expose the vulnerabilities of these (Baldassarre, 2025). In response, the Circular Economy (CE) has emerged as one of the most visible and politically influential approaches for rethinking how resources are produced, used and retained in the economy (Figge et al., 2023). Its ambitions have gained substantial traction across policy, industry and academia, showing considerable efforts to translate them into practice. Yet despite growing attention, global circularity continues to decline (Savini, 2025). This gap between the ambitions articulated in CE discourse and their realisation in industrial practice is the focus of this doctoral dissertation.

The gap may partly reflect the way the CE has been constructed. Far from being a novel paradigm, the CE brings together a range of practices that were not necessarily originally developed to achieve its objectives but are now expected to contribute to its broader ambitions (Morseletto, 2023; Blomsma and Brennan, 2017). These practices are commonly captured by the so-called R-strategies: refuse, reduce, rethink, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover; hierarchically ordered after their perceived circularity potential (Reike et al., 2018). The CE thus encompasses a range of ambitions that articulate how resources should ideally be used and managed, providing a reference or lens against which practices or systems can be assessed in terms of their contribution to circularity. What constitutes a desirable form of

circularity, though, remains contested (Korhonen et al., 2018a) and different visions of a CE exist (Suárez-Eiroa et al., 2026).

Of all strategies, this thesis focuses on recycling. While remaining at the bottom of the hierarchy, "recycling is currently the centre of the transition, both due to its magnitude and prominence and since it offers a viable experiment on how to apply the principles of CE into practice" (Abbas et al., 2026, p.3). Recycling is the most practiced and most readily engaged-with circular strategy among industry actors (Baldassarre and Saveyn, 2023) and has also been the primary focus of policy-related initiatives (Losa, 2025). As a CE strategy, recycling is intended to contribute to the recirculation of materials. However, circularity entails more than returning materials to the system, it concerns minimising reliance on virgin resources, keeping products and materials in use for longer, retaining their quality and value over time, and reducing waste and material losses across successive cycles (Figge et al., 2023; Blomsma and Tennant, 2020). These objectives, however, do not necessarily align. Extending material circulation may involve losses in quality, while minimising waste may not lessen reliance on virgin resources. Recycling therefore contributes to circularity only to the extent that all these objectives are realised or pursued.

Assessing the contribution of recycling to CE requires clarifying what is understood as recycling in the first place. As a long-established practice that predates the CE, it is necessary to examine what recycling constitutes and whether its definition now reflects the ambitions of the CE. Beyond its interpretation, recycling's contribution ultimately depends on how it takes place in practice. A substantial body of work has examined the economic, market and technological conditions shaping recycling outcomes and potential contribution. Complex product compositions, material losses across collection and processing, high processing costs, and fluctuating and uncertain markets can all limit what recycling can achieve in practice (Hagelüken and Goldmann, 2022; Meskers et al., 2024). These conditions, however, do not operate independently but come together in the organisation and performance of practices.

Changes in technologies, policies or market dynamics are thus reflected in changes in practices (Greene and Hobson, 2025). At the same time, resources do not circulate by themselves but do so through the operators who keep material flows *flowing*. Through practices of discarding, collecting, dismantling, sorting and processing, operators determine what materials are recovered, transformed and ultimately directed towards different uses, thereby shaping

their quality and value (Fuentes and Hedegård, 2025). All this draws on Practice Theories.

Practice Theories emerged as a shift from explaining social life through individual attitudes or overarching structures towards understanding how it is organised, reproduced and transformed through practice (Schatzki, 2001). This approach has become increasingly influential in sustainability research, where it has been used to examine both the reproduction of (un)sustainable practices and the conditions for their reconfiguration (Shove, 2023). In CE research, Practice Theories have similarly been used to examine how circularity is enacted through everyday practices (Schulz et al., 2019). However, this work has focused predominantly on consumption, paying comparatively little attention to the practices of the industrial operators involved in recovering, transforming and recirculating materials. Looking at operators' routine actions however is particularly relevant for recycling, since these directly shape what happens to materials and therefore what circularity can be achieved.

Recycling, however, does not end with a single cycle. Materials are expected to go through successive cycles of use, recovery and transformation, where the outcomes of one cycle influence the conditions for the next. Accumulation, degradation and changes in material availability can extend the consequences of recycling practices beyond their immediate enactment, shaping the conditions for future recycling. Understanding circularity in recycling consequently requires attention not only to operators' routine actions at a given point in time, but also to how these actions and their consequences unfold across successive cycles (Grafström, 2026).

All these conditions, practices, challenges and trade-offs are unlikely to be uniform across materials, products and regions. This thesis, thus, builds on three contrasting contexts: steel recycling in Sweden and Austria, representing a well-established system for a theoretically infinitely recyclable material; metal and e-waste recycling in Kenya, where formal and informal recycling operate within a markedly different institutional setting; and solar panel recycling in Sweden, where a specialised recycling system is yet to emerge and is constrained by low volumes of waste. Together, these contexts form the empirical basis for examining the gap between expected and realised circularity in recycling.

1.1 Research aim and objectives

This dissertation aims to bring nuance to the gap between CE ambitions and their realisation through the empirical study of industrial recycling practices. Central to this is understanding ***whether and how current industrial recycling practices produce circularity, and with what implications for achieving CE ambitions over time.*** Three research objectives (ROs) guide this investigation:

RO1. To examine whether and how existing recycling definitions and interpretations reflect the ambitions of the CE. Definitions establish which activities and outcomes count as recycling. They therefore reveal, from the outset, whether and to what extent circularity is embedded in what is understood as recycling. Through a comparative analysis of recycling definitions across policy, standards and academic sources, this objective contributes to understanding how recycling is connected to circularity at the definitional level, and whether different definitions, embed different assumptions about what constitutes recycling and, subsequently, circularity.

RO2. To analyse whether and how current industrial recycling practices produce circularity and which types of circularities they produce. This objective examines the practices of the actors involved in industrial recycling and how these practices affect and produce different forms of circularity. Through the observation of, and interviews with, practitioners engaged in industrial recycling across three case contexts, this objective contributes empirical knowledge on how circularity is produced through recycling practices and which dimensions of circularity these practices enable (or constrain).

RO3. To investigate whether and how current industrial recycling practices enable future circularity and which types of circularities they enable. Assessing circularity at a single point in time cannot capture whether current practices come at the expense of future recyclability and circularity. This objective extends the analysis over time and situates recycling within its interactions with adjacent practices like design and decommissioning, recognising that practices are interrelated (Hui et al., 2017). Drawing on observations, interviews, focus groups, workshops and documents, the analysis uses System Dynamics to examine how these interactions shape future circularity. Through this, this objective contributes knowledge on how current

recycling practices enable or constrain the conditions and forms of circularity achievable in the future.

1.2 Research significance

This dissertation advances current understanding of circularity by bringing two often-overlooked considerations to the centre of the analysis: the routine practices through which operators circulate materials and the temporal dynamics through which present practices influence, and sometimes compromise, future circularity. Its contribution spans theory, methods and practice. Theoretically, this thesis extends the application of Practice Theories to industrial recycling practices, highlighting the role of operators' routines in shaping circularity in practice. Methodologically, it demonstrates the value of examining circularity at the level of practice and over time, including feedback loops, delays and accumulations that can reveal implications that remain hidden in static assessments. Practically, it suggests that achieving circularity requires evaluating and governing circularity through metrics and interventions that extend beyond the mere circulation of material, accounting for its different conflicting dimensions and their future implications.

1.3 Structure of the thesis

The remainder of the thesis is structured as follows. Chapter 2 reviews how the CE has been conceptualised and studied in the literature, with particular attention to the tensions and mismatches between its vision and its practice. Chapter 3 introduces recycling as a site for exploring circular practice, presenting its origins, evolutions and role inside and outside of the CE. Chapter 4 presents the theoretical framework that informs the synthesis and (re)interpretation of the assembled body of work. Chapter 5 describes the research design, methodological choices and the academic journey through which the research evolved. Chapter 6 presents and summarises the appended papers. Chapter 7 discusses the main findings of the thesis and situates them within ongoing conversations in CE research and practice-based approaches to circularity. Finally, Chapter 8 concludes the thesis by summarising the key contributions and broader implications of the research.

2 CIRCULAR ECONOMY: FROM VISIONS TO PRACTICE, AND THE GAPS IN BETWEEN

The Circular Economy (CE) encompasses a range of normative ambitions aimed at keeping resources in use for as long as possible. In this thesis, CE is not treated as a formal theory, but as the reference through which (recycling) practices are assessed, shaping what is understood as desirable or undesirable, right or wrong, acceptable or problematic. The following chapter briefly presents the evolution and ongoing discussion on the CE as both a vision and a practice, highlighting the gap between the two.

2.1 The vision of a Circular Economy

As an idea, the origins of the CE remain relatively recent and somewhat ambiguous, commonly dated back to the "environmental awakening" during the 1960s and 70s (Valenturf and Purnell, 2021). CE has taken shape from the integration of heterogeneous sources of inspiration, drawing upon cradle-to-cradle, performance economy or natural capitalism, among others (Geissdoerfer et al., 2017). Although influenced by seminal writings like Kenneth Boulding's metaphor of the Spaceship Earth (1966) and intellectuals like Nicholas Georgescu-Roegen or Walter Stahel, the formal introduction of the term is most commonly credited to Pearce and Turner (1990), who used it to describe a closed-loop system of economy-environment interaction in contrast to

prevailing linear models[1]. The CE is connected to and has been studied from a range of academic disciplines, most notably Industrial Ecology and Ecological Economics (Bruel et al., 2018). Through time, the idea has evolved and bifurcated in various streams, creating what Alvesson and Blom (2020, p.3) call a *hembig*: "a scientific concept characterised by its broad scope and ambiguous meanings, (…) [preventing] the development of a more precise terminology".

Extensive reviews such as Homrich et al. (2018) or Kirchherr et al. (2023) and meta-umbrella reviews like Hossain et al. (2024) have covered the multiplicity of definitions and understandings of CE with no success in reaching a consensus on what CE is or should be. In other words, CE remains a contested concept (Korhonen et al., 2018a). There is, thus, little analytical value in either reproducing or choosing from the many existing definitions or adding yet another to the already extensive body of literature. It is therefore more meaningful to clarify what is meant by CE, focusing on its underlying principles.

Several studies have attempted to distil the underlying principles and core logics of CE (e.g. Valenturf and Purnell, 2021). These efforts vary depending on disciplinary orientation and normative intent, but they broadly converge around a few central ideas. In simple terms and common to most accounts, CE aims to (1) design out waste, either by preventing waste generation on the first place, or through recycling, repair or reuse (Eelager et al., 2025). Ideally, this would lead to (2) minimising or avoiding the extraction and use of virgin materials from Earth (Figge et al., 2023), and thus their substitution with secondary resources (Blomsma and Tennant, 2020). By reallocating and revalorising waste as a resource, CE aspires to (3) close resource loops through the implementation and enactment of the R-strategies (Reike et al., 2018). This means that resources are continuously cycled back into the system, (4) keeping them in use at their highest value for as long as possible (Hagelüken and Goldmann, 2022).

Through these R-strategies, CE seeks to (5) maintain or create value from what otherwise would become waste. Some scholars further highlight that the CE should not only prevent future harm but also (6) restore the harm caused in the

[1] The term linear economy or linear economic model, commonly characterised by the take-make-dispose model, is widely used to describe dominant modes of production and consumption. Although visually compelling, this tends to overlook the long-standing presence of practices such as repair, reuse and recycling. Accordingly, while the term is maintained where appropriate to reflect this established narrative, this thesis recognises that industrial systems have rarely been purely linear (Morseletto, 2023).

past (Murray et al., 2017). Achieving this requires a (7) multi-level or systemic perspective, applying CE principles at the micro-, meso- and macro-levels (Kirchherr et al., 2023). Lastly, and perhaps most controversial, CE has increasingly been framed as (8) a pathway to economic prosperity and growth, promoted as a means to decouple environmental impact from economic activity (Ghisellini et al., 2016). In this way, CE is expected to (9) create jobs, new business opportunities and markets, reduce costs and dependency on imports, and increase supply resilience (Geissdoerfer et al., 2017). In essence, the CE envisions a "spaceship" system in which resources circulate indefinitely, material losses are minimised and, optimally, nothing becomes waste (Boulding, 1966). In fact, the notion of waste is largely absent (or deliberately avoided) in CE debates.

There is, however, no unanimous vision of a CE. The prioritisation and pursuit of any or all these principles varies across discourses (Suárez-Eiroa et al., 2026). These span across two broad positions: a techno-optimistic perspective that emphasises digitalisation and innovation as central to CE's success and/or a more critical perspective that questions growth-oriented models altogether, centring instead on a less wasteful, more conscious production and consumption (Bauwens et al., 2021; Calisto Friant et al., 2020). Across these visions, the following principles tend to recur and are therefore given primary focus in this thesis.

Primary CE principles considered in this thesis

- Minimise or avoid the extraction and use of virgin materials, substituting these with secondary resources.
- Keep products, components and materials in use for as long as possible and at their highest possible quality and value.
- Design out waste and close resource loops through the implementation and enactment of the R-strategies.

The promise of CE has not come without criticism. Critics have increasingly challenged CE's underlying assumptions, subjecting their taken-for-granted claims to closer scrutiny (Corvellec et al., 2022; Figge et al., 2023). These have questioned CE's environmental and social benefits, unclear implementation pathways, reliance on corporate-led win-win narratives and the tendency to aggregate practices without delivering systemic change (Corvellec et al., 2022). Further work has pointed to physical limits like thermodynamic constraints, as

well as spatial, temporal, organisational and institutional barriers, including path dependencies and conceptual ambiguities around waste (e.g. Korhonen et al., 2018b). Collectively, they call for empirical evidence of how CE works in practice (Mignacca et al., 2025).

2.2 Circular Economy in practice

Circular Economy has become a buzzword present in political debates, legislative agendas, business strategies and even everyday conversations (Desing et al., 2020). Yet far from new, it was the dominant economic model, practiced for economic purposes for hundreds of years (Morseletto, 2023). In fact, it was only after low-cost mass-production techniques reduced the cost of materials, products and processes, that circular strategies experienced decreased attention (Worrell, 2014).

In many ancient societies, people routinely reused materials out of necessity or scarcity. For instance, old pottery pieces were turned into new clay for ceramics and clothes were reused and shared across generations (Werret, 2013). Circularity was the norm and required no special vocabulary for its practice. In the Roman Empire and Middle Ages, recycled metals and glass existed because these materials were valuable and scarce (Furlan and Andreatta, 2023). Even in the rise of industrialisation, reuse and recycling practices were present. Thus, while the formal concept of CE has been articulated only in recent decades, the practices underlying it, such as reuse, repair, recycle and repurpose, have deep historical roots and have been part of human economic activity all around, yet for different purposes (Morseletto et al., 2023).

These practices already embodied some core principles and aims of today's CE vision. Yet "the current challenge of CE is not to return to the previous model but to invent a new one, where requirements of traceability, hygiene, lower environmental impact and quality are respected" (Aggeri, 2020, p.9). This means that achieving a CE is not simply a matter of reverting to past ways of doing things, contemporary circularity unfolds with different socio-political contexts and institutional structures, is shaped by concerns such as hygiene and environmental impacts, and takes place under pressure from resource depletion or geopolitical tensions and as part of a world focused on advancing digital infrastructures, global supply chains and sophisticated lifestyle standards (Savini, 2019; Valenturf and Purnell, 2021). Consequently, circularity today must be understood as historically situated and context-dependent, rather than a straightforward revival of earlier models.

In principle, CE practices reflect a shift from conventional waste management towards more transformative approaches that aim to extend product lifetimes and prevent waste generation from the outset (Morseletto, 2020). In practice, however, their implementation remains uneven. Downstream practices, particularly recycling, continue to dominate (Baldassarre and Saveyn, 2023), while upstream practices like reducing or refusing resource use are hardly considered or implemented (Schöggl et al., 2020; Schulz et al., 2019). This may be because the former are often "the easiest to implement [since] they do not require systemic reorganisation" (Kirchherr and Hartley, 2025, p.1053). Figure 1 visualises these practices across a product's lifecycle, where each represents different forms of intervention across these, ranging from strategies that avoid or extend the use of products and materials to strategies that act at the end-of-life.

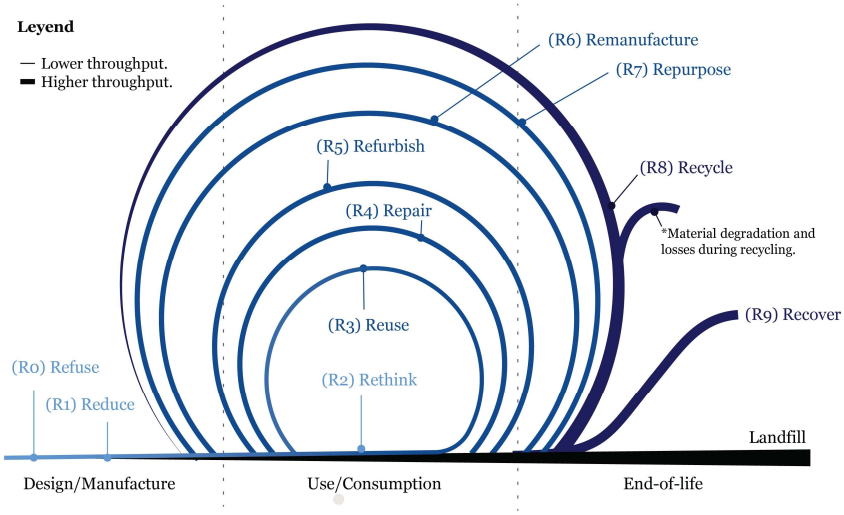

Figure 1. Circular Economy practices across lifecycles.

While these practices predate the concept itself, the way they have been brough together and promoted under the CE framework has been largely shaped and advanced "by actors in the government and private sectors, which have specific political and economic agendas" (Calisto Friant et al., 2020, p.1). The institutionalisation of CE and its establishment in the political debate have seen two distinct routes: the top-down integration in China and the bottom-up approach taken by the EU and other countries like Japan (Ghisellini et al., 2016). In Europe, the publication of the Circular Economy Action Plan in 2015, followed by its updates in 2020 and 2025, integrated CE into policy (Baldassarre

and Saveyn, 2023). CE is now a central pillar of the EU Green Deal and is widely regarded as a key strategy for achieving sustainable development (Hagelüken and Goldmann, 2022). However, the emergence of CE in public discourse was not driven by policy alone; organisations such as the Ellen MacArthur Foundation played a significant role in promoting the concept (Murray et al., 2017).

Beyond its articulation in policy, the CE has increasingly been translated into practice across multiple levels: from firms and individuals (micro) to industries and sectors (meso) and cities, regions and nations (macro) (Kirchherr et al., 2023). At the micro-level, individuals engage in actions such as reusing, repairing, sharing and sorting materials. However, these rely on the availability of infrastructures, services or products that make them feasible and convenient (Hedlund and Jaca, 2025). These options are partly shaped by firms, which seek to reduce resource use, costs and waste by redesigning products, reorganising supply chains, adopting new business models or increasing the use of secondary materials (Grafström and Aasma, 2021).

At the meso-level, CE implementation is primarily pursued through the inter-organisational exchange of materials, energy, water and by-products (Ghisellini et al., 2016). Here, the feasibility of the CE depends on sector-specific conditions, available infrastructures, institutional arrangements, technological capabilities and the functioning of secondary material markets (Abbas et al., 2025; Suárez-Eiroa et al., 2026). The scope for circularity therefore differs across sectors. While activities such as reuse and repair have proven viable in sectors such as fashion or automotive, many industries struggle to implement the full spectrum of strategies economically (Hossain et al., 2024).

At a macro-level, circularity is further shaped by the institutional and market contexts in which practices take place. Countries differ in the extent to which policies, standards, infrastructure investments or instruments like carbon pricing support or constrain circularity (Abbas et al., 2026; Losa, 2025). Sustainability challenges also vary across regions, requiring context-specific responses rather than uniform solutions (Valenturf and Purnell, 2021). As a result, CE implementation is embedded within existing institutional and market structures and often builds on established systems, which influence both the opportunities for change and the forms that CE takes place in practice (Suárez-Eiroa et al., 2026).

2.3 The gap between vision and practice

Taken together, the preceding sections point to a gap between the normative ambitions associated with the CE and the ways in which it is realised in practice. As Desing et al. (2020, p.1) caution, "there is no guarantee that simple strategies of material cycling will lead to an economy able to manage the world's resources, pollution and societal demand within environmentally sustainable levels". The circulation of materials, then, should not be equated automatically with the achievement of a CE.

This gap has been attributed to a combination of physical, economic, cultural and market conditions. At a fundamental level, perfectly closed material cycles are physically impossible since quality and quantity losses are unavoidable (Korhonen et al., 2018b). These limitations are reinforced by economic and market conditions that continue to favour linear forms of resource use. Prevailing price structures favour cheap, accessible primary resources over circular ones, that instead demand high upfront investments and organisational adjustments (Valenturf and Purnell, 2021). These are embedded within broader cultural and institutional structures that have historically developed around extractive and wasteful linear models (Greer et al., 2021). Introducing circular strategies under such conditions therefore does not necessarily produce systemic transformations (Calisto Friant, 2025). Instead, stakeholders prioritise incremental improvements in resource efficiency over more fundamental reduction in production and consumption (Schulz et al., 2019).

This gap between vision and practice is mostly measured through circularity metrics or indicators. Such metrics typically seek to quantify how effectively resource flows are closed, slowed or narrowed. Estimates based on these approaches suggest that only 8.6% of the world was circular in 2021 and has declined ever since (Kirchherr et al., 2023b). While such figures provide a useful indication of the scale of the challenge and enable comparisons across products, systems and over time, they largely depend on how circularity is defined and operationalised. That is, circularity indicators may only capture part of what the concept aspires to achieve. Commonly measured through Material Flow Analysis (MFA) and Life Cycle Assessments (LCA), estimates may be less equipped to capture material quality degradation, resource depletion or the consequences of repeated cycling over time (Corona et al., 2019). As a result, they may reward activities that appear circular while "overlooking value loses that undermine long-term value retention" (Vulsteke et al., 2026, p.2).

2.4 Summary of the chapter

To conclude this chapter and provide a foundation for the rest of the thesis, this section synthesises the key aspects discussed above. While the CE has gained significant traction across academia, policy and industry, its precise meaning and objectives remain contested. Different CE visions prioritise different goals and imply different pathways for achieving them. Nevertheless, most perspectives share a common set of ambitions: to keep materials and resources in use and circulation for as long as possible, maintain their highest value and quality over time, and reduce waste and virgin resource extraction. These principles provide the normative basis against which CE practices are commonly evaluated.

A persistent gap exists between these ambitions and their realisation in practice. Although CE frameworks encompass a wide range of strategies with varying transformative potential, their implementation has been uneven. In practice, attention has largely concentrated on a limited set of activities, most notably recycling. This raises important questions about the extent to which current CE practices deliver the outcomes they promise. Existing research identifies numerous barriers, including technological limitations, economic constraints and weak markets for secondary resources. However, limited research exists on the limitations stemming from practice dynamics. Building on the insights above, this thesis examines how circularity emerges through the organisation and interaction of industrial recycling practices.

3 RECYCLING: NEITHER FULLY CIRCULAR NOR ENTIRELY LINEAR

Recycling sits at a crossroads between circular and linear systems (Morseletto, 2023). While it allows to return materials back to production, degradation and losses over successive cycles ultimately constrain their continued circulation and maintain reliance on virgin resources. Recycling should therefore not be assumed to be inherently circular. In fact, it did not emerge with the CE but has been practiced for thousands of years (Werret, 2013). Recycling is therefore better understood as a long-standing set of practices[2], later incorporated into CE discourse.

This in-between position has led some scholars to propose the notion of a *recycling economy*: an intermediate condition in which recovery loops are central to slow down linear systems and ensure materials re-enter but do not fully close them (Geist and Balle, 2025). Often treated as the most tangible manifestation of CE in contemporary contexts (Kirchherr and Hartley, 2025),

[2] This thesis does not treat recycling as a single or universal practice or process. Quoting Romagnoli (2015, p.1), "recycling involves a time gap between two use events". In the intervening period, multiple processes and practices take place, and consequently multiple actors (or practitioners) participate in the transport, trade or processing of materials and products. Moreover, recycling looks very different across products, materials and regions. Even the same product and material can be treated differently across recycling sites, depending on factors like infrastructure, skills or end goals (Jørgensen, 2019).

recycling offers a relevant entry point for examining whether CE practices meet CE ambitions (Abbas et al., 2026). The following paragraphs in this chapter examine how previous literature has conceptualised recycling's historical evolution, its practice within "linear" systems, and the way it has adapted (or is suggested to adapt) to advance CE ambitions.

3.1 Recycling outside the Circular Economy discourse

As a term, recycling is said to originate in the 1920s; as a common practice, however, it dates back all the way to prehistoric times (Romagnoli, 2015). Historical examples illustrate how used materials were long understood as valuable resources rather than waste. In the Bronze Age, copper was recycled by melting down metal scraps to create new tools and items; in ancient Roman Empire, glass was collected, broken, melted and reformed into new vessels and containers (Furlan and Andreatta, 2023). These practices supported material continuity and availability within relatively closed systems. This shifted significantly with the Industrial Revolution. Rapid industrialisation and mass production generated unprecedented volumes of waste, which soon became one of the first large-scale environmental problems (Bergquist et al., 2023). As production expanded and costs declined, Western societies entered what Morseletto (2023) describes as an "age of opportunities", in which material recovery became less of a necessity and increasingly an add-on. Recycling gradually moved from being an embedded routine practice of production toward a specialised waste management strategy, aimed primarily at addressing disposal challenges rather than to retain material value.

The evolution of recycling has been influenced by changing governmental policies, market conditions and technological capabilities (Bergquist et al., 2023). Early forms of recycling were largely driven by resource scarcity and economic value and relied on labour-intensive sorting and relatively low-precision recovery methods (Morseletto, 2023), many of which remain in contemporary recycling systems in developing countries (Velis et al., 2022). In industrialised regions, recycling has increasingly incorporated automated sorting systems and product- or material-specific processing technologies, alongside policy targets and market incentives, to improve the separation, purity and usability of recovered materials (Hagelüken and Goldmann, 2022; Vulsteke et al., 2026). Innovations such as advanced separation techniques and chemical treatments have expanded the range of materials that can be recovered and, in some cases, improved the economic viability of recycling operations (Karreman,

2024). Yet, despite these advances, recycling fails to displace virgin materials of the same kind (Kara et al., 2022). In fact, according to Savini (2025, p.1), "the EU is now even more dependent on raw material imports than it was a decade ago".

In the contexts of the traditional "linear economy", where materials are extracted, processed, used and disposed, recycling operates primarily as a final waste management tool rather than a mechanism for true systemic closure (Kara et al., 2022). Contemporary products are often shaped by market practices, such as planned obsolescence, and are rarely designed for easy disassembly and material recovery (Valenzuela and Böhm, 2017). This frequently results in downcycling, where progressive thermodynamic and material degradation reduces the quality and economic value of recovered materials (Helbig et al., 2022), and in material losses throughout all and every stage from collection to final processing (Worrell et al., 2024). Recycling can therefore operate within, and even thrive in, predominantly extractive and waste-generating systems without necessarily transforming them. This raises a fundamental question: does current recycling contribute to a CE, or does it instead function as a downstream extension of a linear system?

3.2 Recycling's role in the Circular Economy

In spite of the above, recycling occupies a central position in CE debates and remains the most cited and widely implemented strategy within this (Kirchherr et al., 2023). Because all products and materials will eventually become obsolete, unusable or unrepairable, recycling remains indispensable to any vision of a CE (Worrell et al., 2024). Its role and form, however, differs across imaginaries (Suárez-Eiroa et al., 2026). Within techno-optimistic visions, recycling is positioned as a means of keeping materials in circulation while supporting continued economic activity; whereas opposing perspectives place greater emphasis on reducing material throughput and recycling primarily addressing remaining waste streams (Bauwens et al., 2020; Savini, 2025). Thus, while recycling stays present across visions, its intended role varies between a central mechanism or as a supporting practice following reductions in production and consumption.

As a practice theoretically capable of infinitely cycling back materials into the system, recycling contributes to material conservation, enhances supply resilience, and reduces the environmental impacts associated with primary production or landfilling (Hagelüken and Goldmann, 2022). However, this idea

of perfect closed-loop recycling ignores the practicalities of the real world (Figge et al., 2023). In practice, the ability of recycling to meet circular ambitions is constrained by (1) limited scrap availability, (2) technical difficulty, (3) low economic viability of advanced processes, (4) inevitable material losses, and/or (5) the difficulty to find a viable market for recovered materials (Hagelüken and Goldmann, 2022). Moreover, recycling is itself energy-intensive and can involve degradation in product and material quality, for what it does not necessarily promote circularity (Morseletto, 2020). More fundamentally, recycling depends on waste generation (Jørgensen, 2019; Savini, 2019) and by providing a means to managing discarded materials, recycling may alleviate pressure to reduce primary resource extraction and, under certain conditions, enable continued or even increased resource consumption (Zink and Geyer, 2017).

For recycling to contribute meaningfully to CE ambitions, it must go beyond diverting waste from landfills. Recycling should provide high-quality recycled materials that are marketable (Gregson et al., 2015) and ensure substitutability of virgin material resources (Geist and Balle, 2025). In line with the ideal CE principles, recycling must contribute to prevent waste generation, minimise the use of virgin materials and preserve the value and quality of both materials and products (Blomsma and Tennant, 2020). At present, recycling is mostly promoted through measures like Extended Producer Responsibility (EPR), which holds manufacturers accountable for the recycling and full lifecycle of their products, and Ecodesign directives, that set targets for problematic materials and require products to be designed for recyclability, repairability and to incorporate a minimum recycled content (Losa, 2025). However, as of now, these initiatives remain insufficiently enforced and current targets mainly emphasise recycling rates rather than the broader systemic outcomes required for genuine circularity (Geist and Balle, 2025; Kristensen and Mosgaard, 2020).

3.3 Summary of the chapter

Among the practices associated with the CE, recycling occupies a particularly ambiguous position. On the one hand, it is widely regarded as a cornerstone of CE implementation because it diverts materials from disposal and reintroduces them into economic systems. On the other hand, recycling does not necessarily fulfil the broader ambitions commonly associated with the CE. Recycling often entails losses in material quality, functionality and value, limiting the ability of secondary materials to substitute for virgin resources and, in some cases, reinforcing rather than transforming linear patterns of production and consumption. Furthermore, because recycling depends on the generation of waste, its role within an ideal CE is paradoxical. Consequently, recycling cannot be understood as either circular or inherently linear. Instead, it occupies a position between the two, simultaneously enabling material recirculation while reproducing some of the characteristics of linear systems. Whether recycling contributes to the CE (and to what extent) depends on how it is defined, organised and performed in practice. Understanding this ambiguity requires moving beyond assessments based solely on technical performance or material flows and examining the socio-material practices through which recycling is enacted.

4 APPROACHING CIRCULARITY THROUGH PRACTICE

"Transformation processes – such as the transition towards a CE – are always rooted in changing individual perceptions and practices" (Schulz et al., 2019, p.2). This chapter starts from the premise that circularity is produced, maintained or constrained through the performance and interaction of practices. Inspired by Practice Theories, this thesis examines the gap between CE ambitions and their real-world implementation, looking at recycling as a system of interacting practices (Watson, 2012). Consequently, this chapter introduces Practice Theories and their application in CE studies, expanding the framework through a more in-depth analytical engagement with three essential elements of circularity: time, recursivity and accumulation.

4.1 Introducing Practice Theories

Practice Theories are a family of approaches focusing on how practices are organised and unfold (Schatzki, 2002), how these are formed, reproduced, maintained, challenged and broken over time (Shove et al., 2012), and/or how they interact and interrelate with one another (Klitkou et al., 2022). Practice-based approaches shift attention away from individualistic explanations and motivations, and away from structuralist understandings that reduce action to the pure result from social norms and structures towards understanding the social world as constantly evolving through practices and their representations (Jonas and Littig, 2015; Schulz et al., 2019).

Within the various definitions, understandings and analyses of practices across scholars, this thesis finds inspiration in Schatzki's (2002, p.87) conceptualisation of practices as "temporally evolving, open-ended set of doings and sayings linked by practical understandings, rules, teleoaffective structures and general understandings".

(1) *Doings*. In Schatzki's view, both doings and sayings hold equal importance in practices (Schulz et al., 2019). Doings refer to the actual performance of everyday practices: the situated, bodily and routined activities that constitute social life (Goldenstein and Walgenbach, 2024).
(2) *Sayings*. Sayings refer to how people speak within and about the practice (Goldenstein and Walgenbach, 2024). This means, the sayings during the performance of the practice but also the public and political discourses that convey the meaning of the practice in the way they frame and refer to it (Schulz et al., 2019).
(3) *Shared understandings*. Schatzki (2002) divides between practical and general understandings. Practical understandings concern knowing what to do, when to do it and how; whereas, general understandings concern more the shared beliefs and justifications (Welch and Warde, 2016).
(4) *Rules*. These refer to both explicit formal rules of how to do things (laws or regulations), what is allowed or not, but also tacit or implicit rules (Jonas and Littig, 2015).
(5) *Teleoaffective structures*. This term is used to refer to the (normative) goal or direction of the practice, "a range of acceptable or correct ends, acceptable or correct tasks to carry out these ends, acceptable or correct beliefs (etc.) given which specific tasks are carried out for the sake of these ends, and even acceptable or correct emotions out of which to do so" (Schatzki, 2001, p.60-61). These are "shared understandings about what matters and what should be done, at a social, not individual, level" (McLean et al., 2025, p.4).

Beyond these, there are two other key elements: material arrangements and practice arrangements. Material arrangements refer to the specific constellation of material entities (human, artifacts, infrastructural settings, and things in nature) that are linked with human practices; whereas practice arrangements refer to the entanglement of practices (Schatzki, 2002). Practices do not take place in isolation but are connected in complexes or bundles (Shove et al., 2012), nexus (Hui et al., 2017) or systems (Watson, 2012), with the latter being the approach taken as part of this thesis.

Systems of practices as explained by Watson (2012, p.493) refers to how practices are "embedded in systemic relations constituted first by relations with other practices and (…) through the systemic elements – including infrastructures, technologies, rules, norms and meanings – which those practices constitute and sustain". Consequently, practices cannot be reduced to the internal configuration of practices alone but need to be understood within their dynamics and interrelationships (Klitkou et al., 2022). These interconnections can be synchronous (where the same resource is used in multiple practices at the same time) or sequentially ordered (Shove et al., 2012). Moreover, practices can also connect through forms of competition and collaboration (Hui et al., 2017).

Building on this, Reckwitz (2002) and Shove et al. (2012) propose an alternative simplified version of the framework in which practices are constituted through the dynamic integration of three elements: materials, competences and meanings. Materials encompass the physical objects, technologies and infrastructures through which practices are enacted; competences refer to the skills, know-how and techniques required to perform them; and meanings comprise the symbolic significance, ideas and aspirations that render practices understandable, appropriate and desirable (Shove et al., 2012). In positioning materials as one constitutive element of practice, they emphasise the importance of the material in action (Hui et al., 2017). From this perspective, social practices "emerge, persist or disappear as links between their defining elements are made or broken" (Shove et al., 2012, p.21). These two frameworks should not be understood as competing or mutually exclusive. Whereas Schatzki's (2002) framework provides a rich understanding of how practices are organised and relate to wider social orders, institutions or rules, Shove's et al. (2012) serves as more operationally ready for analysing how practices emerge, persist or change.

4.2 Practice Theories in Circular Economy research

Practice theories have become increasingly influential in the study of (un)sustainable consumption and production, providing analytical tools to understand how practices emerge, persist and change, as well as how these could be redirected towards more sustainable outcomes (Klitkou et al., 2022). Shove (2023) has done a great work studying social change and (un)sustainability through daily practices like showering or driving. From a practice-theoretical perspective, transitions come to be because of changes in practices (Watson,

2012). These changes may involve reshaping existing practices and their elements, replacing them with alternatives or altering the ways in which practices connect and influence one another (Spurling and McMeekin, 2015). This perspective does not imply that institutions, policies, markets or regulations are irrelevant in transitions. Instead, their role can be examined in relation to the practices through which they are enacted and reproduced. Changes in these conditions can, thus, become visible through changes in practices (Greene and Hobson, 2025; Spurling and McMeekin, 2015).

Practice Theories remain underrepresented in CE research, yet an emergent body of literature suggests that circularity and circular transitions should be understood through the lens of everyday practices (Greene and Hobson, 2025). That is, how everyday practices can or should be (re)configured to incorporate CE principles. Most of this work has focused on consumption. For example, Shove (2023) and Åberg and Greene (2024) investigate how daily practices and routines influence plastic consumption; whereas Hedlund and Jaca (2025) use it to examine how routines, know-how, infrastructures and cultural meanings lead consumers to choose whether to recycle or reuse functional or repairable products in Sweden. Practice Theories have thus proven useful for identifying and assessing the transformative potential of everyday practices towards the CE (Schulz et al., 2019). While Shove et al. (2012) acknowledge the roles of feedback, recursivity, temporal (delays) and accumulation in shaping practices, this thesis examines more closely how such dynamics shape the emergence of circularity through practices (Grafström, 2026).

4.3 Time (delays), recursivity and accumulation

Practices and time are bound together (Holmes, 2015). Time is integrated in the study of practice through their sequencing (Åberg and Greene, 2024), length or historical persistence (Schatzki, 2009), the repetition of a practice over time (Shove et al., 2012), its rhythm (Hopwood, 2016), duration (Holmes, 2015) or the temporal connections that dictate the intervals of time between them (Schatzki, 2009). Although practice research has predominantly focused on past and present practices, scholars increasingly recognize that practices are inherently future-oriented, meaning that when practitioners engage in a practice they are acting towards a future imaginary (Åberg and Greene, 2024). In other words, present practices shape future practice conditions in the same way that current practices are shaped by the past (Hui et al., 2017). In Hopwood's (2016, p.142) words: "past, present and future occur at a single

stroke. What is done or said now (the present) happens both motivatedly (responding to what is past) and teleologically (with a view to what lies ahead). […] all three occur together by virtue of a particular action and its motivation and intention".

Equally important, practices are inherently transformative of materials; that is, material elements are continuously reconfigured through their enactment within practice (Shove et al., 2012). Because practices are repeatedly performed over time, materials are continuously subjected to practices of valuation (Fuentes and Hedegård, 2025) and transformation (Savini, 2025), which in turn change the practice over time (Watson, 2012). This increases the importance of recursivity, or feedback loops, in circular practices: as materials pass through successive cycles, the effects of previous practices accumulate, continuously altering their properties and influencing future possibilities and conditions (Åberg and Greene, 2024).

Accumulation has received comparatively little attention, despite its relevance for understanding how the consequences of practices build up over time. Using the example of microplastics, Shove (2023) touches on processes of material reconfiguration and accumulation, where multiple material-practice conjunctions can alter the material conditions shaping future practices. Building on this perspective, greater attention is needed to how such effects accumulate, recursively reshape subsequent rounds of action and unfold with temporal delays. In this context, practice-based studies on CE point to the need for tools and methodologies to study future-oriented practices (Åberg and Greene, 2024), alongside analyses of how practices enable, constrain or reconfigure interrelated practices (Klitkou et al., 2022).

Time, recursivity and accumulation are key to understand how CE unfolds. Time shapes the pace at which materials move through supply chains, particularly in industries where efficiency and speed are prioritised, and influences product lifespans and the economic viability of certain circular practices (Grafström, 2026; Holmes, 2015). Recursivity refers to the repeating feedback processes through which actions and their consequences shape subsequent actions; and accumulation refers to the build-up of e.g. materials, whether as resources or waste, over time (Savini, 2019; Shove et al., 2012). Together, these help explain why consequences of circular practices may emerge gradually, accumulate over time, and shape future possibilities for circularity. Their consideration is therefore essential to understand circularity beyond its immediate outcomes. While Practice Theories have engaged in depth with these dynamics in

descriptive and philosophical terms (e.g. Shove et al., 2012), they offer limited explicit analytical tools for examining these. Therefore, to complement this perspective, this thesis draws on System Dynamics (Sterman, 2000).

Developed by Forrester (1961) and further advanced by Sterman (2000), System Dynamics (SD) is an analytical tool for examining the behaviour of complex systems over time, emphasising interdependence, non-linearity and change, and representing these through stocks (accumulations), flows (rates of change) and feedback loops. While these involve a degree of simplification, they enable to analyse the dynamic complexity that would otherwise remain difficult to grasp. A key contribution of System Dynamics is its capacity to explicitly introduce time delays between actions and outcomes, as well as the cumulative effects of past activities, particularly relevant in systems characterised by material circulation (Guzzo et al., 2022). Moreover, practices related to dismantling, sorting, pricing, production, consumption, or disposal are not independent; they influence one another in often non-linear ways with delayed effects, producing unintended consequences (Sterman, 2000). Thus, in this thesis, System Dynamics is used to analyse the interrelationship between practices to better understand how circularity is constituted both in the present and over time (Guzzo et al., 2022).

These two approaches inform different aspects of the thesis. Practice theories provide the basis for examining how practices are organised and performed, and how they enable or constrain circularity (Greene and Hobson, 2025), whereas System Dynamics is used as an analytical tool to trace how these practices interact and evolve over time through accumulations, delays, and feedback processes (Guzzo et al., 2022). This combined approach is particularly suited to the study of recycling as a circular system, where socially embedded practices and long-term material dynamics are deeply intertwined.

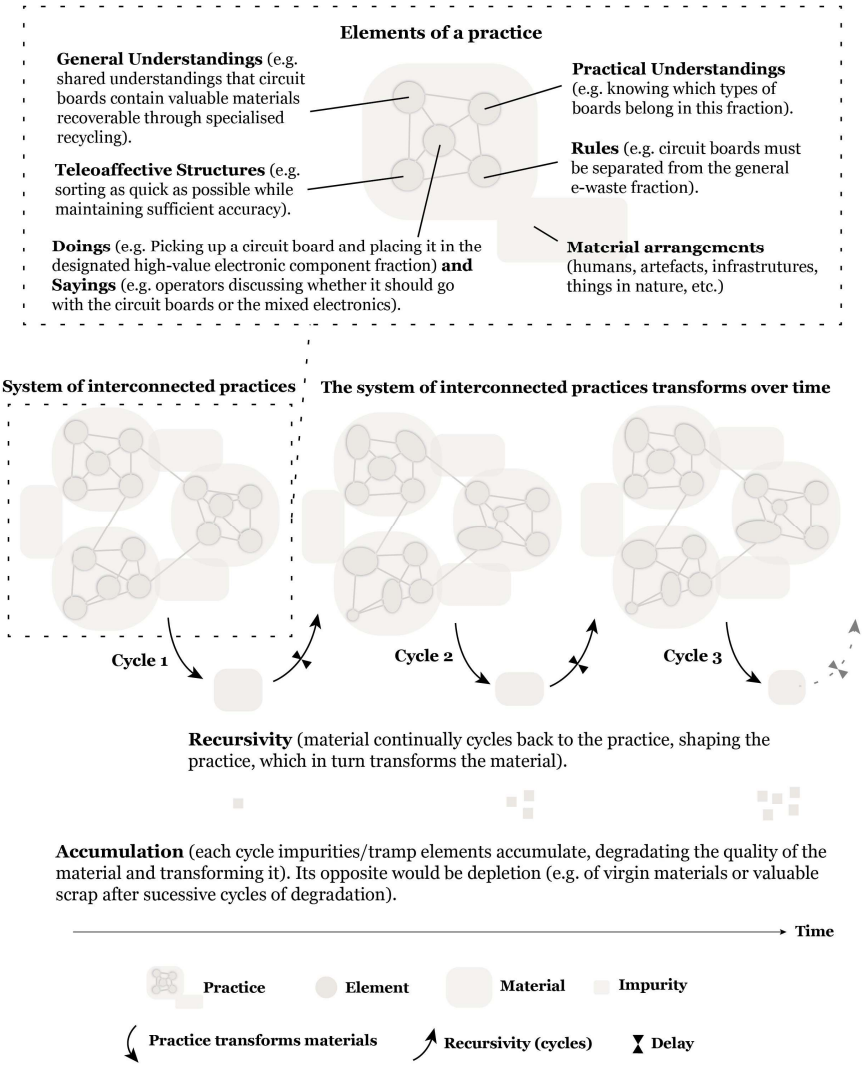

Figure 2. Practice elements, systems of interconnected practices and their transformation through time, recursivity and accumulation.

4.4 Recycling as a socio-material practice

Inspired by Practice Theories and stressing the analytical relevance of the notions above (time, recursivity and accumulation), this thesis looks at recycling as a *set of interrelated socio-material practices that recursively shape one another and the materials involved, such that the present practices influence how future practices take place and the possibilities for continued material circulation (See Figure 2).*

Within the breadth of studies in consumption, recycling has been studied as a household practice (e.g. Hedlund and Jaca, 2025); that is, household sorting of waste or discard at municipal "recycling centres". Yet, their application to industrial recycling remains underexplored. Operators, though, play a central role in reintroducing material into circulation, making circularity ultimately dependent on the expertise and actions of the workers involved in these practices (Fuentes and Hedegård, 2025). Overlooking these actors, thus, constitutes an important analytical omission.

In this context, recycling is interpreted as a system of interconnected practices (Watson, 2012): the practice of dismantling, the practice of sorting, the practice of blending metal grades, etc. It consists both of doings (e.g. the physical act of dismantling or sorting) and sayings (e.g. what is said during the practice and what is said to be recycling) (Schatzki, 2002). It involves the shared understandings, such as the economic rationales that justify the performance of certain practices, as well as definitions of what is considered recyclable or worth recycling (Welch and Warde, 2016) and the rules determining what to separate and how, the categories of grades that define how materials belong to one another and the informal and experience-based tacit knowledge of what is worth doing (Jonas and Littig, 2015).

The recycling practices comprising the system follow a sequential order where the outcomes of one practice serve as the input for another (Shove, 2023). Other practices operating in parallel can draw on the same material and thereby compete over its use (Hui et al., 2017). Repair, reuse and recycling, for example, may represent alternative ways of handling the same material, for what directing a material towards one practice can affect its availability for another. This is particularly relevant for recycling practices since they depend on waste (Savini, 2019).

Moreover, practices are embedded within wider nexus of interconnected practices such as production, consumption, pricing and regulation (Schatzki 2015). This interconnectedness is essential for understanding how developments in one shape and delimit possibilities in another, for instance, how past design practices influence or constrain current recycling practices. This reinforces the relevance of analysing recycling not as a discrete activity, but as part of a broader constellation of interconnected practices (Hui et al., 2017). In current practice studies, these interdependencies are acknowledged but remain largely implicit rather than analytically specified.

4.5 Summary of the chapter

Practice Theories inspired this thesis by conceptualising recycling as a socially and materially organised set of practices shaped by practitioners' understandings (know-how), rules (formal regulations, informal conventions and tacit judgements) and teleoaffective structures (the ends and purposes that orient action), as well as by materials and available infrastructures. It highlights how "sayings" shape what is recognised as recycling, which in turn conditions "doings", what is carried out and evaluated. This framework proved particularly useful for analysing how recycling is constituted and how it may (or may not) contribute to the CE.

Building on this, the thesis studies recycling systems as sets of interconnected practices. To capture these dynamics and their system-level consequences, it integrates feedback loops and time delays in the analysis. This integration shifts the focus from individual practices to how multiple practices interact to produce emergent system behaviours, such as material degradation and tramp element accumulation. Practice-based approaches are used to explain how circularity is enacted and shaped through recycling practices, while System Dynamics trace how these practices play out over time, where delays appear and cumulative consequences shape the future conditions of circularity. As such, this thesis develops a practice-theoretical account of circularity as a temporally emergent property of interconnected socio-material practice configurations, showing how CE outcomes arise through the temporal reconfiguration of practices and their recursive material transformations.

5 METHODS

Understanding how (recycling) practices reflect and produce circularity over time requires methodological approaches capable of capturing both situated practices and their temporal evolution. This chapter outlines the research journey, design choices, empirical settings, and methodological approaches underpinning the thesis and demonstrates how they collectively enabled the investigation of recycling and circularity as multidimensional, dynamic and recursive. The chapter begins by presenting the overall research design and journey, followed by a description of the methods used for data collection and analysis, a discussion on the research quality and a disclosure of AI use. Limitations and considerations are included throughout the chapter.

5.1 Research design and research journey

Inspired by practice-based approaches, this doctoral thesis developed an empirically grounded understanding of whether and how circularity is produced and reproduced through the everyday practices of industrial recycling operators (Nicolini, 2012). Accordingly, practices (and the system of practices in which they are embedded) constituted the primary unit of analysis and epistemic object (Gherardi, 2019). To pursue this aim, this thesis was organised into three empirical studies, resulting in five appended papers. Figure 3 illustrates the temporal distribution and the relationship between the individual studies and the papers derived from them. A more detailed account of each study and its corresponding empirical context can be found in the subsequent sections, while

Table 5 (in p.58) presents an overview of the aims, methodological approaches, empirical material and research objectives associated with each study.

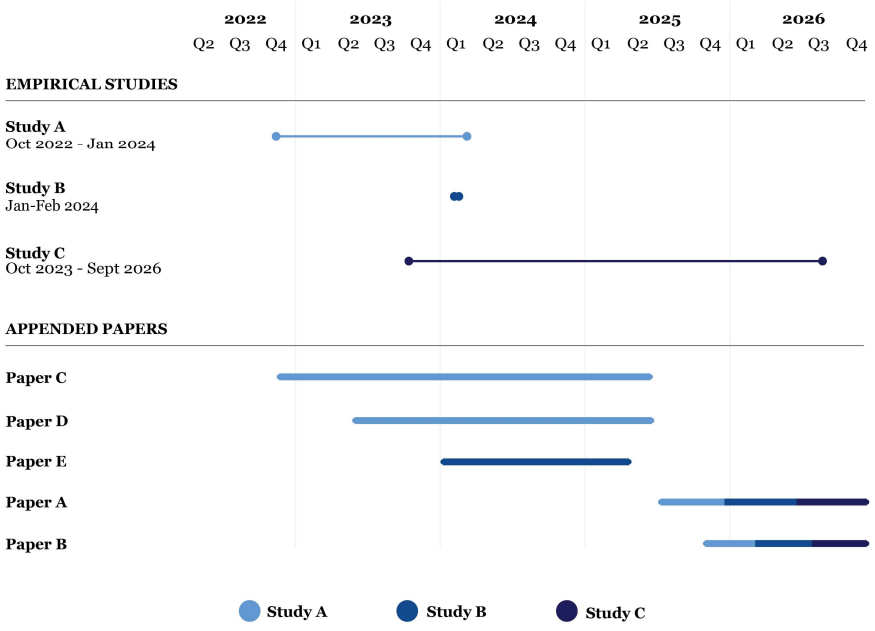

Figure 3. Timeline of appended papers. Papers C and D belong to Study A. Paper E to Study C, and Papers A and B sit across all, including the investigation in Study B.

These studies and papers did not follow a predefined sequence or publication plan, but evolved as empirical insights, practical constraints and opportunities for access shaped subsequent directions (Pailthorpe, 2017). As the empirical work progressed, findings that proved analytically and conceptually significant provided the basis for developing individual publications and manuscripts. The appended papers, as shown in Figure 3, reflect this progression: early papers (**Papers C**, **D** and **E**) were written before completing the entire data collection process, analysing findings from specific empirical problems and studies, whereas later papers (**Papers A** and **B**) synthesise insights across the entire body of empirical material. The research thus moved from applied questions within individual recycling systems towards broader conceptual examinations of how recycling itself is understood and configured, providing a more critical and reflexive interrogation of the assumptions that underpin what is doable, desirable or circular (Figge et al., 2023).

Across studies, the analysis shifted iteratively between specific practices and the wider configurations in which they are situated, resonating with Nicolini's (2012) analytical strategy of moving between *zooming in* and *out* of practice. *Zooming in* involved examining everyday recycling activities in situ, seeking to understand how CE is produced or constrained through each concrete socio-material arrangement. *Zooming out*, in turn, situated these in relation to the wider system of interconnected practices, analysing related activities that affect, enable or constrain the practice in consideration, such as design, use or decommissioning practices. Other R-strategies, such as reuse or repair, were also evaluated in Studies B and C in relation to their implications for recycling. This iterative movement between zooming in and out involved repeated cycles of observation, analysis and reflection.

The theoretical engagement was likewise emergent. The thesis did not begin with a predefined theoretical framework, but with an empirical interest in understanding whether and how recycling practices produce circularity (Nicolini, 2012). Early studies therefore drew primarily on applied research and the use of System Dynamics to examine the feedback processes, accumulations and temporal dynamics generated through these practices. Practice Theories were introduced at a later stage, not as a replacement for earlier analyses, but as a theoretical lens through which the findings could be reinterpreted or synthesized. This enabled an examination of how rules, norms, meanings or teleoaffectivities come together as integral elements of recycling practices, shaping variations in how recycling is performed and the forms of circularity these enable or constrain (Hui et al., 2017). This is reflected specifically in **Paper B**. The empirical focus thus remained consistent on industrial recycling practices throughout the whole doctoral work, while the conceptual vocabulary used to explain those practices developed progressively. Some of the earlier papers, for example, refer to a "process perspective" when focusing on the sequence of material transformations involved in recycling (such as dismantling, shredding, sorting, and blending metal grades), yet these studies do not focus on automated processes, but the socio-material practices embedded within these processes.

5.2 Overview of empirical studies

Recycling constituted the empirical entry point in this thesis for examining whether and how circularity is produced in practice. Since this choice has been motivated throughout the preceding chapters, this section focuses on the empirical breadth through which recycling was examined.

The thesis draws on three studies, each investigating a distinct recycling system. Together, they encompass established and emerging systems and recycling practices involving both products and materials. This contrasting cases allowed for examining the challenges of producing circularity through recycling under different conditions. Studying steel recycling (**Study A**) provided the opportunity to investigate the challenges of maintaining material quality within a well-established recycling system, whereas the emerging solar photovoltaic sector (**Study C**) enabled the examination of throughput challenges and the repercussion of other practices like design and decommissioning in a fast-evolving technological context. The Kenyan study (**Study B**) further broadened this perspective by illuminating how recycling is enacted within a substantially different institutional context, where informal and formal practices coexist. These studies were analysed both individually and in relation to one another, allowing recurring patterns and tensions across different forms of recycling to be identified while retaining the specificities of each context.

Each of these studies differed significantly in their starting points. **Study A** built upon an ongoing research project on the presence of tramp elements in steel scrap (Berlin, 2023; Compañero, 2024)[3], with the present work contributing to the later stages of the data collection and analysis. In that case, the empirical exploration began by interrogating which practices in steel recycling (where and how) contribute to the contamination of scrap. In contrast, **Studies B** and **C** initiated with more open-ended exploratory aims, seeking to map and understand systems where limited prior empirical knowledge was available (Yin, 2018). These started by interrogating how current "linear" systems work and which practices take place within these systems.

[3] This research project started as a continuation and last stage of the research conducted by my colleagues Daniel Berlin (2023) and RJ Compañero (2024). This is important because the empirical material for this study, presented in the following sections, should be understood as a continuation of earlier on-site observations and interviews which, although not conducted by myself, informed the study as a whole.

Together, these studies provided a rich empirical basis for examining how CE is produced or constrained through industrial socio-material practices across diverse materials, industries, institutional contexts and stages of system maturity (Abbas et al., 2026). Table 1 synthesises the specific characteristics and challenges of each analysed context, whereas the following subsections provide further detail on each study.

Table 1: Synthesis of empirical contexts analysed in this thesis.

	Steel-containing products	**E-waste/solar panels**
Sweden	**Mature system** with established scrap collection and processing, steady input volumes, technological capacity and strong downstream demand. **Challenge**: Tramp element accumulation reduces recycled steel quality and usability and leads to resource losses.	**Emerging system**, with uncertain and low-volume waste streams and limited demand for secondary products. Collection is fragmented and leakage and exports occur. **Challenge:** Low waste volumes discourage investment in specialised recycling.
Additional European context	Similar characteristics to Sweden where perceived in **Austria**, yet there is a **lower demand for recycled steel,** since the main industry is automotive and requires high-purity materials.	Solar panel recycling was explored in **The Netherlands**, since these have sufficient volumes to start investing in **specialised recycling techniques**. Yet these innovations have yet to scale.
Kenya	**Mostly informal system.** Low-capital labour-intensive activities involving informal collectors, small-scale intermediaries and rudimentary processing. Strong domestic demand and high scrap value drive rapid turnover. **Challenge**: Maintaining material quality across fragmented recycling chains with limited sorting and processing capacity.	**Reuse/repair-oriented system**. E-waste and solar panels are often repaired, remanufactured and reused using rudimentary techniques. Little formal recycling activity. **Challenge**: Once products become fully obsolete, the lack of established formal recycling processes limits their subsequent material recovery.

5.2.1 Study A: Steel recycling in Sweden and Austria

In Sweden and Austria, steel recycling is a long-established and highly industrialised recycling system. It is often presented as an example of successful (even perfect and infinite) recycling (Hagelüken and Goldmann, 2022). Characterised for established scrap collection and processing, steady input volumes, high recycling rates, mature technologies, relatively well-functioning markets and strong demand for secondary materials, "[the recycling of] steel is a good proxy to evaluate the potential efficiency and effectiveness of CE strategies" (Kara et al., 2022, p.518).

However, in practice, steel recycling has not been exempted from material or quality loss. The so-called contamination of scrap during the recycling process has gained a lot of attention from metallurgists and material scientists, who have investigated ways to remove or even recover such contaminants (also called tramp elements) (Meskers et al., 2024). The literature, however, has not yet moved beyond a predominantly reactive, process- and technology-centred approach.

As a response, this study adopted a proactive perspective by examining where, how and through which industrial practices these unwanted elements entered the recycling system (**Paper C**). It traced its origins across interconnected recycling practices, revealing how routine practices upstream shape material quality downstream. Building on these findings, subsequent work examined how the repeated introduction and accumulation of contaminants generate delayed consequences that constrain future recycling possibilities (**Paper D**). Thus, the first half of this doctoral work centred on the recyclers (such as dismantlers, sorting facilities or smelters) and their practices.

This study drew on on-site observations and semi-structured interviews across actors in the steel recycling system, providing a nuanced understanding of how actors navigate the trade-offs between economic viability, material quality, material circulation and policy expectations in the course of everyday practice (Jonas and Littig, 2015). It initially developed from the concluding stage of an ongoing project on steel recycling in Sweden (see section above). To broaden the empirical material, expertise and incorporate an additional recycling context, the sampling was extended to Austria (Flick, 2022). This extension was facilitated by Sabine Dworak, a researcher specialised in steel recycling with established contacts across the Austrian steel industry. For triangulation purposes, interviews and observations were conducted with Andreas Feldmann,

Peter Samuelsson and RJ Compañero in Sweden, and with Sabine Dworak in Austria.

Picture freely available at https://www.gd.se/naringsliv/skrot-in-300-sorter-specialstal-ut/. The picture illustrates a sorted metal grade at one of the steel mill scrapyards visited during Study A.

5.2.2 Study B: Circularity of metals and solar panels in Kenya

A bridging study investigated the handling of metal (mostly steel) scrap and e-waste (including solar panels) in Kenya. There were three main motivators for conducting this research. First, the earlier study suggested that manual sorting could achieve more effective separation, but its substantial labour costs limit its viability (Hagalüken and Goldmann, 2022). In Kenya, manual sorting remains central to recycling, providing an opportunity to examine how it is carried out in practice. Second, developing countries are known for actually pushing recycling as a last resort and genuinely prioritising activities like reuse, repair or remanufacture (Collacott, 2023). Last, many discarded products in Europe end up exported to countries like Kenya, for what exploring this site would only mean exploring a "hidden" or externalised continuation of the European recycling system (Reike et al., 2018). This study thus provided an opportunity to examine what recycling can reveal about circularity when practices and priorities differ from those of established European recycling systems.

Most of the recycling sector in Kenya is informal and connected to the underground economy (Velis et al., 2022). Recycling systems in Kenya differ significantly from Europe regarding its organisation or structure, actor networks, supply chains, technology, security or formal policies and regulations. In this context, waste accumulation is not the main driver. Instead, *waste is wealth*. Metals and valuable products like solar panels disappear from the

dumpsites in no time. The recycling system here is significantly larger when compared with European systems, they are unstructured and unregulated and supply networks are rarely fixed but depend on “who pays more”. Thus, the Kenyan context offered the opportunity to examine how a different institutional arrangement, particularly the role of informal recycling practices, shape circular outcomes.

This research study thus consisted of observations and interviews with both formal and informal practitioners. Given the largely informal (and at times illegal) nature of recycling activities, access relied heavily on snowball sampling and opportunistic engagement in the field (Patton, 2015). Initial contacts led to further introductions, enabling entry into networks of practitioners. Observations often began through direct engagement with ongoing activities, followed by semi-structured conversations. This study was conducted in collaboration with two local researchers from Kenya Climate Innovation Centre (KCIC), Emmanuel Yahuma and John Musyoka. Their contextual knowledge, networks, and familiarity with the national context were instrumental in facilitating access to and navigation of the field. This highlights the importance of local collaboration in qualitative research, particularly in contexts where access is otherwise limited. These insights were analysed in **Paper B**.

Original picture from one of the on-site observations in Study B.

5.2.3 Study C: Handling decommissioned solar panels in Sweden

The final empirical context focused on the emerging system for solar panel recycling in Sweden. This work initially sought to understand future waste volumes to assess when investments in advanced, high-quality recycling technologies would become economically viable. This became the basis for **Paper E**. Only a few locations in Europe host innovative processes capable of recovering the most valuable elements in solar panels, such as silicon or silver, and where they exist, these solutions remain pilot-scale or confidential. European guidelines currently classify solar panels within the general waste electric and electronic equipment (WEEE) stream. However, processing them alongside other WEEE, risks downcycling and the loss of valuable resources. In Sweden, volumes remain too low to support dedicated recovery, so decommissioned panels are typically stockpiled, exported or processed together with other WEEE. Thus, investing in advanced recycling systems that can enable the high-quality recovery of valuable resources requires bigger volumes of waste, reflecting another key challenge in recycling (Hagalüken and Goldmann, 2022). This, thus, represents a research context where infrastructures, technologies and expertise are under development and where low throughput limits high-quality recycling possibilities.

The second half of the thesis engaged in on-site observations, semi-structured interviews, participatory workshops, informal meetings with industry actors and document analyses; covering the practices, impressions and concerns of a broad range of actors in the solar power value chain. Sampling was shaped by the broader research project within which the study was embedded. Initial participants were selected through the project consortium, bringing together actors from across the system. This included, among others, the importers and installers of panels in Sweden, logistic organisations, policy actors, producer responsibility organisations and sorting organisations ("recyclers"). Additional participants were identified through professional networks, courses, conferences and ongoing interactions with experts (Patton, 2015). Beyond Sweden, this study included a brief observation and interviews at a recycling centre in the Netherlands, where specialised solar panel recycling infrastructure was under development, as well as an online interview with the founders of a specialised solar panel recycling plant in Italy. Data collection here extended over a longer period and included multiple workshops reflecting a more longitudinal and participatory approach. Johanna Olofsson Behrmann

participated as an interviewer throughout the data collection to support triangulation.

From an analytical perspective, this study provided insights into how recycling systems emerge in contexts characterised by volume uncertainty, lack of infrastructure and secondary markets, and competing priorities; posing the challenge of volumes and throughput in achieving higher-quality (and thus, more circular) recycling. Besides, this study allowed not only the study of the individual recycling practices, but also their relation within the broader practices of importing or decommissioning. The analysis then investigated how upstream practices, such as design or repowering, influence both the quantity and condition of panels eventually reaching recycling facilities.

Original picture taken during an on-site observation in Study C (Picture taken by Johanna Olofsson Behrman).

5.3 Data collection methods

Studying practices and the systems they constitute (practice arrangements) typically involves close engagement with everyday activities, focusing on how they are carried out, connected and reproduced across different settings (Nicolini, 2012). Practice-based research therefore prioritises methods that allow access to situated action, most commonly through forms of ethnographic engagement that follow practices over time (Gherardi, 2019). However, this is limited in some contexts, for what McLean et al. (2025) suggest employing a combination of interviews and observations. This is further supported by scholars like Jonas and Littig (2015) or Hedlund and Jaca (2025), arguing that practices involve both, physical and verbal activities, that is: what they do and how practitioners make sense of what they do.

This thesis therefore combines relatively brief, targeted observations into how practices are organised and performed with other qualitative methods like interviews, workshops and document analysis. It prioritised the development of rich empirical understandings of practices and their interconnections, with interpretive and theoretical positioning introduced at later stages of the analysis. This grounding in empirical practice allowed the thesis to examine how recycling is actually organised and performed, rather than relying on abstract or idealised assumptions about how it should operate.

Data was collected at multiple points throughout the doctoral project, with my direct involvement in collecting the empirical material for all five appended papers. The tables and paragraphs below provide an overview of the material, indicating the study in which they took place and the papers they informed. Where the same data sources were used across multiple papers, the material was analysed separately in relation to the specific research questions and objectives of each study.

5.3.1 On-site observation

This thesis gave on-site observations a central role in the empirical work. Observations allowed access to situated, embodied and material dimensions of practice, making it possible to examine how activities are carried out in real time and under specific conditions (Nicolini, 2012). The 22 observations are listed in *Table 2*. Each observation corresponds to a site visit conducted at a specific empirical site, where recycling-related practices were observed in situ. Site visits lasted between two and five hours and were conducted at different points in time and different locations. By empirical site, this thesis refers to a situated setting (typically within a single organisation) where multiple practitioners, practices and material arrangements come together. Each site visit, therefore, captured not a single practitioner or activity, but a bundle of interrelated practices involved in handling, sorting, processing or trading materials.

Table 2. List of site visits conducted throughout the doctoral work. All informed the perspective Paper A.

	Empirical site	Study	Used in
1	Sorting facility	A	Paper B.
2	Steel mill	A	Papers B, C and D.
3	Steel mill	A	Papers B, C and D.
4	Sorting facility	A	Papers B, C and D.
5	Sorting facility (Solar panels)	B	Paper B.
6	Unregulated scrapyard	B	Paper B.
7	Unregulated scrapyard	B	Paper B.
8	Dumpsite	B	Paper B.
9	Informal dismantling and repair market	B	Paper B.
10	Sorting facility (E-waste)	B	Paper B.
11	Informal dismantling and repair market	B	Paper B.
12	Informal dismantling and repair market	B	Paper B.
13	Steel mill	B	Paper B.
14	Steel mill	B	Paper B.
15	Metal foundry	B	Paper B.
16	Steel mill	B	Paper B.
17	Sorting facility	B	Paper B.
18	Steel mill	B	Paper B.
19	Repair (E-waste)	B	Paper B.
20	Sorting facility	C	Paper B and E.
21	Sorting facility	C	Paper B and E.
22	Sorting facility	C	Paper B.

5.3.2 Interviews

The interviews represent the largest data source in this thesis (See *Table 3*). Interviews were conducted to obtain the practitioner's own experiences at length (Shah and Corley, 2006). In contrast with observations, these provide insights into how actors interpret, justify and organize their actions, including the norms, formal and informal rules and constraints that shape what is considered appropriate and feasible (McLean et al., 2025). Hence, these provided in-depth insights into practitioners' motivations, constraints and justifications in recycling practices, as well as their interpretations of recycling within CE frameworks.

The interviews took place throughout the whole four years of the doctoral study, yet there are certain periods in time where these were more concentrated. All interviews were semi-structured and typically lasted about 60 minutes, with some slightly shorter. The interviews were not recorded verbally but through interview notes, as requested by the interviewees (Yin, 2018). Investigating recycling, especially within the confines of CE, has proven to be a very sensitive topic. However, in their study, Rutakumwa et al. (2019) show that the data quality between transcripts and interview notes during and immediately after the interview are comparable in detail. Since recording often influences what is said and done, authors acknowledge the relevance of notes. Notes included the capture of key quotes, providing material for use in the appended papers (Patton, 2015).

After each session, the notes were cross-checked with the other interviewers (Carter et al., 2014). These notes were polished, anonymised and compiled in a coherent text that was then sent to the interviewees for confirmation. Sharing the notes with the interviewees was important to ensure that there were no misinterpretations (Patton, 2015). These notes were never tagged in the submission process of any papers, yet they are all open for request. Few of the interviews took place in a group setting where three or more interviewees were responding to the questions or contributing to the discussions (Flick, 2022). These are listed separately in *Table 4*. (Focus) group discussions brought comments and conversations that wouldn't have happened individually, yet individual interviews were preferred given the sensitive topic of discussion (Carter et al., 2014).

Table 3. List of interviewees throughout the doctoral work. All informed the perspective Paper A.

	Role	Empirical site	Study	Used in
1	Sorting Ex-manager	Sorting facility	A	Papers B, C and D.
2	Production Ex-manager	Steel mill	A	Papers B, C and D.
3	Furnace manager	Steel mill	A	Papers B, C and D.
4	Scrap yard manager	Steel mill	A	Papers B, C and D.
5	Dismantler	Sorting facility	A	Papers B, C and D.
6	Head of sales	Steel mill	A	Papers B, C and D.
7	Steel mill ex-director	Steel mill	A	Papers B, C and D.
8	Steel recycling expert	Research	A	Papers B, C and D.
9	Steel recycling expert	Academia	A	Papers B, C and D.
10	Scrap yard manager	Sorting facility	A	Papers B, C and D.
11	Metal recycling expert	Research	A	Papers B, C and D.
12	Founder	Solar panel dismantler	B	Paper B.
13	Director	Aggregator	B	Paper B.
14	Project manager	WEEE centre/dealer	B	Paper B.
15	Manager	Informal WEEE dismantle and repair	B	Paper B.
16	Collector	Collector	B	Paper B.
17	Director	Scrap metal council	B	Paper B.
18	Manager	Environmental Management Association	B	Paper B.
19	Operations manager	Steel mill	B	Paper B.
20	Business Development	Broker	B	Paper B.
21	Director	Metal foundry	B	Paper B.

22	Head of quality	Sorting facility	B	Paper B.
23	Head of compliance	Steel mill	B	Paper B.
24	Scrap dealer	Sorting facility	B	Paper B.
25	Operations manager	Steel mill	B	Paper B.
26	Manager	Repair WEEE	B	Paper B.
27	Operations manager	Repair WEEE	B	Paper B.
28	Founder	Repurpose centre (solar)	B	Paper B.
29	Senior technical advisor	Sorting facility	C	Paper B and E.
30	Researcher	Research Institute	C	Paper B and E.
31	Founder	Silicon production	C	Paper B and E.
32	Supply chain expert	Logistics	C	Paper E.
33	Vice-director	Producer Responsibility Org.	C	Paper B and E.
34	Head of Sustainability	Solar panel importer and installer	C	Paper E.
35	Head of WEEE recycling	Sorting facility	C	Paper B and E.
36	Recycling manager	Sorting facility	C	Paper B and E.
37	Co-founder	Solar panel recycling	C	Paper B and E.
38	Co-founder	Solar panel recycling	C	Paper B and E.
39	Product manager	Solar panel importer and installer	C	Paper E.
40	Business developer	Solar panel installer	C	Paper E.
41	Procurement	Solar panel retailer	C	Paper E.
42	Procurement	Solar panel retailer	C	Paper E.
43	Product design engineer	Solar panel retailer	C	Paper E.

44	Business operations	Solar panel retailer	C	Paper E.
45	Business leader	Solar panel retailer	C	Paper E.
46	Sustainability developer	Solar panel retailer	C	Paper E.
47	Circular specialist	Solar panel retailer	C	Paper E.

Table 4. List of short (focus) group discussions. All informed the perspective Paper A.

	Study	Empirical site	Used in
1	A	Steel mill	Papers B, C and D.
2	A	Steel mill	Papers B, C and D.
3	C	Sorting facility	Paper B.

5.3.3 Workshops

Workshops provide a flexible, collaborative space where diverse stakeholders can creatively address complex, forward-looking challenges (Eidenskog et al., 2024). As part of the latter project in which Study C takes place, workshops were conducted with a broad range of actors from the solar power sector in Sweden. In this study, workshops were designed to engage actors in reflecting on and shaping the broader system within which these practices are embedded. Contrary to observations and interviews, which provided access to situated actions and their meanings, workshops operated at the system-level, bringing multiple actors, including two recyclers, to explore how the system could transition from linear to more circular configurations. As such, they served as spaces where existing practices were not only described, but collectively examined, questioned and reconfigured in relation to future possibilities. In this sense, workshops complement observations and interviews by extending the analysis from how practices are currently performed to how they may evolve.

These workshops provided an opportunity to explore each actor's aims, visions, challenges and opportunities in the transition toward the CE. Bringing together a diverse group of actors, the workshops facilitated the exchange of perspectives, the identification of common challenges and shared concerns, the identification of collaborations and points of tension, and the possibility of creating joint efforts to explore potential pathways to transition towards a CE.

Workshops were done as part of the elaboration of the roadmap to transition the Swedish solar power sector towards the CE. While some of these workshops only informed **Paper E** and additional manuscripts intentionally excluded from this thesis to maintain a focused empirical scope, they inevitably influenced the reflections underpinning this thesis. Meetings with the partners of the project, which included recyclers or sorting organisations, producer responsibility organisations and importers and installers, were regularly taking place several times a year. An additional workshop was conducted with some scholars of the University of Bern: Roger Nyffenegger and Anna Siemer. This workshop was conducted with the purpose of joining our efforts in mapping what had been done and what is pending to be done in terms of CE in the solar power sector.

5.3.4 Document analysis

To triangulate the data from onsite observations, interviews and workshops, documents like industry or project reports and legislative and policy documents were analysed (Shah and Corley, 2006). Key sources included reports from the European Commission, standards from the Swedish Iron and Steel Industry or National and International Reports from the International Energy Agency. This material offered insights into the visions, strategies, standards and commitments of national and supranational organisations in transforming recycling, and metal and energy sectors towards the CE (Schulz et al., 2019). This material supported a more robust and informed analysis across the papers, helping to understand how circularity is enacted and framed in practice. While this data was used across papers, it was specifically interesting for the development of **Paper A**, where these were used to analyse how official documents and standards define and make use of the term recycling; and **Paper E**, where these were used in the development and validation of the model.

5.4 Data analysis techniques

The analysis of the empirical material combined three complementary methods. The first, thematic analysis, was the base analytical method employed across papers. This technique involves generating codes from the analysed data which are then grouped in themes once patterns of meaning and relationships are identified (Braun and Clarke, 2006). This could be theory-informed as in **Paper B** or theory-absent as in **Papers C, D** and **E**. In the theory-informed thematic analysis, theoretical concepts inform the coding process and subsequent development of themes. In **Paper B**, practice elements and circularity principles provided the analytical basis for examining the data and for

identifying and interpreting meaningful patterns. By contrast, in the analysis without an explicit theoretical framework, codes were developed inductively through the identification of meaningful patterns in the data, which were subsequently organised into themes in relation to each study's analytical purpose. The specific process varied slightly across **Papers C, D** and **E**, reflecting their distinct objectives: identifying types of tramp elements, tracing causal structures and relationships, and identifying decommissioning streams, respectively. These are described in greater detail in the respective appended papers.

The second analytical method was System Dynamics (SD). System Dynamics is a modelling approach or technique based on systems thinking principles of non-linearities, feedback loops, delays, and accumulations (Forrester, 1961). It offers the opportunity to analyse and discuss the impacts of short-term practices in the long-term behaviour of a system, often leading to unintended or unexpected rebound or side effects; and enables examining resource behaviour over time (Guzzo et al., 2022). This method was mainly used in two papers: in **Paper D** through a Causal Loop Diagram (CLD) and in **Paper E** through a Stock-and-Flow Diagram (Sterman, 2000). System Dynamics helped visualise feedback loops, while including recursiveness, accumulations and time delays into the analysis. Consequently, the models helped estimate and analyse the consequences that the continuation or disruption of these practices could bring to recycling and their role in meeting CE ambitions. A key advantage of System Dynamics in this study arises from the better understanding of interactions and practice evolution, rather than providing concrete forecasts.

Lastly, **Paper A** analysed how recycling is defined across academic literature, policy and standards. The analysis was informed by an extensive review of literature, books, reports and other documents. Definitions were purposively selected from these sources based on their influence and ability to illustrate the tensions and divergencies across understandings. The selected definitions were then analysed comparatively, examining similarities and differences in both: how they delimit the practice and the extent to which they reflect circularity.

5.5 Research quality

Given the qualitative nature of this research, quality is understood as the outcome of a rigorous, transparent and iterative research process, demonstrated through its ability to generate credible, meaningful and practically useful insights from the field (Shah and Corley, 2006). Based on Lincoln and Guba (1985), there are four key criteria commonly applied in qualitative inquiry: credibility, confirmability, transferability and dependability.

Credibility is strengthened through triangulation, peer debriefing and member checks (Shah and Corley, 2006). Here, triangulation is pursued in three forms: methodological triangulation, investigator triangulation and data source triangulation (Carter et al., 2014). For methodological triangulation, the researcher made use of multiple data sources, such as on-site observation, interviews, workshops and document analysis; for investigator triangulation, interviews were conducted by more than one interviewer; and for data source triangulation, the studies included participants from different types of organisations, professional roles and stakeholder groups, allowing practices and implications to be examined from multiple perspectives. To strengthen the above, the studies counted with a member-checking process, whereby interview summaries based on notes were shared with participants. Lastly, peer debriefing at academic conferences provided an additional opportunity to challenge and refine the interpretative findings (Patton, 2015).

Correspondingly, confirmability is the impartiality and objectivity in findings. This is also ensured through sharing careful and clear notes of observations and interviews across interviewers and with the interviewees for confirmation. Notes were further cross-checked with literature (Patton, 2015). Together, these measures strengthen the transparency and traceability of the analysis and research. Recognising that complete objectivity is neither possible nor intended in qualitative research, these measures ensure that interpretations are consistently anchored in the empirical material.

Transferability is addressed by providing rich, contextualised descriptions of the empirical settings, enabling readers to assess the applicability of the findings to other contexts (Shah and Corley, 2006). While some specific cases were suggested as relevant for other contexts, for instance, the case of tramp elements in steel has also been experienced in aluminium or plastic; the research provides a detailed description of the practices, processes and contexts. The time of the interviews and observations was also specified to ensure the correct allocation

of the practice, in case some of the practices seen during this study might not represent their enactment in the future.

Dependability is supported through transparent documentation of the research process, including methodological choices and their evolution over time (Patton, 2015). In this thesis, dependability is addressed through the detailed documentation provided across the appended papers and this kappa, which together provide a thorough description of the research design, data collection procedures, data management and analytical approaches. The iterative development of the research process is also explicit, allowing the reader to trace how empirical examinations, analytical insights and theoretical considerations informed subsequent methodological choices. Furthermore, Shah and Corley (2006) emphasise the importance of protecting informant confidentiality. This consideration was particularly relevant in the present thesis and shaped the collection and management of the empirical material (See Section 5.3).

5.6 Use of AI

This thesis represents my own original work. Any use of AI (ChatGPT and/or Grammarly) was limited to supporting language editing, including improving clarity and phrasing, correcting grammatical errors, formatting text, reducing length, and organising ideas. All AI-assisted text was critically reviewed and revised to ensure its accuracy and appropriateness. AI tools were not used to review literature, analyse data, generate findings or provide substantive research insights. All cited sources were independently read and assessed by the author and identified through established literature databases. All references included in this thesis were manually compiled and entered by the author. I therefore retain full responsibility for the content, analysis, interpretations and conclusions of this thesis.

I hereby declare that the above information is accurate and that I have disclosed all AI-generated content that directly influenced or contributed to my thesis. I understand that failure to disclose AI tool usage accurately may be considered a violation of academic integrity policies. This submission represents my own original work. Any use of AI tools has been appropriately disclosed, detailing their purpose, extent of contribution, and adherence to ethical guidelines.

5.7 Summary of the chapter

This chapter began by guiding the reader through the overall academic journey underpinning the thesis, outlining the key decisions and research design choices that shaped the study from start to completion. It provided explicit detail on how the research evolved over time, explaining the rationale behind the approaches, studies, overall decisions and the final sequencing of the appended papers. The chapter also included a description of the data collection and analysis behind each of the individual studies that constitute the thesis, while transparently acknowledging methodological limitations and practical constraints. In summary, the chapter established the methodological foundations of the thesis, making transparent the reasoning, processes and limitations that underpin the empirical and analytical contributions presented in the following chapters.

6 SUMMARY OF APPENDED PAPERS

This chapter summarises the papers underpinning this thesis, highlighting for each their purpose, methods, key findings, and contributions. The papers are not presented in the order they were developed or published; instead, they are arranged to support an easier-to-follow narrative. Its chronological order can be found in *Figure 3*. A synthesis of the papers with an overview of their aim, methods, materials, status and research objectives is laid out in *Table 5*. Together, the papers show how the empirical studies and analyses address the research objectives and advance understanding of recycling practices and their role and limitations in achieving the CE over time.

As the lead author on all appended papers, I was responsible for developing the research, collecting and analysing the data, writing the manuscripts, and submitting them for publication. Co-authors contributed through feedback, critical discussion, and comments that helped refine the work. Andreas Feldmann, main supervisor and co-author on most papers, also contributed to the development of ideas and concepts, and supported data collection in the early stages of the PhD, particularly through interviews and site visits; whereas Peter Samuelsson and Cali Nuur, co-supervisors for Studies A and C respectively, contributed with feedback, positioning and participation in some of the data collection.

Table 5. Summary of appended papers.

	Paper A	Paper B	Paper C	Paper D	Paper E
Aim	Analyse recycling definitions and their reflection of and implications for the Circular Economy.	Analyse how different configurations of recycling practices lead to various forms of circularity and trade-offs between CE objectives.	Explore where and how contaminants enter the steel recycling system, identifying the possibility of reducing impurities before melting.	Explore how feedback loops, time delays and accumulations in the recycling system shape material quality, loss and the evolution of recycling over time.	Explore the practices that lead to early decommissioning and develop a dynamic method for estimating decommissioning volumes of solar panels.
Method	Comparative analysis of definitions.	Theory-based thematic analysis.	Thematic analysis to build a taxonomy framework.	Thematic Analysis and Causal Loop Diagram.	Thematic Analysis and Stock and Flow Diagram.
Material	Purposively sampled recycling definitions from a review of reports, standards, books and articles.	22 onsite observations, 36 interviews and 3 group discussions.	3 onsite observations and 14 interviews.	3 onsite observations, 14 interviews and 3 validating interviews.	20 interviews, 3 on-site observations, 2 workshops and report reviews.
Status and Dissemination	Under review in Journal of Industrial Ecology. Presented at NORSI Conference 2026.	Under review in Journal of Industrial Ecology. Presented at SCAIEM Doctoral Workshop 2026.	Published in Waste Management & Research. Presented at iRSC 2023.	Published in Discover Sustainability. Presented at NOFOMA 2024.	Published in Resources, Conservation and Recycling Advances. Presented at System Dynamics Conference 2024.
Research Objectives	Examine whether and how existing recycling definitions and interpretations reflect the ambitions of the CE.	Analyse whether and how current industrial recycling practices produce circularity and which types of circularities they produce.		Investigate whether and how current industrial recycling practices enable future circularity and which types of circularities they enable.	

6.1 Paper A

Title - What is this thing called recycling?

Purpose – The aim of this perspective paper is to highlight the different meanings and definitions attributed to recycling (and by extension, to what counts as recycled and who counts as recycler), examining also whether these reflect the objectives of the CE.

Methodology – This paper draws on over four years of sustained engagement with recycling practices and discourses, including the analysis of hundreds of policy and industry reports, academic articles and books. From this broader body of material, definitions of recycling, recycled and recycler were purposively selected based on their relevance to the article's argument. The paper examines these definitions comparatively to illustrate the different interpretations of what counts as recycling and their implications for the CE.

Findings – Recycling remains inconsistently defined and used across policy, industry and academia, with the same term referring to different activities and outcomes. The comparison reveals substantial variation in what is considered to constitute recycling and in whether, and to what extent, CE ambitions are incorporated into its definition. Recycling is therefore not a universally shared nor a self-evident concept. Neither are the terms recycled and recycler.

Research implications – Meanings shape what is recognised as a "good" or "accurate" practice and how it is consequently evaluated and governed. The study shows that differing understandings of recycling limit comparability and accumulation of knowledge. When the same term refers to different activities and outcomes, findings across studies cannot be directly compared without first considering what is meant by recycling in each case. The paper therefore calls for CE research to critically examine the meanings and assumptions that define what constitutes a successful circular practice in the first place.

Originality – The originality of this paper lies in challenging the taken-for-granted status of recycling as a shared and self-evident concept. By comparing how recycling, recycled and recycler are defined across policy, standards and academia, the paper shows that the same term can encompass different activities, actors and outcomes, with consequences for how recycling (and its contribution to CE) are studied and compared. In doing so, it makes visible a conceptual inconsistency that otherwise remains hidden.

Theoretical contribution

Paper A advances CE knowledge by conceptualising recycling as a socio-material practice whose meaning has important material consequences. It supports that the discursive framing of a practice establishes the boundaries of what is recognised as legitimate, thereby influencing which material transformations become acceptable and desirable. In particular, the study shows that many meanings legitimate forms of recycling that involve substantial degradation of material quality, and dismiss substitutability. By recognising these as successful recycling, dominant discourses reinforce a conception of circularity centred on waste diversion rather than long-term value retention.

Practical relevance

Recent policy developments increasingly recognise that effective recycling governance requires clear definitions, transparent reporting and enforceable accountability mechanisms, aligning with the arguments advanced in this paper. If prevailing understandings of recycling continue to equate any form of material recovery with circularity, policies and performance indicators risk rewarding practices that divert waste while simultaneously reducing material quality, limiting future recoverability and increasing dependence on virgin resources over successive recycling cycles. Definitions embedded within legislation, standards, reporting frameworks and corporate sustainability strategies should better distinguish between forms of recycling that retain material quality and future utility and those that focus on material recirculation. Hence, changing recycling outcomes involves changing the meanings that legitimate action, redefining the role and purpose of recycling.

6.2 Paper B

Title – Competing Circularities: How different socio-material practice configurations generate competing circularity objectives in recycling systems.

Purpose – This paper questions the inherent circularity of recycling by examining how different configurations of recycling practices prioritise and generate trade-offs across different circularity objectives. In doing so, it contributes a practice-based perspective on how different recycling configurations produce different forms and degrees of circularity, stressing the multidimensionality of CE objectives.

Methodology – This paper draws on qualitative material collected throughout the course of four years, including the 36 interviews, 3 group discussions and 22 on-site observations. This material is analysed individually and comparatively, focusing on recycling practices and the configuration of its elements.

Findings – Based on the analysis, the paper makes two main contributions. First, it demonstrates that circularity is not an inherent property of a given CE strategy, but an emergent outcome from the configuration of the practice and its elements. Second, it shows that each practice configuration prioritises different CE objectives, creating trade-offs between e.g. material recirculation, quality retention, long-term value retention, waste reduction, virgin material substitution and reduced use. These findings challenge the assumptions embedded in conventional CE hierarchies and performance measures, which often treat practices as intrinsically circular while overlooking the diversity of configurations and the multidimensionality of circularity. The paper, therefore, calls for more nuanced approaches to assessing circularity that account for both practice variation and competing CE objectives.

Research implications – This study has practical implications for measuring circularity, showing how these may lead to mistaken generalisations about the circularity potential of all practices involved. Circularity is multidimensional, relational and cannot be reduced to universal measures, overlooking how different CE objectives and priorities conflict and give rise to trade-offs in the pursuit of circularity risks producing oversimplified assessments that fail to capture the complexity within CE.

Originality - This paper is original in challenging established hierarchies and performance measures, and in systematically unpacking the complexity of (recycling) practices, showing that not all forms contribute equally to circularity. Its value, thus, lies in providing a more nuanced understanding of how different practices contribute to various dimensions and levels of circularity.

Theoretical contribution

First, Paper B contributes to Practice Theory by extending its application beyond its predominant focus on consumption to the routine practices of industrial operators. It thus demonstrates the value of practice-theoretical approaches for examining how operator's everyday actions shape material processes and outcomes. Second, Paper B contributes to CE research by challenging the assumption that circularity can be attributed to individual strategies or practices. Instead, it suggests that circularity emerges from practice configurations, with different configurations prioritising different dimensions of CE. In doing so, the paper supports discussions on the multidimensionality of circularity and the trade-offs between its objectives, challenging simplified hierarchies that imply a universal ranking of practices according to their assumed circularity potential without accounting for contextual variations. It consequently highlights the need to explicitly define how CE objectives are balanced and which are prioritised.

Practical relevance

The findings have important implications for organisations, policymakers and practitioners seeking to implement CE strategies. The study highlights that adopting practices labelled as circular does not automatically result in circular outcomes; rather, outcomes depend on how these practices are configured, prioritised and combined within specific contexts. Consequently, CE assessments should move beyond simplistic and absolute rankings of individual practices and require recognising trade-offs between competing objectives. By accounting for contextual variation and multiple dimensions of circularity, practitioners can better evaluate alternative strategies and practice configurations, understand their implications and design interventions aligned with the specific circularity outcomes they seek to achieve.

6.3 Paper C

Title – Lost in the shuffle: A taxonomy for the accumulation of unwanted elements in steel recycling.

Purpose – This paper aims to explore the possibility of reducing or limiting impurities before the melting stage, looking into the routine practices that lead to the mixing and accumulation of (unwanted) elements during dismantling, shredding, sorting and melting steel scrap.

Methodology – The study builds upon and extends previous research conducted by the co-authors (See Section 5.2). Since these studies investigated the same system, it allowed for more focused data collection. The work combined 3 direct observations of scrap yards and mills, and 14 interviews with industrial and academic experts. The retrieved information was analysed using thematic analysis.

Findings – This study examined where and how unwanted elements accumulate in the recycling system, leading to three key findings. First, the study demonstrates that tramp element accumulation is an ongoing challenge influenced by operators' socio-material practices. Accumulation occurs at multiple stages and needs a practice-oriented approach for contaminant prevention, meaning that changes in practices are essential to reduce impurity levels early in the recycling chain. Second, it maps entry points of unwanted elements. These include primary raw materials, secondary scrap, alloy additions and surface treatments. Finally, the study proposes a taxonomy that categorises the different types of elements present in the pre-melt stockpile at the furnace after the intentionality of their addition and their desirability in the final product. This means that not all tramp elements are the same and therefore require different approaches to their management.

Research implications – This study underscores the importance of proactive contamination management in recycling processes. It aims to support the development of strategies for contaminant prevention, quality control, and resource management in metal recycling, recognising variation across tramp element types. By introducing a taxonomy of unwanted elements, it provides a foundation for research and practice focused on reducing or preventing their presence in recycled materials, ultimately improving recycling quality. The taxonomy framework can be extended to other metals and non-metallic materials, fostering integrated contaminant management strategies across industries.

Originality – This study is original in proactively identifying how unwanted elements accumulate in steel recycling and highlighting the practices that drive contamination. By developing a taxonomy, it provides a structured framework for researchers and practitioners to understand contamination pathways, inform strategies for prevention and quality control, and ultimately improve the quality and effectiveness of recycling processes.

Theoretical contribution

Paper C enriches the understanding of impurities in scrap by introducing how contamination can emerge through practices of handling and processing scrap at different stages in the recycling system. It also distinguishes between the intentionality with which elements enter the material and their desirability once present in the metal: elements can be introduced intentionally or unintentionally through these practices, while their desirability depends on the subsequent recycling process and material requirements. Framing contamination as a systemic issue influenced by socio-material practices, it illustrates the way in which practitioners shape material quality and resource flows. The paper therefore highlights the importance of examining contamination from the perspective of practices and practitioners, reinforcing the need for proactive intervention.

Practical relevance

Practically, the study offers a framework for practitioners to identify critical entry points where impurities are introduced, enabling targeted intervention strategies. Although these may already be aware of certain, the taxonomy synthesises experiences across stakeholders and facilitates proactive management of resources. It supports evidence-based decision-making aimed at minimising material degradation and maximising resource recovery, thereby directly contributing to operational improvements within CE initiatives. The framework offers insights into contamination pathways, informing policies aimed at improving scrap management practices, setting quality standards and promoting transparency in material supply chains. Understanding entry points and types of unwanted elements can guide the design of improved sorting technologies, process controls and monitoring tools aimed at early detection and reduction of impurities.

6.4 Paper D

Title – Mapping the dynamics shaping the future of steel recycling.

Purpose – The purpose of this paper is to examine how present practices and dynamics shape future system behaviour and material flows. It does so by looking into how tramp element accumulation, scrap availability and resource availability are connected through feedback loops and time delays within the steel recycling system, and how these relationships shape recycling's evolution over time.

Methodology – This study draws on the same dataset as Paper C, comprising 14 expert interviews and observations conducted in two steel mills and one sorting facility. For analytical purposes, practices and outcomes were translated into variables and used to develop a Causal Loop Diagram. The model and its underlying assumptions were validated through three follow-up interviews.

Findings – The findings suggest that continuing current practices risks accumulating highly contaminated, unusable scrap, thereby undermining the future of metal recycling and reinforcing linear economy dynamics. Interacting feedback loops and both material and perceptual delays obscure the consequences of current practices, allowing resource degradation to accumulate before it becomes apparent. The analysis identifies opportunities to alter these dynamics, showing that interventions like improved source separation and designing products for dismantling and recyclability can interrupt reinforcing feedback, delay resource depletion and improve long-term material quality. Together, these findings highlight the importance of incorporating temporal delays and dynamics into the analysis of circular systems and show that maintaining their long-term sustainability requires not only technological improvements but also changes in operational approaches and everyday practices. Failing to make timely shifts in these practices may have significant consequences for the long-term viability and profitability of recycling systems.

Research implications – A key contribution of this study is the development of the Causal Loop Diagram that integrates industry practices and outcomes. By providing a systemic perspective, it enables the identification of feedback loops, interdependencies, and delays that are often overlooked in recycling analyses. This allows for anticipating the long-term consequences of current practices and highlights actions where interventions can reduce contamination, improve material quality, and support more effective resource management.

Originality – This study is a first attempt to analyse how practices and outcomes interact to drive the accumulation of unwanted elements and the loss of resources in metal recycling. It uniquely incorporates temporal dynamics and delays at the centre of the analysis, showing how practices shape outcomes over time. Using Causal Loop Diagrams to map these interdependencies, the paper offers a novel way to visualise and understand how these dynamics contribute to contamination and affect the future of the steel recycling industry.

Theoretical contribution

Paper D advances the understanding of CE dynamics, particularly steel recycling, by explicitly modelling feedback loops, delays and stocks and illustrating how these dynamic structures influence the long-term behaviour of the industry. It emphasises the importance of temporal dynamics and interdependencies in shaping material quality, resource availability and long-term or future circularity. The findings underscore the necessity of adopting longitudinal future perspectives when designing policies and solutions for a CE.

Practical relevance

While recycling practitioners may be aware of many practices and conditions that affect recycling outcomes, this study makes visible how their interconnections can generate delayed and cumulative consequences that are not readily apparent from individual actions. The Causal Loop Diagram provides industry stakeholders and policymakers with a broader basis for assessing the longer-term implications of interventions, identifying potential unintended consequences and considering where changes in the system may have effects beyond the immediate stage of recycling. This systemic perspective reveals that marginal improvements or short-term operational adjustments may be insufficient or even counterproductive if implemented without consideration of the underlying feedback mechanisms and delays. Thus, it underscores the necessity of long-term interventions and timely responses to resource depletion and quality decline, informing strategic decision-making aimed at sustaining the viability of (steel) recycling and progressing towards a long-term CE.

6.5 Paper E

Title – Shedding light on decommissioning solar panel streams: A system dynamics model for volume estimation.

Purpose – The primary objective and contribution of this paper is to develop a more accurate and dynamic model for estimating decommissioning volumes of solar panels, accounting for the many practices that lead to their discard.

Methodology – The study started from a pre-investigation and comparison of results from reports and publicly available literature. This was expanded with 20 interviews, 3 on-site visits and 2 workshops. The insights were carefully interpreted and translated into model variables, parameters and structures that are then integrated in a Stock and Flow Diagram.

Findings – This paper makes three key contributions. First, it identifies previously overlooked streams like unsold overstock and panels discarded through repowering practices, which together account for a substantial share of functional discarded panels. This shows that discarding is often driven by practices of valuation rather than technical failure. Second, it shows that decommissioning volumes may reach significant levels earlier than previously anticipated, highlighting the need for urgent action, but also shows that these will balance out over time. Third, as a result from the above, new and old panels, functional and non-functional accumulate simultaneously. This point to the need for differentiated strategies that account for the volume, efficiency and functionality of each stream.

Research implications – This study underscores the importance of integrating dynamic modelling and time delays into forecasting decommissioning volumes. The findings have practical implications for policymakers, industry actors, and recyclers, highlighting the urgency of developing tailored management strategies for each decommissioning stream (especially for functional but discarded panels), acknowledging the diversity of new, old, functional and non-functional discards. Accordingly, the study emphasizes the need for policies that incentivize reuse and repair, alongside the creation of secondary markets for still-functional panels.

Originality– The study's uniqueness stems from the comprehensive integration of heterogeneity in panel lifetimes, time delays, multiple decommissioning pathways and the explicit incorporation of dynamic fluctuating variables within a unified modelling framework. Unlike previous static approaches, this research disaggregates decommissioned panels into distinct streams and analyses their timelines and characteristics, providing granular understanding of the evolving decommissioning landscape. Moreover, the paper is original revealing overlooked waste streams that are rarely considered in volume estimations. Last, the use of System Dynamics in its study offers a more realistic and temporally informed understanding of decommissioning dynamics and volumes.

Methodological contribution

The contribution of Paper E is mostly methodological, in the sense that it shows the potential of applying System Dynamics in the study of Circular Economy practices. Thus, Paper E introduces a novel dynamic modelling technique to estimate solar panel decommissioning volumes, explicitly capturing the heterogeneity, temporal variability and multiple coexisting decommissioning pathways. Unlike static or linear models, this dynamic framework captures temporal fluctuations and complex interactions within the decommissioning system. By employing a Stock and Flow Diagram that explicitly models coexisting lifetimes, heterogeneous decommissioning streams and fluctuating variables, the study provides a nuanced framework that reflects the complex, evolving nature of decommissioning streams. This approach offers a more realistic basis for forecasting decommissioning volumes, aligning better with real-world complexities.

Practical relevance

The study offers a detailed, adaptable System Dynamics model providing policymakers, industry actors and researchers with foresight into future decommissioning volumes, highlighting critical streams. Its insights inform opportunistic planning for secondary markets and circular resource flows, policy measures incentivising reuse or repair, and strategic investments in advanced and specialised recycling.

7 DISCUSSION

This dissertation set out to explore ***whether and how current industrial recycling practices produce circularity, and with what implications for achieving CE ambitions over time.*** In other words, it takes recycling as an example to investigate how current so-called R-strategies contribute to or obstruct present and future circularity. Drawing on the findings of the five appended papers presented in *Chapter 6*, this thesis argues that circularity is a **multidimensional, temporally embedded** and **emergent** outcome of **recursive** socio-material practices. The remainder of this chapter synthesises the findings from the appended research papers and situates them within the existing body of knowledge to critically explore what they reveal about circularity and the gap between CE visions and their realisation in practice.

7.1 Circularity beyond circulating

Ongoing debates tend to treat circularity as an inherent property of practices and systems involved in the (re)circulation of products and materials (like recycling, repair or reuse), that can be assessed, optimised or improved (Desing et al., 2020). This view implies that the mere implementation of practices intended to circulate materials are, in themselves, sufficient to achieve a CE, and that their success can be measured through quantitative material-flow indicators. While it recognises circularity variations, e.g. practices higher up in the hierarchy will produce higher levels of circularity than those at the bottom (Morseletto, 2020), in all instances circularity is conceived as embedded in the practices themselves. This thesis argues otherwise. Based on the analysed

strategy, recycling, the following paragraphs motivate why the mere circulation of materials should not be equated with circularity.

Recycling has been extensively studied, with hundreds of thousands of academic papers and books examining its performance, role and limitations in relation to the CE. This literature has explored many aspects: from whether recycling can fully recover materials, tackling issues of contamination and resource dissipation, to the assessment of costs, efficiencies and profitability of recycling processes (e.g. Meskers et al., 2024). Despite this breadth of analysis, little attention has been paid to more fundamental questions: What is recycling? And what do we mean when we invoke it as a solution toward CE? Previous research has done a great job in defining quality recycling (Tonini et al., 2020), downcycling (Helbig et al., 2022) or recyclability (Geist and Balle, 2025), yet scholars have rarely questioned what recycling fundamentally entails. Revisiting **RO1**, this thesis examined ***whether and how existing recycling definitions and interpretations reflect the ambitions of the CE.***

Existing definitions of recycling provide only a partial account of circularity. After a close engagement with literature and practice, **Paper A** reveals that, despite its long-standing and widespread use, recycling is understood and defined differently across academic literature, books, policies and standards. Definitions and interpretations, however, shape what counts as acceptable, desirable, feasible and expected (Figge et al., 2023). If definitions encompass practices that conflict with the goals of CE, these implicitly legitimise and normalise practices that e.g. accept or involve material loss or quality degradation, affecting whether recycling delivers circularity. Noteworthy, recycling takes a fundamentally different meaning within a CE. In a CE, recycling should aim to deliver high-quality outputs capable of substituting virgin materials, thus displacing their extraction (Geist and Balle, 2025; Tonini et al., 2022). However, only a subset of the activities currently described as recycling would truly align with these objectives.

Where **Paper A** establishes the breadth of practices, outcomes and actors encompassed in definitions, **Paper B** demonstrates that each of these practices can be configured differently across materials, products and regions, giving rise to different forms of circularity. Taking a practice-based approach, this paper shifts the focus from whether practices are circular in principle, to how they contribute to CE ambitions in practice through the specific configurations of materials, meanings, competences, rules and teleoaffectivities (Shove et al., 2012; Schatzki, 2002). Instead of treating circularity as a given property or

outcome of recycling, the paper exemplified how different types of circularities emerge through the alignment and interaction of practice elements (Hui et al., 2017).

In discussions around how to achieve a CE, some scholars argue that gradual enhancements in technologies and operations can cumulatively deliver system-wide change (Kirchherr and Hartley, 2025), whereas others contend that without deeper structural and institutional shifts, such incremental steps will have limited impact (Bauwens et al., 2020). The findings in this thesis suggest that while improvements to individual elements of the practice (e.g. technology) can lead to incremental gains, these remain constrained when the underlying meanings (e.g. valuing quantity over quality), competences (e.g. focused on speed rather than careful sorting) or material arrangements (e.g. infrastructures designed for bulk processing) remain unchanged (Schulz et al., 2019). Thus, practice-based approaches suggest that change requires a reconfiguration of all these elements across interconnected practices, rather than isolated improvements within existing configurations (Shove et al., 2012). Without changing meanings, purposes or teleoaffective structures, current R-strategies will not likely deliver circularity.

While these insights may not be entirely new, they suggest that the contribution of recycling to CE depends less on the label of the practice and more on how it is organised, governed and enacted. **Paper C,** for example, shows how practices within steel recycling cause tramp element accumulation, material loss, and the overall reproduction of "linearity". These material transformations are not external nor necessarily unintended side effects as argued by Helbig et al. (2022) but are directly linked to how recycling is performed in practice. As such, variations in practice configurations produce different material outcomes.

This suggests that circularity is much more than circulating materials and products. It suggests that all practices, including the R-strategies, should be exposed to adaptations and modifications to fit CE objectives beyond material circulation. This thesis thus argues that circularity should be recognised within practice definitions and interpretations (**Paper A**) and reflected in the configuration of all elements of the practice (**Paper B**). Thus, circularity is not something we implement, but something that emerges through practice. It also extends beyond the circulation of resources to include retaining material quality and value for as long as possible, substituting and reducing the use of virgin materials and minimising waste generation (Geist and Balle, 2025).

Lastly, the above suggests that circularity cannot be fully measured by indicators such as recycling rates, circularity rates or resource efficiency (Kristensen and Mosgaard, 2020). While these indicators enable comparability and partial assessment, they simplify the complexity of CE into measurable proxies failing to cover other dimensions, like qualitative losses from changes in material properties. Taken together, the preceding discussion and the following section engage with **RO2**, which analysed ***whether and how current industrial recycling practices produce circularity and which types of circularities they produce.***

7.2 Multidimensionality in a Circular Economy

Before prescribing pathways towards a CE, it is necessary to ask which CE is being pursued. Research has shown that there is no singular vision of a circular future (Suárez-Eiroa et al., 2026). Scholars have identified multiple CE imaginaries that differ in how they conceptualise desirable futures, the role of technology and markets, and the broader societal transformations required to achieve circularity (Calisto Friant et al., 2020). Since these futures rely on different priorities, they require different forms of governance, organisation and changes in everyday practice. Thus, the ways in which CE strategies are currently designed and enacted may enable certain circular futures while simultaneously constraining others. Following the previous section, a strong focus on material circulation and recycling rates might come at the expense of alternative CE objectives such as preserving material quality, extending product lifetimes, reducing overall virgin resource demands or maintaining future circularity potential. Circularity is therefore best understood not as a singular outcome, but as a multidimensional one composed of multiple and sometimes competing objectives that may not always be simultaneously maximised (**Paper B**).

This is not new, the many CE objectives as well as the existence of trade-offs and unintended consequences have been highlighted by authors like Corona et al. (2019), Guzzo et al. (2022) or Zink and Geyer (2017). However, these have predominantly focused on trade-offs between sustainability outcomes across environmental, economic and social domains. For instance, material recirculation processes may lead to increased energy consumption, higher emissions or broader social impacts (Corona et al., 2019). The findings in this thesis extend this line of argument by demonstrating that trade-offs are not only external but often embedded in how circularity is constituted. Findings in **Paper B** showed that different configurations prioritise some circular

objectives over others creating conflicts. For example, dilution strategies in recycling ensure the resulting recycled material meets the required technical specifications and minimum quality, yet they do not necessarily reduce the dependence on virgin inputs since dilution requires virgin iron. In that case quality is retained, at least for one cycle, yet virgin resource use is not fully avoided. This inevitable degradation of quality then limits the substitution of the virgin counterpart (Tonini et al., 2022).

Another example is the classical quantity vs quality trade-off. The same paper shows that while products and materials in the Kenyan context quickly and easily find a market to be immediately sold, they often involve quality losses. This trade-off has also emerged as a result in other papers within this thesis. **Paper C** showed how a throughput- and cost-efficient focus on recycling practices in Sweden or Austria tends to lead to the degradation in material quality and resource losses. **Paper D** expands this suggesting that these trade-offs could expand rather than shrink in the future unless they are balanced timely and could lead to high quantities of scrap but of a low quality. Conversely, **Paper E** highlights how high-quality recycling still depends on this throughput-oriented system, since the investment on processes that enable higher purity recovered materials depend on the perception of high volumes of waste.

Circularity trade-offs must then be balanced to ensure that moving towards one dimension of circularity does not fully compromise the possibility to move towards another dimension. This balance of trade-offs may already be reflected in the different R-strategies, where each reflects a different circular dimension: from rethinking consumption through sharing, to reducing virgin material use and waste or extending the life and value of products and material through reuse and repair (Morseletto, 2020).

Researchers involved in CE hierarchies often suggest that meeting all objectives require the holistic implementation of multiple R-strategies (e.g. Reike et al., 2018). However, in contexts where material volumes are limited, different circular strategies may compete rather than reinforce one another. **Papers B** and **E** show how other strategies, like reuse or repair, can reduce the volumes of waste that reach recycling. Given how important volumes are for investing in higher-quality recycling, these papers illustrate how such activities could delay the recovery of high-quality materials through recycling. This reinforces the idea that recycling operates within, and depends on, "linear" economic logics and waste generation (Gregson et al., 2015; Savini, 2019). While materials are temporarily fed back into the system, recycling often fails to maintain them at

their highest value for as long as possible and/or displace the use of virgin resources. More recycling thus may not automatically mean more circularity.

Consequently, it is not analytically meaningful to ask whether recycling (or any practice) is *"circular"*, since recycling is interpreted and configured in multiple ways and circularity is not a singular, directly measurable outcome, but the extent to which multiple and partially conflicting objectives are realised and balanced in practice. Circularity is thus not a fixed end-state that systems move toward (Suárez-Eiroa et al., 2026). Instead, circularity takes different forms in different contexts. Debates should, therefore, move from singular to plural circularities. That is, moving from questions like *"How much circularity…?"* or *"How circular is…?",* measured through recycling rates, recycling content or material recovery rates; towards questions on "Which circularity is being produced?", *"Through which practices?", "At the expense of what circularities"* and *"With what consequences for future possibilities?"*. This shifts CE governance and assessments to future material quality, recyclability and availability of resources, and involves reflecting on which dimension of circularity is being prioritised and measured.

7.3 Ensuring future circularity

Despite its relevance to material recirculation, time has received limited analytical attention in CE literature (Grafström, 2026). While present in the most cited definitions of Geissdoerfer et al. (2017) and Kirchherr et al. (2017, 2023), future circularity seems to be lost in current circularity assessments. A central concern of this thesis therefore has been how circularity unfolds over time. The following discussion builds on **RO3**, which examined ***whether and how current industrial recycling practices enable future circularity and which types of circularities they enable***.

Present practices actively shape future circularities, in the same way that today's circularities are a reflection of past practices (Grafström, 2026). The findings in **Paper C** point towards a more proactive approach: one that seeks to prevent avoidable quality degradation by adjusting how practices are configured, so that circularity can be sustained over time. This includes, for example, the avoidance of mixing products and materials in shredding or melting stages, and the careful dismantling and, when possible, manual sorting before loading products to the shredder. This temporal dimension is further and mainly developed in **Papers D** and **E**, where time is primarily introduced in their analysis through time delays. **Paper D** illustrates how both material and perceptual delays can

accumulate into large volumes of unusable scrap that may only be detected when it is *too late*. Quality degradation and material loss, thus, does not happen suddenly but cumulatively and progressively over time. What starts from minor quality losses within tolerance thresholds, can become major over successive cycles.

These outcomes are not shaped by recycling practices alone. Practices are interdependent and mutually shape one another (Klitkou et al., 2022). Together, **Papers D** and **E** highlight how design practices influence material quality through complex compositions and product architectures and with the inclusion or not of recycled material, while discarding practices influence recycling by determining when products are declared as waste. The solar panel case in **Paper E** highlights the importance of time lapses where the time difference between when products are designed or used and when they actually reach recycling can take decades. However, this study also shows that decommissioning practices can happen almost immediately, meaning that the materialities perceived in the present are a result from practices that span in a wide range of past times, from e.g. installations 30 years ago to last year's panels that did not get sold (that is, recycling facilities receive all new, old, functional and non-functional products).

Recycling practices, thus, must deal with consequences from past and present practices simultaneously, making it increasingly difficult for recycling to be optimal to all product designs. Standard processes may be able to handle all but will inevitably lead to degradations and losses. This invites to reflect also in the nature of the concept of waste which is no longer defined by a physical or technical property but by the value attributed to a product or material within a given context (Corvellec, 2025). Examining the interrelationship of current practices, thus, provides critical insights into how recycling systems produce present and future outcomes.

Beyond time, studies frequently underrepresent the complexities of multiple cycles and the consequences of downcycling over time (Corona et al., 2019). Recursivity is an essential aspect of circular practice, yet it is rarely included in the Material Flow Analyses or Life Cycle Analyses that dominate current assessments of material circularity (Schöggl et al., 2020). Novel adaptations of these have included dynamism but fail to include the accumulating result of socio-material practices (Corona et al., 2019). In circular practices, materials are fed back over cycles ideally constantly, meaning that these practices and their outcomes (e.g. quality) keep affecting themselves over time (Greene and

Hobson, 2025). That is, the practices in themselves shape the material element that will affect the future performance of that same practice. The studies included in this thesis have consistently demonstrated how everyday practices contribute to contamination, resource loss and declining material quality. For example, **Paper D** shows how practices like diluting contaminated scrap with virgin material instead of removing impurities allows contaminants to persist and accumulate over successive cycles, reducing the quality of the material every cycle. Consequently, while scrap volumes are expected to increase, these may result in materials that are unusable, limiting the potential to substitute primary resources.

Combined, temporalities (time delays) and recursive material processing, cumulatively shape future circularities. Throughout this thesis, recycling and circularity have been explored both as a present practice and as a vision for the future. **Papers D** and **E** make a key analytical contribution by showing that understanding circular practices requires explicitly accounting for temporal dynamics, including time delays and the accumulation of effects across multiple cycles, in shaping their role in circularity outcomes. This thesis demonstrates that present performance may short-term qualify as circular yet may hinder future circularity. Conclusively, this thesis pushes for shifting circular evaluations from present performance to future consequences and moving from short-term (recycling) performance toward managing the long-term recursive conditions that enable multiple future forms of circularity.

7.4 Linear incentives, circular expectations

A final point for discussion emerged from reflecting on the data collection process itself. What initially appeared as a methodological limitation, the reluctance of practitioners to fully disclose their practices, proved revealing in its own right. During interviews, practitioners carefully managed what they shared, what they avoided and which issues they emphasised. These often reflected an unease with exposing the limits of their circularity, highlighting the tensions between public narratives of CE and the realities of everyday operations. In this sense, the data collection process offered insight into how practitioners navigate, negotiate, and sometimes conceal the boundaries of what is considered circular in practice.

This selective disclosure points to the presence of strong pressures surrounding recycling practices, particularly in relation to CE expectations. Their reluctance should not always be interpreted as a resistance to CE ambitions. Instead,

practitioners operate within a system that rewards throughput, efficiency and volume, not material quality or circular outcomes. As a result, practitioners find themselves simultaneously incentivised to act linearly but criticised for doing so. The issue, therefore, is not whether they are unwilling to become circular, but whether they have the capacity to change the *rules of the game* (Schulz et al., 2019). Expecting them to deliver circular outcomes without altering the meanings, teleoaffective structures, rules and value structures places responsibility on actors who, individually, lack the power to transform the system.

7.5 Summary of the chapter

This thesis demonstrates that the limitations of recycling in contributing to broader CE ambitions go beyond technological constraints, economic feasibility or insufficient infrastructure; they are embedded in the ways recycling is interpreted, configured, performed and reproduced over time. Across the appended papers, recycling emerges not as a neutral or inherently circular practice, but as a heterogeneous socio-material accomplishment shaped by competing interpretations, practice configurations, material transformations and temporal dynamics. The thesis shows that the interpretations and definitions that determine which recycling practices are legitimised, the priorities embedded in their organisation, the pursuit of throughput and efficiency over material quality and substitutability, the intentional yet avoidable practices that compromise future recyclability and the interdependencies between design, use, decommissioning and recycling all shape what forms of CE become possible and which remain unattainable.

The recursive consequences of present practices extend beyond immediate outcomes, influencing the material conditions, technological possibilities and circularity opportunities available in the future. Taken together, these findings challenge the assumption that increasing recycling necessarily advances circularity. Instead, this thesis shows that circularity is an emergent, multidimensional and temporally embedded accomplishment whose outcomes depend on how practices are configured and interconnected across time. In doing so, the thesis shifts attention from how to optimise recycling within existing systems to a more fundamental question of which forms of circularity current practices enable, constrain and reproduce over time.

8 CONCLUSION AND CONTRIBUTIONS

This thesis addressed the gap between CE's normative ambitions and their practical realisations by investigating how industrial recycling practices produce circularity and how their outcomes shape the possibilities for circularity over time. Across different materials, products, contexts and temporal scales, this thesis demonstrates that circularity is not an inherent property of so-called circular strategies, but an emergent outcome of how practices are interpreted, configured and sustained over time. Through a compilation of five independent papers, this thesis advances the understanding of recycling and its role in achieving a CE through several conceptual, practical and methodological contributions. Collectively, the findings call for a broader understanding of circularity that recognises both its multidimensionality and future perspective.

Achieving a CE requires balancing multiple and, at times, competing objectives. Circularity extends beyond the recirculation of otherwise waste materials and encompasses prolonging resource use, preserving material quality, retaining value, reducing waste and substituting virgin resources with secondary materials, displacing the use of virgin materials overall (Blomsma and Tennant, 2020; Hagelüken and Goldmann, 2022). These objectives may hardly be maximised simultaneously, making circularity a multidimensional and context-sensitive endeavour that requires explicit consideration of trade-offs between CE objectives.

These trade-offs must also be considered over time. Practices that appear circular in the present may gradually undermine future circularity by degrading

material quality, limiting the substitution of virgin resources or constraining future reuse and recycling opportunities. CE must then be understood not only as the management of current resource flows but also the preservation of future circularity potential. A central insight of this thesis is that circular practices simultaneously respond to past, present and future actions (Hopwood, 2016). Consequently, recycling systems must be sufficiently adaptable to accommodate past, present and future material compositions and designs while avoiding configurations that reinforce material degradation. Feedback loops, temporal delays and accumulations of material degradation mean that the consequences of today's practices often become visible only in the future, when opportunities for intervention might have diminished (Guzzo et al., 2022). Safeguarding future circularity, thus, requires proactive intervention.

This temporal dimension is particularly evident in relation to material quality. As materials repeatedly circulate through recycling systems, degradation accumulates over successive cycles, progressively reducing recyclability and eventually producing unusable waste streams. In a context of increasing resource demand and growing pressure on critical raw materials, preserving material quality is essential for enabling long-term substitution of virgin resources (Geist and Balle, 2025). However, material quality alone does not guarantee such substitution, which also depends on their integration in product designs, market demands and the practices that shape the availability and use of secondary materials (Zink and Geyer, 2017).

Upstream practices, like those related to decommissioning, design and valuation, also influence the quantity and quality of materials entering recycling systems and, consequently, the economic viability of investments in more specialised and advanced recovery technologies. These findings reveal that contemporary recycling remains embedded within and dependent upon waste generation and broader "linear" economic logics, where even well-established and technologically advanced recycling systems, such as steel recycling, continue to prioritise material throughput and short-term economic performance over long-term preservation of circularity (Gregson et al., 2015; Savini, 2019).

Building on Jørgensen (2019), the thesis further demonstrates that recycling is not a singular or universal practice, but a heterogeneous set of practices shaped by different meanings, objectives and socio-material arrangements. These meanings influence what is recognised as legitimate recycling and, consequently, the circularity it enables. As a result, different configurations of

recycling practices produce different circular outcomes, demonstrating that achieving a CE requires more than increasing recycling rates or improving technologies, it requires rethinking the meanings, priorities and practice configurations that determine how resources are valued, managed and circulated over time.

8.1 Contribution to theory

This thesis makes several contributions to CE research combining empirical depth with conceptual and methodological advancement. It provides empirical evidence that substantiates and refines existing understandings but also offers new insights into dimensions that have received less attention.

First, this thesis extends the application of Practice Theories within Circular Economy research from their predominant focus on consumption to the study of industrial recycling. This places practitioner's routine actions and experiences at the centre of the analysis, showing how their routine practices shape material quality, system performance and overall circularity. In doing so, it offers a new analytical lens for examining industrial recycling and illustrates the broader potential of Practice Theory for investigating the circularity of strategies.

Second, the thesis further complements this perspective by demonstrating that the meanings and definitions attached to the practice of recycling are not only descriptive but shape what is recognised as legitimate and acceptable recycling. By exposing the diversity of activities encompassed by the term and the plurality of definitions and meanings attached to it, it challenges the assumption that all forms of recycling are inherently circular and opens a space for more precise and nuanced discussions about what counts as recycling and which practices truly support circularity.

Third, this thesis advances CE knowledge by conceptualising circularity as an emergent outcome of the interplay between, and balancing of, potentially conflicting CE objectives. By foregrounding the trade-offs between material circulation, waste reduction, quality retention, substitution and reduced use of virgin materials and lifetime extension, the thesis demonstrates that circularity cannot be assessed against isolated objectives but must be understood through their interdependencies and temporal dynamics. This approach shifts focus from the presumed benefits of individual circular strategies to the conditions under which their enactment, interaction and cumulative consequences enable or undermine broader CE ambitions.

Last, this thesis advances CE research by integrating temporality into the analysis of its practices. It demonstrates that recycling outcomes cannot be understood through assessments at a single point in time, but must account for recursive material processing, feedback loops, material and perceptual delays and accumulations over successive cycles. In doing so, the thesis raises the notion of future circularity, showing that current practices shape not only present performance but also the conditions under which future circularity can be achieved. Taken together, these contributions advance CE research by providing new theoretical perspectives on how circularity is produced and how it evolves over time.

8.2 Methodological contribution

The principal methodological contribution of this thesis is the integration of dynamism into the analysis of recycling practices. By incorporating feedback loops, temporal delays and accumulations, the thesis demonstrates that circularity cannot be adequately understood through static assessments alone. Recent developments in approaches like Material Flow Analyses and Life Cycle Assessments have introduced dynamism. However, these rarely account for material scarcity, the complexities of multiple cycles, or the consequences of socio-material practices causing material degradation and contamination (Corona et al., 2019). Since these dynamics are fundamental to understand how circularity emerges and evolves and to understand why practices that appear effective in the present may undermine future circularity, this thesis demonstrates the methodological value of System Dynamics.

This thesis further points to the methodological potential of bringing Practice Theory and a System Dynamics perspective into closer dialogue to better capture the temporal evolution of circular practices. Existing practice-based studies have examined practice variation and repercussions through longitudinal and historical analysis of how practices evolve across time (Shove, 2023). While insightful, this thesis extends that perspective by showing the importance of explicitly accounting for nonlinear dynamics, feedback mechanisms, temporal delays and accumulations. These dynamics are central for several reasons. First, past practices shape present outcomes, while present practices influence future ones. Reiterating the words of Hopwood (2016, p. 142), the past, present and future "occur together by virtue of a particular action and its motivation and intention". This is particularly relevant for so-called end-of-life practices, where considerable time gaps may exist between production, consumption and

recycling, sometimes spanning decades. Second, circular practices involve recurring material flows across multiple cycles, meaning that each performance of the practice modifies the material conditions that will then shape the future performance of that practice. And third, the consequences of recycling practices can extend beyond the practice itself, influencing upstream activities such as product design or consumption.

8.3 Contribution to practice

An adequate policy landscape is considered one of the most effective ways to encourage the adoption of the CE (Losa, 2025). This thesis offers several insights of direct relevance to policy. First, the findings highlight the need for greater definitional precision in legislation, standards and policy frameworks. Developing more differentiated definitions that explicitly recognise circular objectives would improve clarity, facilitate more meaningful monitoring and create stronger incentives for practices that preserve long-term resource value. Second, the thesis further demonstrates that CE policies should explicitly recognise the multidimensional nature of circularity and the trade-offs between competing objectives. Instead of promoting universal hierarchies of preferred strategies, policy frameworks should support context-sensitive decision-making by clarifying which circular objectives should be prioritised, how trade-offs are balanced and how both present and future circularity are considered in policy evaluation. Third, and related to the latter, circularity assessments and metrics should explicitly account for future circularities.

For industry actors and managers, this thesis underscores that achieving a CE depends not only on technological innovation but also on the everyday practices through which materials are designed, produced, used, discarded or recycled (Abbas et al., 2026). Practices around product design, material selection, decommissioning, sorting and material handling directly influence material quality and the long-term potential for resource recovery. Adopting more proactive practices that preserve material quality and anticipate for the long-term consequences of present actions, industry actors can play a central role in strengthening future circularity. Yet, the thesis demonstrates that individual organisations cannot achieve circularity in isolation when operating within teleoaffectivities that continue to prioritise throughput and short-term economic upturn. Beyond improving recycling technologies or increasing recycling rates, achieving a CE requires aligning policy, industry practices and incentive structures around a shared understanding of circularity that

recognises multiple (conflicting) objectives, long-term dynamics and systemic interdependencies.

Aligned with the above, this thesis could also inform designers in developing products for recyclability and disassembly by clarifying how industrial recycling practices take place and what these can realistically accommodate beyond theoretical assumptions, accounting also for temporal delays. Understanding the practical capabilities and limitations of recycling can help designers identify which material combinations, joining techniques and product configurations facilitate or hinder disassembly, sorting, separation, material recovery and ultimately, circularity. This can help bridge the gap between design intentions and the practical conditions under which circularity is achieved.

8.4 Avenues for future research

Circular Economy has been widely studied over the past decades, yet significant gaps remain, particularly in understanding how it is enacted in practice. This thesis has opened several avenues for future CE research. First, it highlights the need to examine circularity from a long-term perspective by investigating how present practices shape future material conditions, resource availability and long-term viability of circular systems and strategies. Greater attention should be paid to temporal dynamics, including feedback loops, delays, recursivity and accumulations, to better understand how circularity evolves over successive material cycles and how current interventions influence future outcomes. In this regard, System Dynamics offers considerable potential for analysing circular practices and exploring the longer-term consequences of their present configurations. As the application of SD on CE research continues to expand, future research could therefore further strengthen such analysis by comparing model-based estimates with longitudinal empirical studies, or by using longitudinal observations to inform and refine model assumptions and estimates.

Second, the thesis demonstrates the value of analysing CE through a practice approach, encouraging future research to extend this perspective to other industrial strategies like refurbishment, remanufacturing or more transformative takes like refuse. It would also be valuable to examine practices not covered in this thesis, such as the collection of municipal or industrial waste, and how collection practices may affect the mixing of material. For example, whether and under what circumstances separately sorted household waste may be subsequently mixed during collection. This would support more nuanced

assessments of what forms of CE are achievable under what conditions. The thesis has also shown that many of the tensions, limitations and contradictions associated with CE emerge through everyday practices and thus motivates further exploring how CE develops over time, how practices evolve and how changing these redirect outcomes.

Third, the findings encourage further methodological development by combining Practice Theory with System Dynamic approaches, this time within the same study. Integrating both and other temporally explicit methods offers opportunities to better understand how micro-level practices generate long-term system behaviours and how changes in these practices may reshape these systems over time. This thesis then suggests considering these methods beyond conventional Material Flow Analyses and Life Cycle Assessments to be able to discern the future implications of past, present and future practices.

Fourth, future research should continue refining the conceptual foundations of CE by critically examining how circular practices are defined, performed and assessed. This includes examining the correlation between definitions and the enactment of circular practices, which dimensions of circularity may need to be prioritised to preserve the potential of multiple dimensions in the future, how such dimensions and their trade-offs can be incorporated into assessments, and how assessment frameworks can capture not only present performance but also the conditions for maintaining circularity across dimensions over time. Such conceptual development should therefore remain grounded in empirical evidence of what is practically feasible.

In summary, CE is likely to remain a topic that continues to engage policymakers, scholars, industry and society. Future research has the potential to move beyond exploring the technical possibilities of CE, towards critically examining its limits, trade-offs and unintended effects. Taking all the above into consideration, future studies can contribute to more nuanced and realistic understandings of what CE (practices) can achieve, under which conditions and where their potential remains limited.

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