Sustainability transitions in e-waste management:

Insights from field studies in Ghana, Brazil, and China

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We have inherited from our forefathers the keen longing for unified, all-embracing knowledge. The very name given to the highest institutions of learning reminds us, that from antiquity and throughout many centuries the universal aspect has been the only one to be given full credit. But the spread, both in width and depth, of the multifarious branches of knowledge during the last hundred odd years has confronted us with a queer dilemma. We feel clearly that we are only now beginning to acquire reliable material for welding together the sum total of all that is known into a whole; but, on the other hand, it has become next to impossible for a single mind fully to command more than a small specialized portion of it.
I can see no other escape from this dilemma (lest our true aim be lost for ever) than that some of us should venture to embark on a synthesis of facts and theories, albeit with second-hand and incomplete knowledge of some of them - and at the risk of making fools of ourselves. (Schrödinger, 1944, p. 1)

Abstract

Waste from electrical and electronic equipment (e-waste) is one of the fastest-growing waste streams and represents a considerable global challenge. Currently, e-waste is recycled primarily by the informal sector in the Global South and is commonly associated with significant social and environmental hazards. Given these challenges, the overarching aim of this Ph.D. thesis is to explore possible avenues for transitions toward more sustainable e-waste management systems in different countries of the Global South.

The thesis is theoretically framed within the interdisciplinary research field of sustainability transitions and based on a transition management approach. A core assumption is that e-waste management systems require, first and foremost, more established practices for collection and recycling, but also better integration throughout the electronics life cycle. Central concepts that guide the broad understanding include sustainable development, circular economy, and life cycle thinking. The specific research objectives are twofold: (1) Identify barriers and drivers experienced by the informal sector in transitioning to established e-waste management systems and (2) identify barriers and drivers to the growth of the formal sector in the transition toward established e-waste management systems.

The work applies a method of engaged scholarship to capture various perspectives of key stakeholders in different e-waste management systems within the Global South. A central element of the thesis is the empirical studies conducted in Ghana (2017), Brazil (2018), and China (2019). These are among the most impacted countries in their respective continents, thus representing significant locations for empirical research. The investigations focus on current practices within the informal and formal sectors and, where applicable, the impact of policies implemented at a national level.

In Ghana, primary field studies were conducted in Agbogbloshie, a scrap metal yard in the capital. The site has gained international notoriety for social and environmental hazards resulting from improper e-waste processing. Thus, it represents a significant case for investigation within the informal sector.

The empirical study in Brazil focuses on the formal sector. Brazil is the largest e-waste generator in Latin America but has limited e-waste management activities performed by the formal sector. This study comprises observations from four e-waste recycling organizations with diverse levels of operations: (1) A university centre that represents a pioneer project in the country, (2) a company with an established structure for e-waste collection, (3) a branch of one of the largest e-waste recycling companies in the world, and (4), a company with an innovative process for e-waste recycling within the Brazilian context.

Lastly, the study in China combines data from both informal and formal sectors. China is one of the most impacted countries by previous e-waste importation and unregulated recycling activities. However, the country has advanced rapidly regarding the implementation of e-waste legislation. The empirical study comprises field studies from two locations: (1) the e-waste site of Guiyu in Guangdong Province, which gained notoriety in the past as one of the largest informal e-waste processing sites in the world, and (2) a licensed e-waste recycling company in Shaanxi Province.

The thesis presents the main results from the field studies based on a multi-level perspective framework. The framework focuses on three levels of analysis: the micro-, meso-, and macro-level. The primary results of this work comprise the micro- and meso-level. Typically,

innovations emerge at the micro-level and face high uncertainty. Only some innovations successfully drive changes toward transitions, ultimately developing into regime practices. An unsuccessful innovation identified at the micro-level includes the installation of wire stripping machines in Agbogbloshie.

The meso-level relates to the regime, the prevailing structure in current systems. The thesis applies the conceptual framework of sectoral and service regimes to combine the results from the investigations in the three countries. The analysis perceives the e-waste management system as a sectoral regime including several services. It categorizes the service regimes into three stages of e-waste management (i.e., collection, pre-processing, and end-processing) associated with the informal and formal sectors of the economy.

The analysis identifies the following service regimes in the collection stage: individual collection, take-back schemes, business-to-business collection, collection centres, and voluntary collection points. The pre-processing stage of e-waste management includes, for instance, manual dismantling in the open air or shelters, manual dismantling in workshops, manual dismantling in facilities, and mechanical treatment through shredding. Lastly, the end-processing also takes place through various service regimes. Within this stage, the following services are highlighted: open-air burning of cables, high-temperature separation of components from the printed circuit boards (PCBs) in workshops, open-air dumping, export of specific components for the end-processing, smelting process resulting in alloys, high-temperature separation of components from the PCBs in facilities, pyrometallurgy, and final disposal in industrial landfills.

The Ph.D. thesis identifies misalignments at different levels, namely within and between service regimes. It categorizes the service regimes into the following dimensions: (1) technologies & infrastructures, (2) organizational mode, (3) rationale & meaning, (4) internal coordination, and (5) legislation & public financing. Such misalignments potentially pressure the existing systems and act as drivers or barriers toward transitions. For example, a lack of comprehensive processing infrastructure in the three countries within dimension 1 opens windows of opportunities for the emergence of innovations. The analysis of dimension 2 reveals that market prices are drivers for recycling specific, valuable components. A limited level of education in specific settings manifests as a transition barrier within dimension 3. In dimension 4, a lack of environmental awareness for disposal is identified. Lastly, a lack of integration between the informal and formal sectors is emphasized in dimension 5.

The work contributes to the sustainability transition research field by combining various perspectives of critical agents in the studied e-waste management systems in Ghana, Brazil, and China. To the best of the author's knowledge, this is the first time a work combines such empirical studies in these three significant countries. The Ph.D. thesis applies different frameworks from the research field to identify critical barriers and drivers and to provide possible transition pathways for e-waste management.

The findings suggest that transitions toward more sustainable practices require advancing policies while incorporating critical agents in the systems at all scales, from local to global. The work highlights the need to integrate the informal sector into the initial stages of e-waste management and strengthen capacities within the formal sector for end-processing. Moreover, it shows that accounting for the diversity of service provision is of utmost importance to direct sustainability transitions in the Global South.

Keywords: waste electrical and electronic equipment, WEEE, recycling, Global South, informal sector, transition management, circular economy, service regimes.

Abstrakt

Avfall fra elektrisk og elektronisk utstyr (e-avfall) er en av de raskest voksende avfallsstrømmene og representerer en global utfordring. For tiden resirkuleres e-avfall primært av den uformelle sektoren i det Globale Sør og er ofte forbundet med betydelige sosiale og miljømessige farer. Gitt disse utfordringene er det overordnede målet med denne Ph.D. avhandlingen er å utforske mulige overganger mot mer bærekraftige systemer for e-avfallshåndtering i forskjellige land i det Globale Sør.

Denne Ph.D. avhandlingen er teoretisk posisjonert innenfor det tverrfaglige forskningsfeltet bærekraftsoverganger (sustainability transitions) og basert på en overgangsledelsestilnærming (transition management approach). En sentral antakelse er at e-avfallshåndteringssystemer først og fremst krever mer etablert praksis for innsamling og resirkulering, men også bedre integrasjon gjennom elektronikkens livssyklus. Sentrale underliggende begreper inkluderer bærekraftig utvikling, sirkulær økonomi og livssyklustenkning. De spesifikke forskningsmålene er todelt: (1) Identifisere barrierer og drivere som oppleves av den uformelle sektoren i overgangen til etablerte e-avfallshåndteringssystemer og (2) identifisere barrierer og drivere for veksten av den formelle sektoren i overgangen til etablerte e-avfallshåndteringssystemer.

Arbeidet bruker en metode for engasjert forskning for å fange de ulike perspektivene til sentrale interessenter i ulike e-avfallshåndteringssystemer i det Globale Sør. Et sentralt element i oppgaven er de empiriske studiene om e-avfallshåndtering utført i Ghana (2017), Brasil (2018) og Kina (2019). Disse er blant de mest berørte landene på sine respektive kontinenter, og representerer dermed viktige steder for empirisk forskning. Undersøkelsene fokuserer på gjeldende praksis innenfor uformelle og formelle sektorer og, der det er aktuelt, virkningen av politikk implementert på nasjonalt nivå.

I Ghana ble primære feltstudier utført i Agbogbloshie, et skrapmetallverksted i hovedstaden. Stedet har blitt internasjonal kjent for sosiale og miljømessige problemer som følge av feil behandling av e-avfall. Dermed representerer det et viktig sted å undersøke innenfor den uformelle sektoren.

Den empiriske studien i Brasil fokuserer på den formelle sektoren. Brasil er den største generatoren av e-avfall i Latin-Amerika, men kun en begrenset del av e-avfallshåndteringen utføres av den formelle sektoren. Denne studien omfatter observasjoner fra fire organisasjoner for gjenvinning av e-avfall på ulike virksomhetsnivåer: (1) Et universitetssenter som representerer et pionerprosjekt i landet, (2) et selskap med en etablert struktur for innsamling av e-avfall, (3) en filial av et av de største selskapene for e-avfallsgjenvinning i verden, og (4), et selskap med en innovativ prosess for e-avfallsgjenvinning i brasiliansk kontekst.

Til slutt kombinerer studien i Kina data fra både den uformelle og den formelle sektoren. Kina er et av de mest berørte landene på grunn av tidligere import av e-avfall og uregulerte gjenvinningsaktiviteter. Landet har imidlertid raskt beveget seg framover når det gjelder implementering av e-avfallslovgivning. Den empiriske studien omfatter feltstudier fra to lokasjoner: (1) e-avfallsaktivitetene utført i Guiyu i Guangdong-provinsen, som tidligere ble kjent som en av de største uformelle e-avfallsbehandlingsstedene i verden, og (2) et lisensiert e-avfalls-resirkuleringselskap i Shaanxi-provinsen.

Oppgaven presenterer hovedresultatene fra feltstudiene basert på et flernivåperspektiv (multi-level perspective). Dette er et rammeverk som fokuserer på tre analysenivåer: mikro-, meso- og

makronivå. De primære resultatene av dette arbeidet omfatter mikro- og meso-nivå. Vanligvis dukker innovasjoner opp på mikronivå og møter høy usikkerhet. Bare noen lykkes med å drive endringer fram mot overganger, og til slutt utvikle seg til en ny regimepraksis. En mislykket innovasjon identifisert på mikronivå inkluderer installasjon av kabelstrippingsmaskiner i Agbogbloshie.

Meso-nivået relaterer seg til regimet, den rådende strukturen i dagens systemer. Oppgaven anvender det konseptuelle rammeverket med sektor- og tjenesteregimer for å kombinere resultatene fra undersøkelsene i de tre landene. Analysen oppfatter e-avfallshåndteringssystemet som et sektorregime som inkluderer flere tjenester. Den kategoriserer tjenesteregimene i tre stadier av e-avfallshåndtering (dvs. innsamling, forbehandling og sluttbehandling) knyttet til de uformelle og formelle sektorene i økonomien.

Analysen identifiserer følgende tjenesteregimer i innsamlingsfasen: individuell innsamling, returordninger, innsamling fra bedrift til bedrift, innsamlingssentraler og frivillige innsamlingssteder. Forbehandlingsfasen av e-avfallshåndtering inkluderer for eksempel manuell demontering i friluft eller tilfluktsrom, manuell demontering i verksteder, manuell demontering i anlegg og mekanisk behandling gjennom makulering. Til slutt skjer også sluttbehandlingen gjennom ulike serviceregimer. Innenfor dette stadiet er følgende tjenester fremhevet: friluftsbrenning av kabler, høytemperaturseparasjon av komponenter fra kretskortene (PCB) i verksteder, friluftsdumping, eksport av spesifikke komponenter for sluttbehandlingen, smelting prosess som resulterer i legeringer, høytemperaturseparasjon av komponenter fra PCB-ene i anlegg, pyrometallurgi og sluttdeponering i industrideponier.

Ph.D. oppgaven identifiserer manglende tilpasninger på ulike nivåer, nemlig innenfor og mellom tjenesteregimer. Den kategoriserer tjenesteregimene i følgende dimensjoner: (1) teknologier og infrastrukturer, (2) organisasjonsmodus, (3) begrunnelse og mening, (4) intern koordinering og (5) lovgivning og offentlig finansiering. Slike manglende tilpasninger kan potensielt presse eksisterende systemer og fungere som drivere eller barrierer mot overganger. For eksempel gir mangelen på helhetlig prosesseringsinfrastruktur i de tre landene innenfor dimensjon 1 også muligheter for fremveksten av innovasjoner. Analysen av dimensjon 2 avslører at markedspriser er drivere for resirkulering av spesifikke, verdifulle komponenter. Et begrenset utdanningsnivå i spesifikke omgivelser manifesterer seg som en overgangsbarriere innenfor dimensjon 3. I dimensjon 4 identifiseres en mangel på miljøbevissthet for deponering. Til slutt understrekes mangelen på integrasjon mellom den uformelle og formelle sektor i dimensjon 5.

Arbeidet bidrar til forskningsfeltet for bærekraftsomstilling ved å kombinere ulike perspektiver av sentrale aktører i de studerte systemene for e-avfallshåndtering i Ghana, Brasil og Kina. Så vidt forfatteren vet, er dette første gang et forskningsarbeid kombinerer slike empiriske studier i disse tre betydningsfulle landene. Ph.D. avhandlingen bruker ulike rammeverk fra forskningsfeltet for å identifisere kritiske barrierer og drivere og for å gi mulige overgangsveier for e-avfallshåndtering.

Funnene tyder på at overganger mot mer bærekraftig praksis krever mer aktiv politikk samtidig som kritiske aktører innlemmes i systemene på alle skalaer, fra lokale til globale. Arbeidet fremhever behovet for å integrere den uformelle sektoren i de innledende stadiene av e-avfallshåndtering og styrke kapasiteten innen den formelle sektoren for sluttbehandling. Dessuten viser den at det å ta hensyn til mangfoldet i tjenestetilbudet er av største betydning for direkte bærekraftsoverganger i det Globale Sør.

Nøkkelord: avfall av elektrisk og elektronisk utstyr, WEEE, resirkulering, det Globale Sør, uformell sektor, overgangsledelse, sirkulær økonomi, tjenesteregimer.

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List of publications

Paper I

Schneider, A.F., 2019a. Informal processing of electronic waste in Agbogbloshie, Ghana: A complex adaptive systems perspective, in: *Proceedings of the 6th International Conference on ICT for Sustainability*. Presented at the ICT4S 2019, Lappeenranta, Finland, ISSN 1613-0073.2382, p. 8. (Best paper runner-up award)

Paper II

Schneider, A.F., 2019b. Managing change in operations: The case of the wire stripping machine in Agbogbloshie, Ghana, in: *Proceedings of the 26th International EurOMA Conference: Operations Adding Value to Society*. Presented at the EurOMA 2019, Helsinki, Finland, pp. 1479–1488.

Paper III

Schneider, A.F., Aanestad, M., Carvalho, T.C. Exploring barriers in the transition toward an established e-waste management system in Brazil: A multiple-case study of the formal sector. Under revision for an international journal after first-round review.

Paper IV

Schneider, A.F., Zeng, X., 2022. Investigations into the transition toward an established e-waste management system in China: Empirical evidence from Guangdong and Shaanxi. *Current Research in Environmental Sustainability.* Vol. 4, No. 100195, pp 1–10. https://doi.org/10.1016/j.crsust.2022.100195

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Abbreviations and acronyms

B2B: Business-to-business

B2C: Business-to-consumer

CAS: Complex adaptive systems

CRM: Critical raw material

CRT: Cathode-ray tube

CSR: Corporate social responsibility

EoL: End-of-life

EPR: Extended producer responsibility

EU: European Union

EurOMA: European Operations Management Association

E-waste: Waste from electrical and electronic equipment

EWAS: E-waste Academy for Scientists

ICT: Information and communications technology

ICT4S: ICT for sustainability

MLP: Multi-level perspective

NGO: Non-governmental organization

NSD: Norwegian Centre for Research Data

PCB: Printed circuit board

RO: Research objective

SDG: Sustainable development goal

SMART: Sustainable Market Actors for Responsible Trade

STRN: Sustainability Transitions Research Network

TOC: Theory of constraints

UN: United Nations

WEEE: Waste from electrical and electronic equipment

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Preface

My interest in addressing the e-waste challenge started long before the Ph.D. program. It dates to when I was about to finish my bachelor's in business management in Brazil and considering pursuing a master's degree. While I wondered what topic could be interesting for a research proposal, my laptop broke down beyond repair, and I had to dispose of it. Finding a collection point for my old laptop was no easy task, and I started questioning why that was the case. From a business management perspective, it did not seem to make sense not to give proper attention to devices that have various precious metals in their composition. From an environmental perspective, it seemed to make even less sense not to have an efficient collection system established. Suddenly, I had a research topic in mind. Little did I know back then that this was only the beginning of a rather inter- and transdisciplinary research journey.

In my first master's degree in Planning and Sustainability Engineering, I focused on urban planning approaches for e-waste management by comparing the cases of Sweden, France, and Brazil (Schneider, 2015). In my second master's degree in Production Engineering, I focused on corporate strategies related to the reverse logistics of end-of-life electronics (Schneider, 2016). The combination of focuses taken in both programs led to several insights. By then, expanding my knowledge on this topic had become a passion, and finding options to address the e-waste challenge took me further into pursuing a Ph.D. degree.

Chapter 1

Introduction

The intention of moving toward more sustainable societies is not new. In 1987, the concept of sustainable development appeared in the report *Our Common Future*, which became widely known as the Brundtland report. In this report, sustainable development was defined as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987, p. 41).

The concept has gained strength over the decades that succeeded, and several programs have been established since then. In 2015, for instance, the United Nations (UN) adopted a global agreement with 17 sustainable development goals (SDGs) to lead the world toward sustainable development (United Nations, 2023). The SDGs, which are also commonly referred to as the 2030 Agenda, are illustrated in Figure 1.

Figure 1. The 2030 Agenda (United Nations, 2022).

The concept of sustainable development integrates the core pillars of sustainability into a development context. Although there is no consensus on the pillars required for sustainability, the following three are very often highlighted: society, economy, and environment (Glavič and Lukman, 2007). On the social pillar, Missimer et al. (2017a, 2017b) define a socially sustainable society by establishing a connection with the absence of structural societal obstacles to health, influence, competence, meaning-making, and impartiality. The second pillar, economic sustainability, is here understood as a transformation of natural resources into production processes and operational systems that can be maintained over the long term. The third pillar, environmental sustainability, focuses on the preservation of ecosystems and natural resources in combination with the maintenance of human welfare (Goodland, 1995).

Sustainability is considered a science that covers a wide range of disciplines and has a strong inter- and transdisciplinary nature. A primary objective is to better understand core interactions between society and nature, as explained in detail by Kates et al. (2001, p. 641):

> Such an understanding must encompass the interaction of global processes with the ecological and social characteristics of particular places and sectors. The regional character of much of what sustainability science is trying to explain means that relevant research will have to integrate the effects of key processes across the full range of scales from local to global. It will also require fundamental advances in our ability to address such issues as the behavior of complex self-organizing systems as well as the responses, some irreversible, of the nature-society system to multiple and interacting stresses. Combining different ways of knowing and learning will permit different social actors to work in concert, even with much uncertainty and limited information.

To address sustainability challenges, systemic models are critical. One is the circular economy model, which is central to guiding the understanding of this work. Especially since the second industrial revolution, the economy has been based on high patterns of production in a take-make-dispose model. This still prevailing model relates to a linear economy and leads to several damages to both the environment and society (Ellen MacArthur Foundation, 2013).

In contrast, a circular economy proposes looking at a system as restorative, in which the discarded products are perceived as resources that return to the system after use to close the loop of circularity. Although there is no consensus on the origin of the concept, a circular economy was described in 1966 by the economist Kenneth Boulding as a model compatible with sustainability, zero waste, and economic growth in the long term (Greyson, 2007).

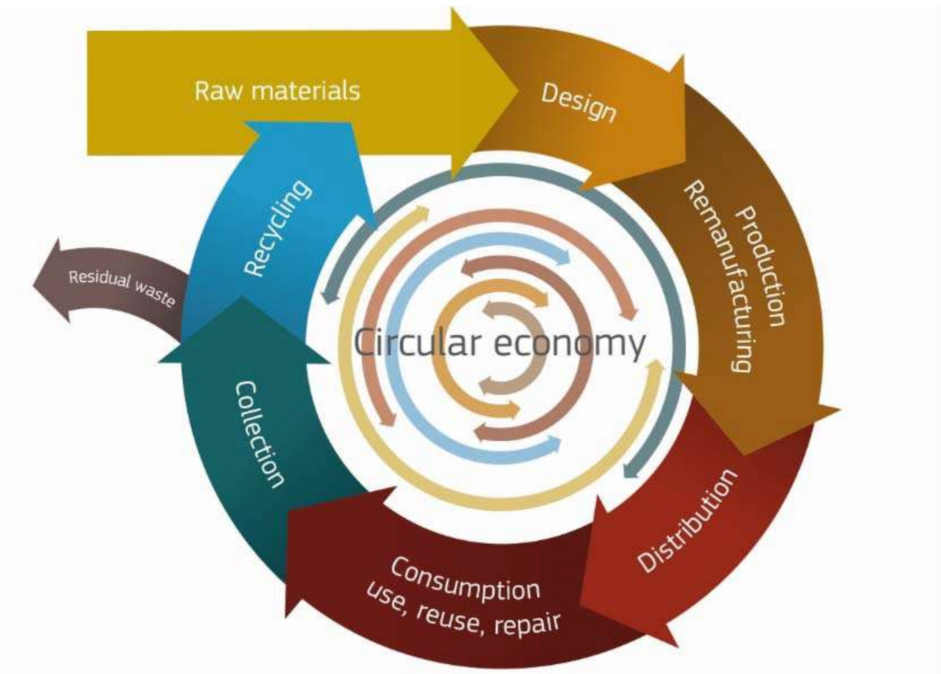

Figure 2. The main phases of a circular economy model (European Commission, 2014, p. 5).

As shown in Figure 2, a circular economy model is categorized into the following phases: raw materials, design, production/remanufacturing, distribution, consumption (use, reuse, and repair), collection, and recycling (European Commission, 2014). The recycling phase is a requisite for closing the loop toward a circular economy and achieving a system aligned with the SDGs (Greyson, 2007; United Nations, 2023). A circular economy can be applied to biological and technical nutrients and may adopt an upcycling approach toward the latter by increasing the quality and functionality of recycled products (Ellen MacArthur Foundation, 2013). The circular model presents opportunities for optimizing the use of scarce materials, for instance, through integrating recycled materials in production.

Life cycle thinking is another guiding concept in this work. The concept relates to seeking improvements across all life cycle phases of products and services through strategies to reduce environmental impacts and the use of resources (European Commission, 2010). This thinking allows the researcher to address environmental impacts while establishing interconnections among the several life cycle phases (Thabrew et al., 2009).

1.1 ICT and sustainability

In the context of information and communications technology (ICT) research, increasing attention has been given to sustainability, especially toward addressing environmental and social challenges. In recent years, several interdisciplinary research fields have emerged and gained strength with a focus on ICT for sustainability. Research fields within this knowledge area include, for instance, Green ICT, Sustainable human-computer interaction, and Environmental informatics (Hilty and Aebischer, 2015). Research at the intersection of ICT and sustainability often focuses on ICT applications as tools toward desired outcomes, such as to counteract various challenges like climate change (Kreps, 2018). Another focus of ICT research, still emergent and requiring further exploration, relates to the sustainability impacts of ICTs.

Studies on the sustainability impacts of ICTs vary substantially in scope and theoretical framings. This subchapter considers the circular economy model to address systemic changes needed across various life cycle phases. It presents multidisciplinary studies on the sustainability impacts of ICTs, specifically in the design and consumption phases.

The design phase has a significant role in moving toward more sustainable ICTs. A cradle-to-cradle design (Braungart et al., 2007) is an example of an approach oriented toward sustainability and based on a circular economy model. Such a design opposes the traditional cradle-to-grave design based on a linear economy model. With an emphasis on biomimicry and the aim of no waste generation, the cradle-to-cradle design perceives materials as nutrients that continuously flow within biological and technical metabolisms.

Studies aiming to integrate biodegradable materials into electronics go in the direction of a cradle-to-cradle design. Such applications show great potential in the biomedical field, such as therapeutic technologies and health monitoring (Feig et al., 2018). Studies with such a focus have advanced significantly in recent years and provided a prospect for breakthroughs at the interface of biology and electronics research. For example, Meysman et al. (2019) report on bacteria able to guide electrical currents through long distances. Another study by Jung et al. (2015) shows positive results with the fabrication of specific electrical components on a flexible cellulose nanofibril paper and argues for using eco-friendly materials in electronics. Despite advancements, much more research is needed, especially to improve electrical and mechanical properties, until biodegradable materials can be fully implemented in the production of high-performance electronics (Feig et al., 2018).

A significant body of literature focuses on the need for improvements in design for recyclability. Specifically focused on electronics, several studies address the importance of moving toward a design more aligned with sustainability ideals. Hagelüeken and Corti (2010), for instance, emphasize the need for a design that facilitates the separation of critical components such as PCBs and batteries to improve the recovery of valuable materials. Laurenti et al. (2015) affirm that the product design of electronics has a crucial role in moving toward a circular economy model. The authors defend the need for conscious choices in the use of materials and design applied in electronics to keep material flows clean, which would ultimately impact the quality of the recycled material reinserted into a circular economy model.

The design phase of electronics comprises not only the design of the device itself but also accounting for possible impacts that such a device will have on the perception of consumers. In transitioning to more sustainable societies, the role of the designer "is not simply to create 'sustainable products,' but rather to envision products, processes, and services that encourage widespread sustainable behavior" (Stegall, 2006, p. 57). Indeed, Althaf et al. (2021, p. 702) point out that moving to a circular economy while meeting the current demand for resources "would require a fundamental shift toward design for disassembly, repair, reuse, and recycling". Aligned with such a life cycle thinking concept, Junge (2021) proposes the development of proto-practices (i.e., practices that do not yet exist and that focus on a desirable future) to be incorporated as a central component of design research.

Strategies of obsolescence go against the rationale of more sustainable futures, instead fomenting waste generation. Planned obsolescence (i.e., in which devices are deliberately designed to become outdated as a way of motivating consumerism) is one such strategy. However, Makov and Fitzpatrick (2021) show that non-technical aspects such as perceived obsolescence seem to play a more significant role in determining the lifespan of smartphones. Similarly, Huang and Truong (2008) find that discount incentives offered by service providers are among the most common reasons consumers change their smartphones. Such findings provide avenues for further studies focusing on more sustainable approaches that tackle behavioural aspects.

1.2 Current e-waste management scenarios

With high levels of technological innovation and widespread consumption of electrical and electronic equipment, a challenge arises once electronic equipment is no longer used. Waste from electrical and electronic equipment (e-waste or WEEE) is often reported as one of the fastest-growing waste streams. In 2016, more than 44 Million tonnes (Mt) of e-waste were generated worldwide, an amount that increased to almost 54 Mt in 2019 (Baldé et al., 2017; Forti et al., 2020).

Electronic equipment is composed of several materials, many of which are hazardous to the environment if not discarded and recycled properly when reaching the end-of-life (EoL) phase. Examples of hazardous materials found in electronics are lead, which is often present in older printed circuit boards (PCBs), mercury, contained in liquid-crystal displays, and brominated flame retardants, added to some types of plastics in electronics (Althaf et al., 2021; Morf et al., 2005). In addition, some minerals (e.g., tantalum, tin, and tungsten) are considered conflict minerals. These relate to minerals contributing to financing armed groups in countries undergoing historical conflicts, such as the Eastern Democratic Republic of Congo (Ayres, 2012; Jameson et al., 2016).

At the same time, electronics have several materials in their composition that have high market demand, but an elevated risk associated with supply availability. These are often referred to as critical raw materials (CRMs) as they are considered economically significant yet becoming increasingly scarce. CRMs include, for instance, antimony, bismuth, cobalt, germanium, indium, and palladium (Diaz et al., 2016; Forti et al., 2020). The possibility of recovering CRMs represents a strong motivation for different subjects in a system (denoted as *agents* in this thesis) to focus on e-waste recycling. It provides several opportunities to improve resource efficiency (Althaf et al., 2021) and can help address some of the SDGs, specifically SDG12, which seeks to "ensure sustainable consumption and production patterns" (United Nations, 2023).

E-waste management is commonly divided into three basic stages, namely: collection, pre-processing, and end-processing (Parajuly et al., 2019). Here, both the pre- and end-processing stages are included in the recycling phase of the life cycle (cf. Figure 2). According to Schluep (2009), the pre-processing stage may include processes such as sorting, dismantling, and mechanical treatment (e.g., shredding), and the end-processing relates to refining and final disposal.

The collection phase represents a major challenge in e-waste management and is often related to behavioural aspects in society. For instance, a common practice in various countries is to store EoL devices at home, particularly in the case of mobile phones (Jang and Kim, 2010; Liu et al., 2019). In addition, studies show that e-waste is often disposed of as regular waste or regular recyclable household waste, especially in the case of small devices (de Oliveira et al., 2020; Rodrigues et al., 2020). Such practices prevent a proper collection of the devices for recycling and ultimately the recovery of materials.

Concerning the recycling phase, studies often point out a need for special attention toward PCBs. "The valuable metals and most hazardous materials tend to be concentrated in the circuit boards, so efficient and environmentally sound processing of the boards requires special attention." (Hagelüeken and Corti, 2010, p. 213). At the same time, the PCBs are among the most complex components to be recycled, demanding state-of-the-art processes to extract the most valuable materials (Ghosh et al., 2015; Priya and Hait, 2017).

The mechanization of recycling processes is a common trend in countries advancing technologies for e-waste recovery (Schluep et al., 2009). Methods such as pyrometallurgy, hydrometallurgy, and electrometallurgy are among the ones applied by the formal sector for refining in the end-processing stage (Priya and Hait, 2017; Schluep et al., 2009). However, only a few facilities in the world have the required infrastructure to recover CRMs from e-waste at high yields (Hagelüeken and Corti, 2010; Hewitt et al., 2015). Umicore in Belgium is one of the largest integrated smelter-refinery companies in the world (Kaya, 2019). The state-of-the-art plant in Hoboken can recover 17 metals from various waste streams through eco-efficient processes, which minimizes the outputs going to waste (Hagelüeken and Corti, 2010; Hewitt et al., 2015).

E-waste management activities performed by the formal sector remain limited. Estimates show that only 17.4% of the e-waste generated worldwide in 2019 was collected and recycled through formal channels and that such a percentage tends to be significantly lower in the Global South (Forti et al., 2020). With a limited infrastructure for e-waste processing, recycling organizations in such countries concentrate on the initial stages of e-waste management (i.e., collection and pre-processing). A significant part of the waste fraction with economic potential is exported to the Global North for end-processing (de Albuquerque et al., 2020; Xavier et al., 2023).

E-waste often crosses national borders for processing. Recycling companies in different countries vary significantly in techniques and processes established for material recovery. Hewitt et al. (2015, p. 8) highlight that "the industrial recycling market is mostly served globally, with pre-processed feedstock shipped from around the world to single smelting and refining sites. The reason is that industrial recycling requires large sites and complex equipment, so recyclers consolidate their operations in one location to serve the global market". However, the transboundary movement of e-waste does not always end in state-of-the-art recycling facilities but often finds its way into the Global South.

Such transboundary movements of e-waste represent a significant challenge. In this context, both intercontinental and intraregional movements play a role. Another challenge relates to the transboundary trade of used electronics to countries of the Global South. Electronics often enter as used electronics and are commercialized in second-hand markets. The trade of used electronics to such countries opens an ethical debate. On one side, it provides the receiving countries access to technologies that might have not been accessible otherwise. In addition, many countries in the Global South have developed a vibrant second-hand market and repair culture as a result of the influx of used electronics, which provides a source of subsistence to a significant part of the population (Grant and Oteng-Ababio, 2016; Samarakoon et al., 2022). However, electronics have usually been extensively used before being shipped, thus the lifespan of such devices is considerably reduced upon arrival. The trade of used electronics to countries of the Global South shifts the location of the problem once the devices become waste.

The reality of e-waste management in most countries is still far from what could be considered optimal. According to The Global E-waste Monitor (Forti et al., 2020), more than 82% of the amount of e-waste generated in 2019 worldwide was undocumented, and little is known about its destination and treatment. These figures tend to be even higher in countries lacking an established e-waste management system.

The informal sector is well-known for having strong participation in the economies of countries within the Global South. Characterized by various challenges such as vulnerable working conditions, the informal sector provides subsistence to a significant part of the population in such countries (Daum et al., 2017; Xavier et al., 2021). This is the case also for the collection and recycling of e-waste, predominantly conducted by the informal sector in countries of the Global South. With little infrastructure and resources, dismantling processes in such a setting tend to be conducted manually.

Without regulations of activities, e-waste management conducted by the informal sector is commonly associated with social, economic, and environmental hazards. Workers in informal sites often focus on the most valuable components, a practice commonly referred to as cherry-picking (Baldé et al., 2022). Here, less valuable components tend to be neglected and end up untreated, without receiving a proper destination. Techniques such as the open-air burning of cables and acid leaching are among the most commonly related in the literature for extracting valuable minerals in informal sites (Awasthi and Li, 2017). Due to rudimentary processes, the levels of material recovery are not ideal and several resources are lost (Hagelüeken and Corti, 2010). Such techniques result in severe environmental impacts, including pollution of soil, water, and air (Böni et al., 2015; Zeng et al., 2017). Informal activities are also commonly detrimental to the human health of the ones directly performing the activity and nearby communities (Parajuly et al., 2019).

Many countries have developed and implemented legislation focused on improving e-waste management practices based on shared responsibility for collection and recycling. Extended producer responsibility (EPR) is among the most well-known principles widely applied. The core idea of the EPR is to extend the responsibility for the environmental impacts of electronics to the producers (OECD, 2023). Such responsibility comprises aspects directly connected with e-waste collection and recycling. In addition, it extends to other life cycle phases, such as promoting more sustainable product design (European Commission, 2016).

The WEEE Directive regulates e-waste management in most countries in Europe. It first entered into force in 2003 and was updated through Directive 2012/19/EU (EU, 2012). The WEEE

Directive is based on EPR principles and sets collection and recycling targets for its member states. It serves as a reference point for countries outside the European Union (EU) to develop and implement their national legislations considering EPR principles. Such principles can be implemented in different ways, for example, through more centralized or decentralized approaches (Ongondo et al., 2011). According to the Global E-waste Monitor (Forti et al., 2020), legislation in various countries has been expanding the scope in recent years from a pure focus on improving collection and recycling targets to also considering design and production aspects. EPR principles represent a powerful tool for improving e-waste management. However, implementation of such principles is complex as it requires a systemic engagement of several agents within the e-waste management systems.

Additionally, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention, 2020) is a multilateral treaty that focuses on regulating the trade of hazardous waste and waste that requires special consideration (referred to as other wastes in the treaty). E-waste is among the types of waste regulated by the convention because it often contains hazardous elements. It is considered the most comprehensive global treaty of its kind, aiming to tackle environmental and social concerns related to transboundary movements of such wastes. The convention, adopted in 1989 and effective since 1992, has been signed by 190 parties to date (Basel Convention, 2023a). Shipments to and from non-member countries, if not having a special agreement, are considered illegal according to the convention. Prior informed consent in writing is applied for transboundary movements among member countries. Therefore, transboundary movements can only take place once both member countries involved have given consent. In addition to the convention, the Ban Amendment came into force in 2019 (Basel Convention, 2023b). The amendment prohibits the transboundary movements of hazardous wastes from member states of the Organization for Economic Cooperation and Development, the EU, and Liechtenstein to other countries. To date, 101 parties have ratified the Ban Amendment.

Implementation of the Basel Convention and the Ban Amendment is complex. For example, factors such as the capacity of inspection in the ports impact the implementation. Such capacity tends to be rather limited in comparison to the number of devices transported, which favours illegal shipments. According to the Global Transboundary E-waste Flow Monitor (Baldé et al., 2022), transboundary movements of e-waste in 2019 were estimated at almost 10% of the total of e-waste generated in the year, of which the majority was shipped in an uncontrolled manner. A common practice of transboundary movements of electronics is the mix of used electronics with illegal e-waste (the latter falsely declared as used electronics). It is estimated that up to one-third of the devices shipped as used electronics arrive already broken at the destination (Baldé et al., 2022).

1.3 Toward more sustainable e-waste management systems

E-waste management represents a considerable global challenge as it often crosses national borders and occurs in different forms worldwide. Given the current practices and legislation outlined above, moving toward more sustainable e-waste management systems is critical. However, changing current practices is not straightforward due to the high complexity involved, which requires large-scale transformations. In this line, the emerging research field of sustainability transitions focuses on understanding the changes required for socio-technical systems to move toward more sustainable practices in societies. This Ph.D. thesis is theoretically framed within sustainability transitions, as detailed in the following chapter. The underlying motivation is to investigate possible ways to transition toward more sustainable e-waste management systems.

In this work, e-waste management is understood as a wicked problem. McCormick et al. (2015) define wicked problems as the ones for which there is no agreed-upon solution, are naturally complex, and have several factors and interlinked causes. Due to the complex nature of wicked problems, attempts to address specific aspects of such a problem might result in unintended consequences for the larger system (Laurenti et al., 2015). For example, if an established e-waste management system is achieved, an unintended consequence could arise in which the consumption of electronics increases even further due to an erroneous perception from various agents that the emerging e-waste management system is "sustainable" independently of consumption patterns. In this regard, the concept of life cycle thinking helps to guide the research with an understanding that e-waste management systems are highly influenced by other life cycle phases and vice versa. In specific, a core understanding that has guided this work from the very beginning is that a crucial aspect in tackling the e-waste challenge is to minimize the generation of e-waste in the first place.

A circular economy model goes in line with a waste hierarchy commonly addressed in waste studies. A well-known hierarchy is the one applied in the EU context (cf. Figure 3). The waste framework directive (European Commission, 2008) determines that legislation regarding waste prevention and management should follow the five steps of hierarchy: prevention, preparing for reuse, recycling, other recovery, and disposal. The steps are presented in order of priority, the first (i.e., prevention) representing the most favoured option. Following the waste hierarchy, recycling would only take place once there is no further possibility of preventing waste generation. Therefore, incentivizing practices that extend the consumption phase (e.g., through reuse and repair) are much preferred over recycling.

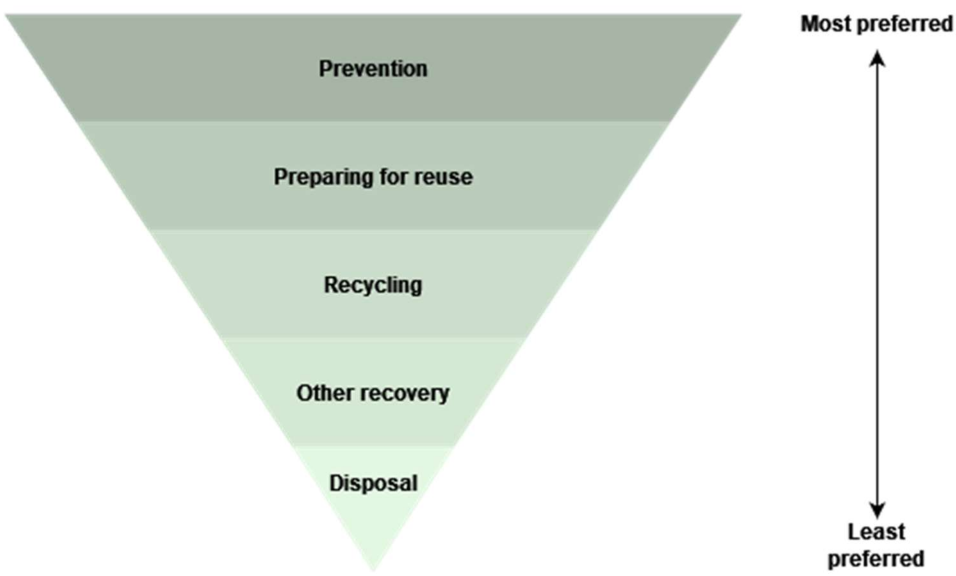

Figure 3. The waste hierarchy (based on Directive 2008/98/EC).

The concept of just transitions has strong relevance in such a context. Corroborating Swilling and Annecke (2012, p. xiii), a just transition is "a transition that reconciles sustainable use of natural resources with a pervasive commitment to what is increasingly being referred to as sufficiency (that is, where overconsumers are satisfied with less so that under-consumers can secure enough, without aspiring for more than their fair share)". The concept emphasizes the social rationale of sustainability, a primary challenge within the Global South. In such countries, more immediate concerns (e.g., social inequalities and lack of access to basic services) tend to predominate over the longer-term environmental sustainability goals (Wieczorek, 2018).

Exploring strategies for transitioning to more sustainable e-waste management globally is critical. One proposed strategy is the Best-of-2-worlds approach (Manhart, 2011; Wang et al., 2012), which aims to obtain high levels of material recovery while connecting the Global South and the Global North. The approach proposes that countries in the Global South conduct pre-processing through manual dismantling and that the end-processing is performed in state-of-the-art facilities in the Global North. The approach combines the low labour costs and existing workforce in the Global South with the technology and infrastructure currently available in a few countries of the Global North. However, the Best-of-2-worlds approach raises several ethical concerns. For instance, the prevailing vulnerable working conditions for manual dismantling in the Global South, the provision of high-quality feedstocks of valuable metals to the Global North, and the impacts of transportation through long distances are among the long-debated topics. Lepawsky et al. (2017) explore some of the ethical grounds of the approach. The authors propose an alternative with a focus on strengthening repair, reuse, and repurposing, in which recycling would take place only as a last resort.

Another of such strategies focuses on providing better working conditions for e-waste management activities within the informal sector. This can be conducted in various ways, for instance, through training projects aiming to educate workers on how to better sort and handle various e-waste components (Portela, 2015). In addition, the implementation of organizations that aim to include such workers deserves a highlight. The creation of cooperatives, for instance, is one example of gradually integrating such workers into a more established system. Although still in an emerging stage concerning e-waste management, studies such as from the International Labor Organization show great potential for implementing cooperatives with a focus on e-waste management (ILO, 2014). Here, it is worth highlighting that an initial manual dismantling process, which is commonly the case within the informal sector, has the potential to lead to higher levels of material recovery than if only mechanical processes were performed (Hagelüeken and Corti, 2010).

Understanding the challenges faced by various countries of the Global South is vital to transitioning toward more established e-waste management systems in a global context. Here, adopting a systemic perspective assists in further investigations of varied rationalities within each Nation-system. Some studies have adopted such an approach by combining the study of e-waste in more than one country based on a review of literature and legislation. Xavier et al. (2021), for instance, consider both economic blocs and country levels in the American continent, with a specific focus on Brazil and Canada. The authors identify drivers for e-waste management from a legal, environmental, and economic standpoint. Awasthi and Li (2017) compare e-waste management practices in India and China, including challenges associated with informal activities. The latter proposes the implementation of measures for increasing recycling capacity while mitigating environmental and social hazards.

However, empirical research combining studies of e-waste management practices in various countries remains limited. Empirical research is vital to investigate and assess the referred challenges and transformations directly on-site. To improve global e-waste management, combining studies from multiple sites has the potential to provide significant insights. Therefore, this work applies a systemic perspective to gather various agents' rationalities from different countries within the Global South.

The following presents the overarching aim and the specific research objective (RO) of the Ph.D. thesis. Next, the research trajectory is addressed and connected to each of the papers included in the thesis. This is followed by the structure of how the thesis is organized.

1.4 Research objectives

The overarching aim of this Ph.D. thesis is to explore possible avenues for transitions toward more sustainable e-waste management systems in different countries of the Global South. The aim of the work is represented by two specific ROs, which are presented in the following:

RO 1. To identify barriers and drivers experienced by the informal sector in transitioning to established e-waste management systems.

RO 2. To identify barriers and drivers to the growth of the formal sector in the transition toward established e-waste management systems.

The work is performed through qualitative research (detailed in Chapter 3). In qualitative research, the objectives are not straightforward and are instead often modified through the course of the work (Gephart, 2004). However, the ROs have guided this work by helping to select the sites for data acquisition, as well as to define the expected contributions.

1.5 Research trajectory

A part of the Ph.D. thesis was connected to the Sustainable Market Actors for Responsible Trade (SMART) project, coordinated by the law faculty of the University of Oslo and in collaboration with the EU through the Horizon 2020 program (SMART, 2020). The SMART project was conducted between 2016 to 2020 intending to find greater policy coherence for development. Specifically, the Ph.D. thesis was part of the research work package on "Policy coherence and the social and environmental externalities in the product life cycle of mobile phones (SMART | Phones)". This work has contributed with a focus on the recycling phase, further addressing its implications for other life cycle phases of electronics.

The Ph.D. thesis is presented in the format of a cumulative thesis. Therefore, the primary contribution comes from the following papers developed through the course of the program. The work consists of the following four papers:

Paper I

Schneider, A.F., 2019a. Informal processing of electronic waste in Agbogbloshie, Ghana: A complex adaptive systems perspective, in: *Proceedings of the 6th International Conference on ICT for Sustainability*. Presented at the ICT4S 2019, Lappeenranta, Finland, ISSN 1613-0073.2382, p. 8. (Best paper runner-up award)

Paper II

Schneider, A.F., 2019b. Managing change in operations: The case of the wire stripping machine in Agbogbloshie, Ghana, in: *Proceedings of the 26th International EurOMA Conference: Operations Adding Value to Society*. Presented at the EurOMA 2019, Helsinki, Finland, pp. 1479–1488.

Paper III

Schneider, A.F., Aanestad, M., Carvalho, T.C. Exploring barriers in the transition toward an established e-waste management system in Brazil: A multiple-case study of the formal sector. Under revision for an international journal after first-round review.

Paper IV

Schneider, A.F., Zeng, X., 2022. Investigations into the transition toward an established e-waste management system in China: Empirical evidence from Guangdong and Shaanxi. *Current Research in Environmental Sustainability.* Vol. 4, No. 100195, pp 1–10. https://doi.org/10.1016/j.crsust.2022.100195

A summary, including a detailed explanation of the contributions of each paper, is presented in Chapter 4, as well as an overview of the specific RO addressed by each.

Participation in several activities has been achieved through the course of this Ph.D. program, which brought contributions to specific research communities and strengthened the learning process. Here, it is certainly worth highlighting the ICT for sustainability (ICT4S) community. At the beginning of the Ph.D. program, participation was achieved in the ICT4S 2017 summer school in the Netherlands, which fostered an extremely positive atmosphere for collaboration among Ph.D. candidates and led to the elaboration of an initial study[1]. This involved different strategies for minimizing the generation of e-waste (mobile phones in particular) by tackling various life cycle phases. Here, an approach combining a modular design, the product-service system business model, and a design for attachment was proposed (Schneider et al., 2018). The broad guiding concept of life cycle thinking applied in such a study assisted throughout the program while diving into e-waste management as the focus of the Ph.D. work and, consequently, this thesis.

Participation was achieved in the ICT4S conferences that followed, namely the ICT4S 2018 in Canada (with the presentation of the aforementioned study), the ICT4S 2019 in Finland (with the presentation of Paper I), and the ICT4S 2020 that took place online (with the presentation of a Poster, cf. Appendix I). Results from this thesis were also connected with the operations management community through participation in the European Operations Management Association (EurOMA) 2019 conference in Finland (in which Paper II was presented).

Research collaboration was established with an e-waste management scholar at the Polytechnic School of the University of São Paulo after field studies conducted in Brazil in 2018. Some results of this collaboration are shown in Paper III. In addition, collaboration has been established with e-waste management scholars in the School of Environment at Tsinghua

[1] Schneider, A.F., Matinfar, S., Martino Grua, E., Casado-Mansilla, D., Cordewener, L., 2018. Towards a sustainable business model for smartphones: Combining product-service systems with modularity, in: *Proceedings of the 5th International Conference on ICT for Sustainability, EPiC Series in Computing*. Presented at the ICT4S 2018, Toronto, ON, Canada, ISSN 2398-7340, pp. 82–99. https://doi.org/10.29007/djcz

University. This was initiated through a research stay in China in 2019 and continued through the Ph.D. program. Some important results of this collaboration are presented in Paper IV.

Finally, results from this Ph.D. thesis have been presented at the E-waste Academy for Scientists (EWAS). EWAS 2022 took place at the University of Limerick, Ireland, and was organized by the United Nations Institute for Training and Research and the United Nations Industrial Development Organization.

This work has applied various theories and frameworks to examine e-waste management. For a part of the research journey, the theoretical framing of the work was complex adaptive systems (CAS) theory. Additionally, a specific study applied the theory of constraints (cf. presented in Paper II). As later described in the thesis, complex systems theory connects to the sustainability transitions research field, specifically as a foundational perspective for transition management. The various theoretical frameworks represent a strength of this work as they have enabled the researcher to analyse the data from different angles. Core notions from CAS theory, for example, have assisted in obtaining a better understanding of the systems when diving into the sustainability transitions research field.

1.6 Expected contributions

This work is highly interdisciplinary and addresses the broad knowledge area of ICT for sustainability regarding the sustainability impacts of ICTs. The thesis is theoretically based on the research field of sustainability transitions, specifically, the transition management approach. The results of the work contribute to the research field of sustainability transitions within the topic of e-waste management.

Field studies have been conducted in three countries within the Global South, namely Ghana, Brazil, and China. The combination of the countries, each located on a different continent, presents a variety of practices that assist in a better understanding of the global e-waste management challenge. Expanding the knowledge in these various settings has helped address some of the diversity of rationalities and depict certain nuances of sustainability transitions within e-waste management in the Global South.

E-waste management in each country is perceived as a system. Identifying drivers and barriers in different stages of e-waste management within the three varied systems assists in better addressing the large-scale transformations required toward sustainability transitions.

Overall, the thesis provides a better understanding of how diverse practices co-evolve in different countries of the Global South through investigations of e-waste management practices and policies implemented in varied countries. The thesis focuses on the co-existence of informal and formal sectors and provides possible transition pathways for e-waste management in the Global South.

1.7 Thesis structure

The Ph.D. thesis comprises seven chapters in addition to the four included papers. The following chapter (2) presents the theoretical framing of the work within the sustainability transitions research field and, more specifically, the transition management approach. It highlights some core ideas related to sustainability transition studies in the Global South and the conceptual framework of sectoral and service regimes that is applied in the thesis.

Chapter 3 presents the research methods applied in this work, including the research approach, the strategy adopted for collecting and analysing data, and a brief background of the cases. Some strengths and limitations of the empirical work and ethical considerations are also highlighted therein. Chapter 4 presents a summary of the four individual papers and an overview of the ROs addressed by each paper.

The analysis in Chapter 5 focuses on the identification of service regimes and misalignments. First, it presents the various service regimes in e-waste management identified through empirical investigations in each stage of collection, pre-processing, and end-processing. Second, it highlights misalignments at different levels, both within and between service regimes.

Chapter 6 is divided into three subchapters. The first subchapter discusses the results at the meso-level concerning barriers and drivers for sustainability transitions. It addresses five regime dimensions: technologies & infrastructures, organizational mode, rationale & meaning, internal coordination, and legislation & public financing. The second subchapter discusses possible transition pathways for e-waste management, namely the need to integrate agents from the informal sector into the emerging regime, strengthening activities within the formal sector, advancing policies on e-waste management, and accounting for the diversity of service provision. The third subchapter highlights the main contributions of the work toward the sustainability transitions research field. The last chapter (7) presents the conclusion, including limitations of the work and suggestions for future research.

Chapter 2

Theoretical background

Transitioning to more sustainable societies requires a systemic perspective to align various goals and rationalities toward a common purpose. As pointed out by Hamdouch and Zuindeau (2010), one of the crucial challenges for the successful implementation of sustainable development policies lies in developing viable institutional conditions that promote more collective forms of rationality.

In the specific case of transitioning toward more sustainable e-waste management systems, it is no different. Indeed, Grant and Oteng-Ababio (2016, p. 17) highlight that creating a "globally sustainable system will require profound changes at various sites – the ore mines, the producer sites, the urban mines – and an appreciation of the circulation of material transformations among spatially separated sites".

This Ph.D. work takes a systemic perspective to investigate e-waste management and is theoretically framed within the emerging research field of sustainability transitions. The research field recognizes that many of the environmental problems currently faced by society derive from unsustainable patterns that span several dimensions, as well as life cycle phases (for instance, elevated consumption and production patterns). The related environmental problems represent grand societal challenges. Addressing these challenges requires radical shifts toward new systems, referred to as sustainability transitions (Köhler et al., 2019).

The thesis applies specifically the transition management approach (Loorbach, 2007; Rotmans et al., 2001) to e-waste management. Rooted in governance and complex systems theory (Loorbach, 2010; Rotmans and Loorbach, 2009), transition management is a policy-oriented approach for addressing different agents, domains, and scale levels (Rotmans et al., 2001). The central objective here is to investigate ways in which desired transitions can be fostered and, hopefully, achieved. To do so, the approach focuses on governance rather than the technology itself.

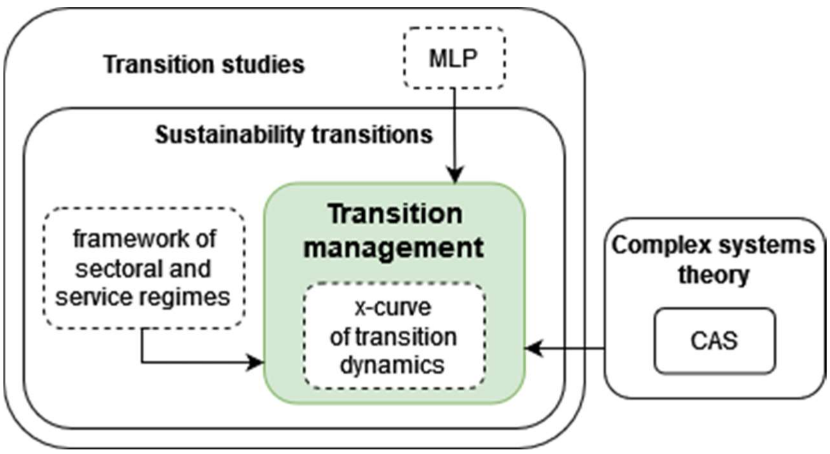

Figure 4. Connection of frameworks and theories applied to the Ph.D. thesis.

The work applies a combination of frameworks and theories as tools to explore transitions in e-waste management systems in Ghana, Brazil, and China. In this chapter, I introduce the primary tools utilized from a transition management approach (as depicted in Figure 4). Initially, I present some foundational perspectives on transition studies, focusing on the multi-level perspective (MLP) framework and the diverse theoretical viewpoints. The MLP framework is applied as an analytical tool in this work and assists in better understanding transition dynamics by analysing interactions among agents, technologies, and institutions at different levels (from micro to macro). Subsequently, I emphasize central concepts to this thesis, particularly of institutions and sectors of the economy.

Third, I introduce complex systems theory as one of the theoretical foundations of the transition management approach. Specifically, the work applies complex adaptive systems (CAS) theory as a tool for a better understanding of the various behaviours of agents within e-waste management systems. Additionally, I present the x-curve of transition dynamics as a tool to guide actions for change through more participation. This work applies the latter to assist in visualizing transition phases and possibilities of the co-existence of regimes, specifically within the informal and formal sectors.

The fourth part describes the core challenges of sustainability transition studies in countries of the Global South, focusing on the variety of development common in such geographies. Here, I present a conceptual framework that distinguishes sectoral and service regimes, applied as a core analytical tool in this thesis. Lastly, I highlight the emergence and relevance of sustainability transition studies that address e-waste management.

2.1 Foundations of sustainability transitions research

Studies on sustainability transitions focus on building a better understanding of large-scale transformations necessary to move away from unsustainable societal structures (Köhler et al., 2019). These desired transformations are addressed as *sustainability transitions*.

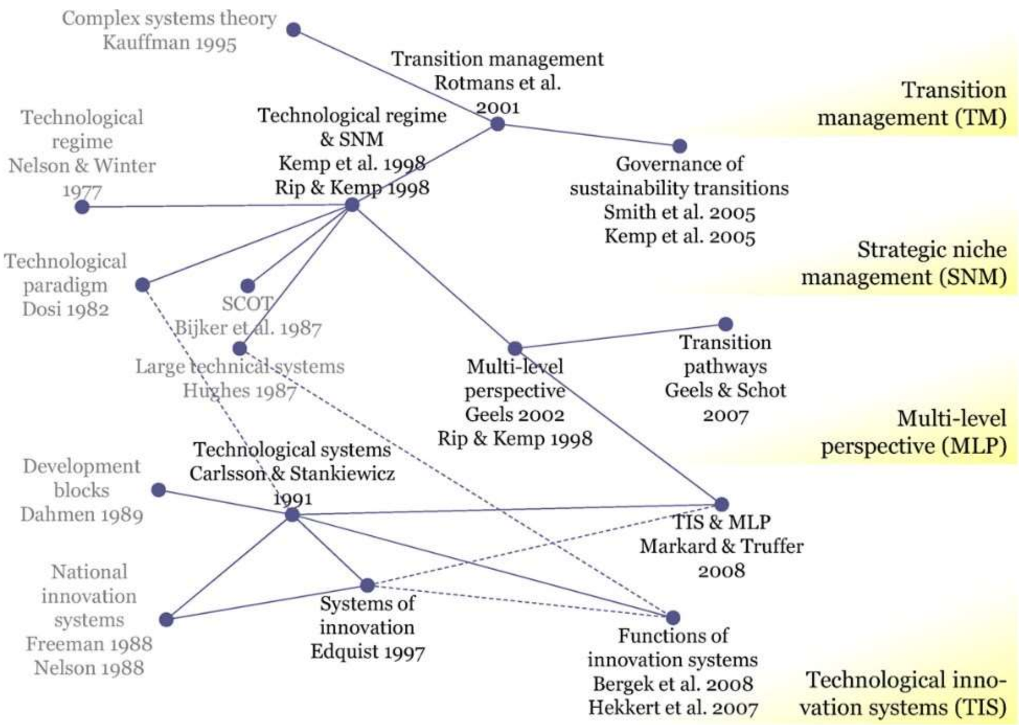

Figure 5. Core contributions and research strands in sustainability transitions (Markard et al., 2012, p.957).

The research field of sustainability transitions has developed from transition studies through various research strands. As illustrated in Figure 5, Markard et al. (2012) highlight four research strands that are among the foundational ones of the research field. These include technological innovation systems, an MLP framework, strategic niche management, and transition management. The following presents the MLP framework, which is applied as an analytical tool in this work.

2.1.1 The MLP framework

A prominent analytical tool that is often applied in transition studies is the MLP framework. Some initial concepts that form the basis of the framework can be traced to studies by Rip and Kemp (1998). The framework and related concepts were further developed by Geels in a study applying the MLP framework to illustrate the technological transition from sailing ships to steamships (Geels, 2002). In several studies that came after, Geels continued to refine the framework (Geels, 2004, 2006, 2010, 2019).

The MLP framework is used to capture the complexity of heterogenous behaviours in a system, specifically from agents in the following three levels of change: the macro-, meso-, and micro-level. The macro-level is referred to as the landscape in transition studies. This level comprehends developments that are external to the system of study, nevertheless impacting transitions in such a system. Landscape developments can pressure the meso- and micro-level, presenting either drivers or barriers toward transitions. For example, the landscape can pressure the meso-level in the form of a driver toward a transition, which, in turn, opens windows of opportunities for the emergence of innovations at the micro-level (Köhler et al., 2019).

The meso-level is referred to as the regime. The regime relates to prevailing practices in the system of study. The regime represents the prevailing structure in existing societal systems (Kemp et al., 1998). Such a structure comprises both tangible and intangible dimensions that appear in the form of, for instance, physical infrastructures and consumer routines (Loorbach, 2007). The understanding of such a dominant structure is essential for a more comprehensive and detailed study, as well as to be best equipped when steering the desired transition in the current system.

The meso-level is a primary focus of analysis in transition studies (Köhler et al., 2019). Specifically, studies often aim to identify and further explore barriers and drivers within the regime. Studies usually categorize the regime into several knowledge dimensions, and often relate to dimensions such as science, technology, markets & user preferences, industry, culture, and policy, as presented in early propositions of the MLP framework (Geels, 2002, 2004, 2006). It is noteworthy to mention that the dimensions are not fixed but can be adapted according to the topic of study and the focus of the analysis, as it is detailed further in this chapter in the context of the Global South.

Current regime practices can influence the appearance and further development of innovations at the micro-level, as well as the emergence of a new regime, having a direct impact on driving or preventing the desired transitions from taking place. Such impact is highlighted by Rip and Kemp (1998, p. 338):

> A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems—all of them embedded in institutions and infrastructures. Regimes are intermediaries between specific innovations as these are conceived, developed, and introduced, and overall sociotechnical landscapes.

> Regimes are outcomes of earlier changes and they structure subsequent change. Novelty evolves within existing regimes and sociotechnical landscapes, starting at the micro-level of local practices. It spreads over time, partly by accommodating to existing regimes; eventually it may irreversibly transform the sociotechnical landscape.

Lastly, the micro-level is denominated as the niche. Innovations typically emerge at this level. Niche innovations have a primary role in making transitions happen as they have the potential of developing into a new regime. However, the success of niche innovations is connected not only to how they are managed at the micro-level but also to how these innovations relate and are influenced by regime practices:

> The processes of niche formation occur against the backdrop of existing technological regimes. Often, some of the actors present in these regimes participate and attempts are made to solve problems identified but not solved within the regime. The success of niche formation is, therefore, linked to structural problems, shifts and changes within the existing regime(s). The ultimate fate of processes of niche formation depends as much on successful processes within the niche as on changes outside the niche: it is the coincidence of both developments that gives rise to niche development patterns. (Kemp et al., 1998, p. 184)

Figure 6 presents a MLP framework based on Geels (2019). The pressures coming from the macro- and meso-levels can act either as barriers or drivers toward emergence and further development of niche innovations.

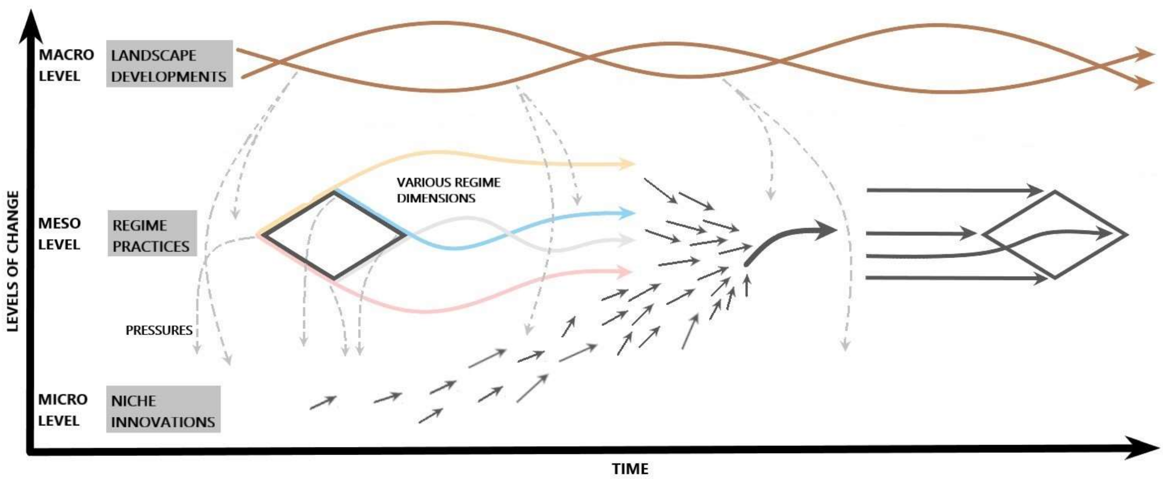

Figure 6. A multi-level perspective (MLP) on transitions (adapted from Geels, 2019).

The MLP framework is often applied in sustainability transitions research. For instance, Buchel et al. (2022) apply the MLP framework to analyse the state of transition of the fashion industry in the direction of sustainable fashion. Rudolph et al. (2020) study the transition to a more sustainable ocean system, arguing for the need for changes in governance across several levels and with the participation of multiple agents.

2.1.2 Variety of theoretical perspectives

The research field of sustainability transitions is highly inter- and transdisciplinary and applies a systemic perspective for investigating various transformations toward sustainability. With multiple conceptual approaches applied from different disciplines, the research field has evolved through several theoretical perspectives used to investigate the required transitions.

Some scholars have attempted to map core theoretical perspectives applied in sustainability transition studies. For instance, Patterson et al. (2017) categorize the following four perspectives to investigate societal transitions and transformation processes: socio-technical transitions, social-ecological systems, sustainability pathways, and transformative adaptation. The authors highlight that such perspectives remain largely fragmented in the sustainability transitions literature.

Loorbach et al. (2017) distinguish three perspectives to analyse transitions: the socio-technical, socio-ecological, and socio-institutional. The socio-technical perspective is rooted in science and technology studies and is considered one of the founding theoretical perspectives in sustainability transition research. The focus of the socio-technical perspective is on analysing a technological innovation and the related emerging socio-technical regime (Loorbach et al., 2017). The socio-ecological perspective, originating from ecology and resilience theory, studies the (lack of) stability in ecosystems. The third perspective, socio-institutional, draws from social sciences to investigate how specific institutions can impact complex societal systems:

> Although technologies might play an important role in understanding transitional change, the emphasis is rather on how incumbent routines, powers, interests, discourses, and regulations create path dependencies and how these are challenged by (transformative) social innovations. The socio-institutional perspective is applied to societal systems facing persistent environmental challenges such as mobility, waste management, and energy but increasingly also to systems such as health care, education, finance, and democracy. [...] Typically this approach focuses explicitly on the role of agency and governance in such transitions and takes a more reflexive stance. It highlights issues of normativity, ambiguity and social construction as well as reflects upon the interaction between multiple regimes. (Loorbach et al., 2017, p. 610)

As a research field in continuous development, the various theoretical perspectives may be applied in different ways to investigate societal transitions, for instance, when investigating changes in socio-technical systems while focusing on institutions. A common approach here is to study the role of specific institutional elements (e.g., policies and values) for processes of innovation and change through the application of tools such as the MLP framework. Another approach, as applied by Fuenfschilling (2019), conceptualizes transitions as processes of institutionalization and de-institutionalization of socio-technical configurations.

Despite the various analytical angles applied to examine sustainability transitions, the theoretical approaches often complement each other. Various frameworks have been developed in the context of each perspective, yet they are often applied interchangeably. Applying such frameworks from different angles helps build a better understanding of how transitions evolve.

In this Ph.D. thesis, I analyse the e-waste management system as a socio-technical system in transition. I emphasize institutional elements, particularly the diverse rationalities observed within the informal and formal sectors of the economy. The following describes in detail some of these concepts.

2.2 Central concepts

2.2.1 Institutions

A relevant concept in sustainability transition studies is institutions. Some of the most widely used definitions stem from neo-institutional theory, which applies various categorizations. For instance, a sociological view on neo-institutionalism usually categorizes institutions as regulative, normative, or cultural-cognitive (Wirth et al., 2013). Fuenfschilling (2019, p. 223) presents in detail such a definition while connecting it to predecessor ideas:

> In their seminal article published in 1983, DiMaggio and Powell described coercive, normative and mimetic processes of reproduction that lead to the homogenization and perpetuation of actors, practices and structures within the same institutional setting. Coercive pressures usually stem from regulations and political oversight through the state. Normative pressures are associated with the effect of professional standards and norms as well as education. Mimetic forces are assumed to be at play in situations of high uncertainty that trigger more routinized and taken-for-granted actions or the imitation of seemingly successful peers. In a similar vein, and building on these three types of institutional pressures, Scott (1995) developed the idea of the 'three pillars' of institutions: regulative, normative and cultural-cognitive. Each pillar rests upon a fundamentally different basis of legitimacy. While regulative institutions work through coercion and respective (legal) sanctioning, normative institutions apply a logic of appropriateness and compatibility that is sanctioned through social shaming or exclusion. Cultural-cognitive institutions, furthermore, provide shared cultural frames that allow for sense-making and common understandings of means-end relationships.

Examples of regulative institutional elements are explicit rules and laws (Geels, 2014). Normative institutions can appear in the form of, for instance, labels and professional codes, which pressure toward standardization of social behaviour (Fuenfschilling and Binz, 2018). Additionally, cultural-cognitive institutional elements exist as beliefs and rationalities (Fuenfschilling and Binz, 2018).

Another categorization of institutions comes from an economic view of neo-institutionalism (Wirth et al., 2013). Institutions are herein defined as *the rules of the game in a society* (North, 1990) and categorized as formal and informal. Formal institutions appear in the form of, for instance, laws and regulations, while informal institutions can represent the values and beliefs of large groups in a society (Webb et al., 2009). Institutions in all forms play a significant role in transitions:

> Institutions, both formal and informal (such as routines, conventions and traditions) are well known to change slowly over time. Institutions are both the product of and a key factor shaping social agency: they provide the stability and predictability needed for social and economic actions and transactions, whilst incrementally responding to and incorporating the outcomes of those actions and transactions. This duality of institutions and social agency necessarily means that institutional evolution tends to exhibit path dependence. Like the economy, institutions thus tend to inherit the legacy of their past. (Martin and Sunley, 2006, p. 10).

2.2.2 Sectors of an economy

A connected yet different concept from institutions is that of the sectors of an economy, which is particularly relevant for studies in the Global South and significant to differentiate within the scope of this thesis. Webb et al. (2009) classify three sectors of an economy, namely the formal, informal, and renegade economy. The formal and informal economy can also be referred to respectively as the formal and informal sector, terminology adopted in this thesis. The sectors proposed depend on whether the means and ends are legal and legitimate. The renegade economy represents a set of activities that exploit illegal and illegitimate opportunities both in means and ends (e.g., drug cartels and bank robberies).

One can establish connections between the sectors of an economy and the institutional boundaries in the context of formality. According to Webb et al. (2009), there is often a gap between what large groups in a society consider as legal (i.e., represented by formal institutions) and as legitimate (i.e., what is socially accepted by large groups in society and depicted in the form of informal institutions). It is in such a gap that the informal sector emerges. Therefore, the informal sector falls outside formal yet within informal institutional boundaries.

The predominance of the informal sector is among the most common characteristics in countries of the Global South. Therefore, the concept of (in)formal sectors of an economy and its connections with (in)formal institutions is particularly relevant for this work.

2.3 Transition management

Transition management is a policy-oriented approach to studying sustainability transitions. A core aim of this approach is to support the development of governance strategies for sustainability transitions. To develop such strategies, transition management considers the interests of various agents (e.g., from science, policy, and business) in designated systems, and seeks to promote cooperation (Köhler et al., 2019).

> A transition can be defined as a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms. Transitions are not uniform, and nor is the transition process deterministic: there are large differences in the scale of change and the period over which it occurs. Transitions involve a range of possible development paths, whose direction, scale and speed government policy can influence, but never entirely control. (Rotmans et al., 2001, p. 16)

A core goal of the approach is to balance short-term objectives with the long-term-ambition in a stepwise manner (Rotmans et al., 2001). The approach draws insights from theories on complex systems (e.g., Kauffman (1995), as illustrated in Figure 5) and governance to build a better knowledge of current processes in societal systems, and to guide the desired transitions through governance (Loorbach, 2010). “Guiding principles for transition management are derived from conceptualizing existing sectors as complex, adaptive societal systems and understanding management as a reflexive and evolutionary governance process” (Markard et al., 2012, p. 958).

The transition management approach relies on the idea that the underlying systems are of a complex nature. Theories taking a systems approach to complexity, such as CAS theory, are considered a theoretical foundation of the approach (Loorbach, 2010). As illustrated in the previous subchapter, the work of Kauffman (1995) is one of the backbones in developing the transition management approach. His work on adaptive systems with insights from evolutionary biology has brought significant advancements for complexity theory and its application to various disciplines, such as economics (Kauffman and Macready, 1995). The following provides a brief introduction into CAS theory.

2.3.1 Brief introduction into CAS theory

The theory of CAS is used to describe and study complex, interconnected systems that comprise a large number of agents capable of adapting, thus evolving with time (Cohen and Axelrod, 2000; Holland, 2006). The theory emerged in the mid-1980s as a school of thought with the formation of the Santa Fe Institute. As a think tank with participants from different fields of knowledge, the institute in New Mexico focuses on advancing the studies in complexity from various perspectives (Dodder and Dare, 2000).

Systems thinking represents an important foundation for the origin of CAS theory, especially because of the focus on analysing the interdependence and interactions of agents in specific systems, as well as ways in which larger systems change due to interactions (Abbott and Hadžikadić, 2017). Examples of CAS are various, such as an ecosystem, the immune system, and the global climate system. An extensive definition of CAS is given by Holland (1992, p. 17):

> […] a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents.

Actions and responses in designated systems are referred to as *feedback* in CAS theory and are typically dependent on the state of other agents. CAS theory challenges the notion of equilibrium addressed in systems thinking. “The notion that equilibrium was the norm to which a system would return if there were a small deviation, via the mechanism of a negative feedback loop, is challenged by the discovery of positive feedback loops that drive a system forward beyond equilibrium” (Walby, 2007, p. 454). Here, interactions can be highly non-linear. These interactions create complexity since changes in the behaviour of one agent often escalate to several, with implications for the whole system.

In CAS theory, a system is understood as having several properties. Nomenclature and categorization of properties vary due to the interdisciplinary nature of CAS theory but are complementary (Fereidunian et al., 2015). One of the properties is a high level of *adaptation* of agents, which leads to resilience in the system (Holland, 2006). A system in CAS theory exhibits interactions of *non-linear* nature, which makes it more difficult to predict the system, that is, the sum of all interactions between agents (Han et al., 2021). This unpredictability can lead to chaotic behaviour and randomness in the system (Nikolic and Kasmire, 2013).

Emergence is also a property commonly addressed in CAS theory, meaning that the state of a system at a given time is a result of the combination of agents’ behaviour, and cannot be isolated into individual behaviour (Holland, 1999). Emergence can occur in the form of *self-organization*, in which there is no central control for the development of new structures in the system. The phenomenon of flocking birds, in which individual birds follow simple rules (e.g., mimicking the speed of and distance from other birds), is an example of self-organization (Choi et al., 2001).

The study of CAS has been applied in several disciplines (Levin, 1998) and provided insights into the characteristics and behaviours of agents, as well as their impact on designated systems. The work of Kauffman (1995, p. 28), for instance, provides reflections on how society is organized from a CAS standpoint:

> People organize into communities, each of which acts for its own benefit, jockeying to seek compromises among conflicting interests. This seemingly haphazard process also shows an ordered regime where poor compromises are found quickly, a chaotic regime where no compromise is ever settled on, and a phase transition where compromises are achieved, but not quickly. The best compromises appear to occur at the phase transition between order and chaos. [...]. Democracy may be far and away the best process to solve the complex problems of a complex evolving society, to find peaks on the coevolutionary landscape where, on average, all have a chance to prosper.

CAS theory has also been applied to the topic of waste management. For instance, Chertow and Ehrenfeld (2012) relate to CAS theory, particularly the property of self-organization, within the context of industrial symbiosis. In addition, Seadon (2010) applies a CAS approach to waste management in New Zealand to produce more sustainable practices.

CAS theory has often been applied through agent-based modeling in waste management research to identify and model agents' behaviour. For instance, Meng et al. (2018) establish a simulation model that considers different policy scenarios to identify the most effective policies for classifying and recycling household solid waste in China: They find conflicting benefits between agents in the system and a potential impact of specific charging policies into residents' behaviour for sorting waste. In addition, Luo et al. (2019) establish a model of a household e-waste recovery system based on agent-based modeling and CAS theory. They suggest applying several policies, including the dissemination of information to guide residents, improvements of the legal system, focus on innovative methods for recovery, improvements of eco-design, and promotion of integration of resources through the establishment of networks.

CAS theory helps navigate the complexities of large interconnected systems and explore the variety of agents' behaviour. The theory has been applied as the primary analytical lens to investigate the interactions among agents in the e-waste processing in Agbogbloshie, Ghana (as presented in Paper I). Additionally, core notions from CAS theory, such as emergence, co-evolution, and self-organization (Rotmans and Loorbach, 2009), are applied throughout this work to assist in building a better understanding while looking at the systems in transition.

2.3.2 The MLP framework in transition management

The transition management approach often applies the MLP framework as an analytical tool. According to Loorbach (2007), the MLP framework requires some adaptations when analysed through a transition management approach based on complex systems theory. The MLP framework "combines qualitatively different levels within one model and thereby does not allow for analysis of external forces or complex system dynamics" (Loorbach, 2007, p. 21).

Based on complex systems theory, the dynamics of a system are determined not only by agents' interaction within the same level of analysis (i.e., niche, regime, or landscape) but also by the interaction of the various agents within the system and between them and the system's environment. Therefore, a transition management approach considers the societal system and the related interactions of agents when applying the MLP framework.

Theories on complex systems assist the transition management approach with the understanding that the boundaries of a system are subjective and can change, as well as the location of different agents within the levels of the framework and the system. For example, "[...] niches can be part of the regime, exist outside the regime or even (partly) outside the system" (Loorbach, 2007, p. 22). Such a model is illustrated in Loorbach's Ph.D. thesis, as shown in Figure 7.

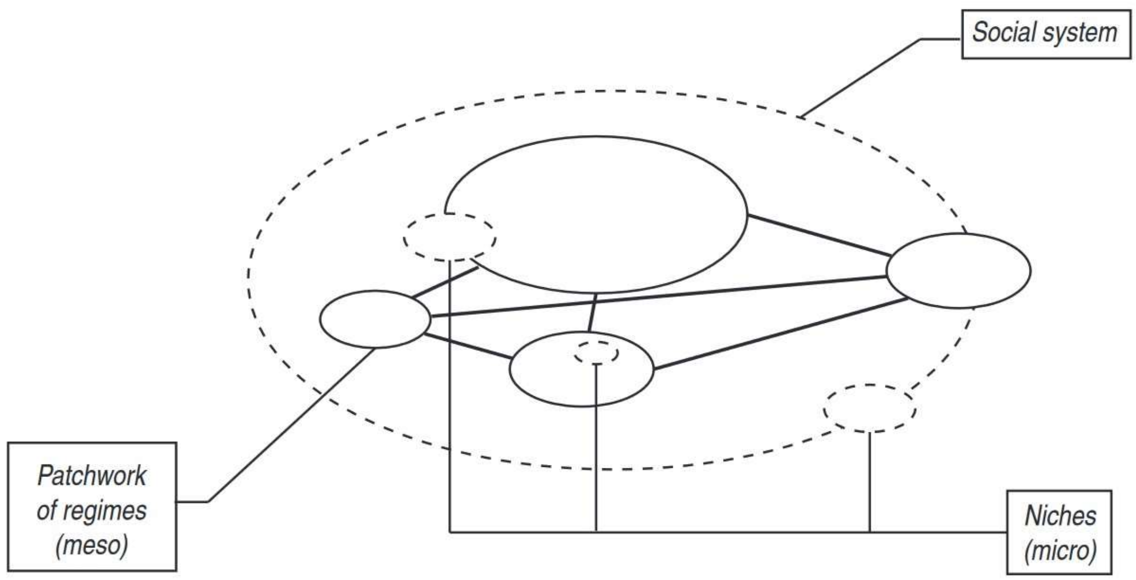

Figure 7. CAS model based on the MLP framework (Loorbach, 2007, p. 21).

An important addition of the model based on CAS theory is that it considers one more layer in the analysis, the social system. The model thus distinguishes at least four levels: the external environment (landscape), the social system, the regime, and the niche. Determining the social system and the components that comprehend each level is, to some extent, fluid. It depends on several aspects, for instance, the pre-established boundaries for the system and the focus of analysis. These are highly linked to how the researcher interprets the social system and its related agents. In the context of this Ph.D. thesis, the social system refers to the e-waste management system.

2.3.3 Phases of transition

A transition occurs through various phases of development. The s-shaped diffusion curve from innovation studies is a tool often applied to transition studies, specifically to categorize different phases of development in which a particular transition takes place (Rotmans et al., 2001). In the s-shaped diffusion curve, the initial phase comprehends an equilibrium before the onset of a transition, in which there is no visible change in the status quo. Next, the system begins to shift, which is followed by a phase of major structural changes. The final phase represents stability once the transition is complete, and a new equilibrium reached (Rotmans et al., 2001).

The x-curve of transition dynamics (Loorbach et al., 2017) is a tool applied to analyse the evolution of co-existing regimes in transition management. Drawing from the s-shaped diffusion curve, the x-curve analyses the combination of two regimes, illustrated in two s-curves: one upward representing the development of the emerging regime toward a new equilibrium, and another downward depicting the phasing out of the previously dominant regime.

Each curve in the x-curve of the transition dynamics framework represents five phases of transition. The upward s-curve begins as an experimental phase from the micro-level, in which several radical innovations take place. Successful innovations go through a phase of acceleration and emergence, becoming part of the regime practices through the institutionalization stage and, finally, stabilization. The downward s-curve represents the established regime, starting from optimization and moving through the phases of destabilization, chaos, and breakdown until the regime completely phases out. Figure 8 presents the framework taken from Paper IV, which is based on Loorbach et al. (2017). The x-curve of transition dynamics is applied in Paper IV and Chapter 6 of this thesis.

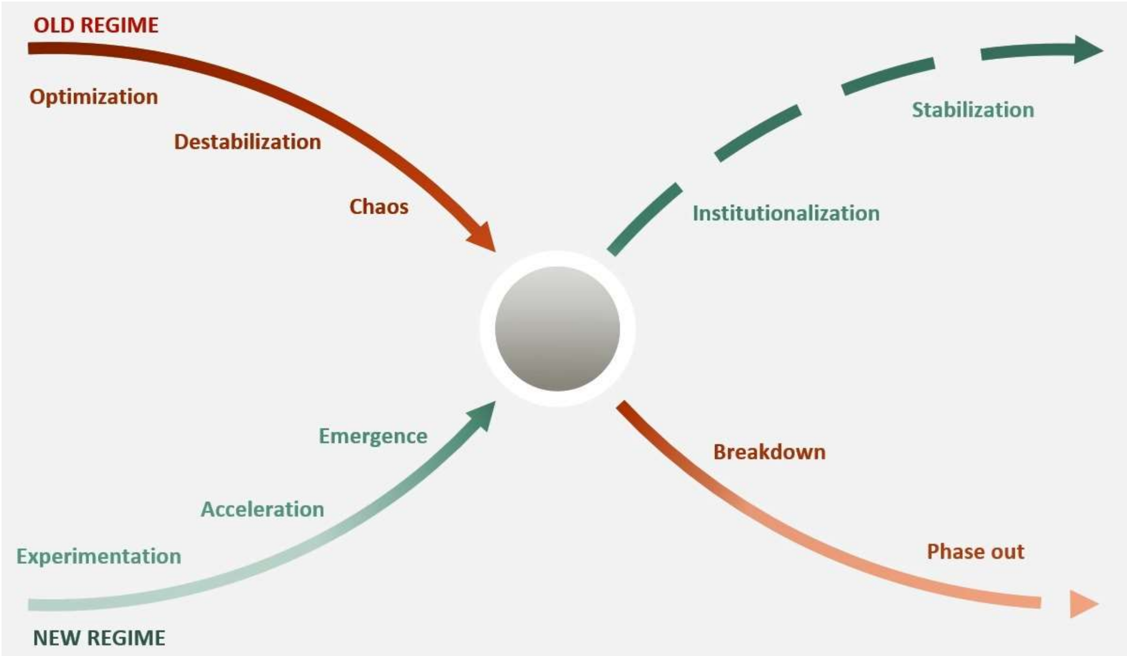

Figure 8. The x-curve of transition dynamics (adapted from Loorbach et al., 2017).

The x-curve is applied in transition management to identify patterns that drive structural change in societal systems. More specifically, the framework is central not only for exploring the co-existence of multiple regimes but also for better-investigating nuances of how these regimes develop through a period of transition.

2.4 Transitions in the Global South

Studies on sustainability transitions have been gaining strength, especially in the last decade. While the earliest publications focused on transport and electricity in European countries, more recent studies cover several societal domains (e.g., cities, food, and waste management) in various geographical locations (Köhler et al., 2019). The Sustainability Transitions Research Network (STRN), founded in 2009, is a relevant platform for gathering scholars in this research field (STRN, 2023).

Transitions can unfold differently across space. One thematic group of the STRN relevant to this work is in the geography of sustainability transitions. This thematic group focuses on theoretically informed spatial perspectives, especially how sustainability transitions unfold across various places and scales, and the need for greater sensitivity to analyse context-specific factors shaping transitions (Binz et al., 2020). Another thematic group of the STRN is in transitions in the Global South, which focuses on exploring challenges and opportunities related to sustainability transitions in developing and emerging economies.

Studies focusing on the Global South context commonly account for significantly different economic, political, and socio-cultural conditions compared to the Global North, as specified by Hansen et al. (2018, p. 199):

> These similar conditions include for example a weaker state apparatus, less efficient bureaucracies, higher levels of political and economic instability, less transparency in legal proceedings and enforcement of legal frameworks and relatively high levels of economic and social inequality. [....] Furthermore, developing countries typically rely on foreign sources of technology, knowledge and financial resources to a greater extent than developed countries – with external donor interventions playing a role especially in the least developed ones – and they are typically characterised by less advanced industrial processes, a dominance of low-tech (primary) sectors, reliance on extended family ties and clientelism, and employment in the informal sector.

Many of the aforementioned conditions translate into various shades of development in countries of the Global South, as opposed to a more unified development common in countries of the Global North. Similarly, Ghosh et al. (2021) argue for *decolonizing* sustainability transitions research in the Global South by focusing on three core aspects: everyday struggles and resistances, nuances of local dynamics, and meaningful and empowering participatory research methods. The authors defend the need to rethink the institutional perspective and social realities in such a context when aiming to study and implement sustainability transitions in the Global South.

As strongly linked with economic and social development, the informal sector prevails the most in low-income countries. Although it is difficult to gather precise data on the presence of such a sector, estimates are that the informal sector represents more than 50% of total employment in most countries of the Global South and reaches more than 90% in several of its low-income countries (ILO, 2023). Therefore, accounting for conditions such as the strong presence of the informal sector is essential when aiming to direct the desired transitions while failing to address them potentially foments patterns of social exclusion (Ramos-Mejía et al., 2018). More specifically, studies of sustainability transitions in the Global South must be attentive to the interconnections of knowledge and power (Schipper et al., 2019).

Transition studies in the Global South often focus on activities within the informal sector and their interplay with the formal sector. For example, Yuana et al. (2019) focus on the sharing economy in Indonesia and the Philippines by analysing the emergence of ridesharing platforms. Additionally, Wainaina et al. (2022) look into the role of institutional logic for participation in upgrading informal settlements in Kenya. Their findings indicate the importance of considering the multiplicity of agents and the variety of rationalities for successfully implementing urban projects.

2.4.1 Conceptual framework of sectoral and service regimes

With origins in the Global North, most frameworks applied in sustainability transition research (such as the MLP framework) have been developed in such a context. An essential critique of studies focused on the Global South relates to the limited applicability of widely used frameworks in the research field (Ramos-Mejía et al., 2018). For example, van Welie (2019) highlights that a *large-scale centralized infrastructure paradigm* is often aimed globally but failed to be achieved in various countries of the Global South. The author points out that one of the central reasons is that institutional and organizational conditions are often absent or weakly developed.

Adapting and expanding frameworks that address nuances commonly present in the Global South is crucial for further development of the research field. One such framework is proposed by van Welie et al. (2018). The framework re-conceptualizes socio-technical regimes by distinguishing two analytical levels: the service and the sectoral regime.

In this context, the definition of service regimes is equivalent to the concept of socio-technical regime often applied in sustainability transition studies, as they "form around specific institutionalized combinations of technologies, user routines and organizational forms for providing the service" (van Welie et al., 2018, p. 261). The sectoral regime, on the other hand, encompasses broad societal functions, such as transport, electricity, and food. Figure 9 presents a part of the conceptual framework that distinguishes the two analytical levels. The grey square represents the sectoral regime, the white circle the service regime, the grey circles the dimensions within the service regime, and the lines between the various circles represent the alignments.

Figure 9. Conceptual framework of a sectoral regime configuration and service regime dimensions (van Welie et al., 2018, p. 263).

The authors point out inconsistencies in the existing sustainability transition literature related to the concept of sectoral regimes. For example, they highlight that some studies merely related to it as a broader domain, while others perceive both service and sectoral contexts as identical. The conceptual framework proposed by van Welie et al. (2018) seems well-aligned with earlier propositions within transition management studies, namely the complex systems model as illustrated in Figure 7 (Loorbach, 2007) as both add a level of abstraction to the analysis based on the MLP framework, and recognize the existence of various regimes.

Van Welie et al. (2018) propose a typology of sectoral regimes with four configurations, namely monolithic, polycentric, fragmented, and splintered. Figure 10 illustrates the four configurations. The monolithic regime comprehends a sectoral regime with one dominant service regime, as exemplified by the urban water management in Switzerland. The polycentric regime consists of several service regimes that are well-aligned both among each other and at the sectoral level, such as the transport (sectoral) regime in the Netherlands and the several modes of transportation (e.g., biking and automobile) representing the service regimes (van Welie, 2019).

The following two regimes refer to sectoral regimes that comprise of several service regimes misaligned at the sectoral level: The fragmented regime with several internally well-aligned service regimes, and the splintered regime consisting of service regimes that are only partially aligned internally (van Welie, 2019). The authors apply such a conceptual framework to the (sectoral) sanitation regime of Nairobi in Kenya and identify the following five (service) regimes: domestic sewer, shared on-site sanitation, public sanitation, coping sanitation, and container-based regime.

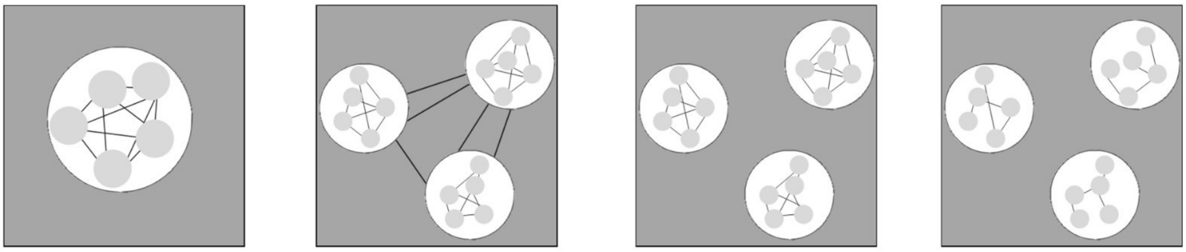

Figure 10. Conceptual framework of four sectoral regime configurations (van Welie et al., 2018, p. 263).

Based on practice theory and with a focus on practices employed for the provision of basic services, van Welie et al. (2018) define five dimensions of a service regime. The first dimension refers to infrastructure & artefacts, that is, artefacts and the physical structures related to their functioning. The second dimension comprehends the organizational mode, "a group of actors with complementary strategies and a particular set of capabilities and procedures to fulfil the provisioning of basic services" (van Welie et al., 2018, p. 262). The third dimension represents time & space, referring to the specific timing and spatial location in which the service is operated. The fourth dimension is the rationale & meaning, which represent the role and expectations of the agents, as well as the rules governing the access and provision of the service. Lastly, the fifth dimension refers to social interaction, "the exchanges between people that enable or hinder the user's access to services and for providers to maintain regular practices" (van Welie, 2019, p. 67).

The framework from van Welie et al. (2018) has been applied to study different socio-technical systems and contexts. For example, Schippl and Truffer (2020) categorize various transport modes as service regimes to analyse diverging trajectories in rural and urban regions in Germany. The authors categorize and define the service regimes in such a context into five dimensions: technologies & infrastructures, organizational mode, societal meaning, user requirements, and planning practices & public financing. Additionally, the framework is applied to the water and sanitation sectors in Bolivia, in which several modes of service delivery are identified. Here, Helgegren et al. (2021) define six service regime dimensions to their analysis: water & sanitation infrastructure, actors & organization mode, prevalent sector values, internal coordination, legislation, and financing. The slight variation of dimensions applied in the studies provides insights connected to the specific topic and focus of study.

2.4.2 Sustainability transitions in waste management

Sustainability transition studies within the Global South have been gaining strength in recent years and address challenges that include the EoL phase. An example on waste management is from Larbi et al. (2022) with two case studies from cities in Ghana and Brazil. The authors focus on transport and waste to draw insights into urban sustainability transitions in the context of the Global South.

However, sustainability transition studies on e-waste management are still very few. One example is from Samarakoon et al. (2022), who draw from empirical research conducted in Malawi to explore the dynamics of off-grid solar devices once requiring repair or becoming e-waste. The authors argue that strengthening repair infrastructures in such contexts could significantly extend the lifespan of the devices.

Studying e-waste management in the Global South from a sustainability transitions theoretical framing is of increasing relevance. Specifically, the research field of sustainability transitions provides a wealth of theoretical and analytical tools that facilitates investigations on e-waste management. Additionally, the intrinsic focus of the research field on large-scale transformations provides a specific angle to explore possible pathways toward more sustainable e-waste management practices and systems.

Chapter 3

Methods

In this chapter, I present the main methods applied throughout the work. First, I present the overall research approach applied to the work, which includes the motivation and justification for empirical research, the guiding epistemological research paradigms, and the chosen methodology. Next, I present the empirical contexts (i.e., in Ghana, Brazil, and China) and describe the methods of data collection. The case background provides both context and justification of the choice of countries for the empirical research. I then present the methods applied for data analysis. In this chapter, I also address some strengths and limitations of the empirical research, as well as ethical considerations throughout the work.

3.1 Research approach

This Ph.D. thesis focuses on practices and policies toward sustainability transitions in e-waste management. Studies on e-waste management have evolved substantially in the recent decade. However, empirical studies on e-waste are still limited and often comprise data collection within delimitated areas. Studies that systemically analyse e-waste management with data sets from various countries most often rely on secondary analysis (e.g., literature review) instead of empirical work in various locations.

There is an ongoing debate in academia on a gap between scientific and practical knowledge. While some scholars focus primarily on advancing theoretical knowledge, there is a common divergence between theoretical advancements and the possibility of practical implementation. To bridge such a gap, Van de Ven (2007) proposes a method of engaged scholarship.

> Engaged scholarship is defined as a participative form of research for obtaining the different perspectives of key stakeholders (researchers, users, clients, sponsors, and practitioners) in studying complex problems. By involving others and leveraging their different kinds of knowledge, engaged scholarship can produce knowledge that is more penetrating and insightful than when scholars or practitioners work on the problems alone. (Van de Ven, 2007, p. 9)

Engaged scholarship can be carried out in various ways and with different purposes. The perspective undertaken by the researcher and the complexity of the work, for instance, impact the form of applying the method. Overall, "the time spent in field research sites is positively related to making higher quality knowledge contributions to science and practice" (Van de Ven, 2007, p. 296). However, the author highlights that engaged scholarship can be practiced through both longitudinal and cross-sectional studies, depending on the research problem and questions that aim to be tackled.

In this Ph.D. thesis, I apply such a method to e-waste management. I start with the assumption that one of the best ways to identify barriers and drivers for sustainability transitions in e-waste management is to attempt to immerse myself into the context and reality of the ones directly facing the problem. Therefore, my aim with the empirical work is to capture various perspectives of key stakeholders (addressed as agents in the thesis). Indeed, one of the primary characteristics of engaged scholarship is to draw on the perspectives of such agents immersed in a real-world problem to develop knowledge aiming to address it (Mathiassen, 2017). Once analysed systemically, such knowledge raises significant insights for addressing the e-waste challenge.

The engaged scholarship method may adopt different epistemological research paradigms. Such paradigms form the philosophical basis and assist in guiding the research. This work relies upon a well-known classification that distinguishes the following research paradigms: positivist, interpretive, and critical (Myers and Avison, 2002; Myers and Klein, 2011; Orlikowski and Baroudi, 1991).

The positivist research paradigm assumes "that reality is objectively given and can be described by measurable properties, which are independent of the observer (researcher) and his or her instruments" (Myers and Avison, 2002, p. 6). Here, it is common to quantify measures of variables or test hypotheses. The interpretive research, on the other hand, aims to better understand certain phenomena through the assumption that such phenomena are contextual and dependent on social constructions, for instance, of consciousness, language, and shared meanings (Myers and Avison, 2002).

Unlike positivist and interpretive research, critical research is a non-neutral scientific research perspective, applying a critical view on assumptions taken for granted. The assumption here is that "social reality is historically constituted and that it is produced and reproduced by people [...]. The main task of critical research is seen as being one of social critique, whereby the restrictive and alienating conditions of the status quo are brought to light" (Myers and Avison, 2002, p. 7). It can provide historical and structural insights, often revealing contradictions and opening up the possibility of transformations (Gephart, 2004).

Sustainability transitions studies often rely upon similar classifications of epistemological research paradigms. Methodological investigations and reflections are still underdeveloped within the research field, and tend to draw from different paradigms and multiple knowledge areas (Zolfagharian et al., 2019).

Wittmayer (2016) distinguishes two main focuses within transition studies, specifically researching *about* transitions and *for* transitions. The first focuses on analysing and describing historical transitions, while the second investigates current ones to support or enable action toward sustainable development (Wittmayer, 2016). This thesis, as well as the transition management approach, focuses on the latter.

The sustainability transitions research field focuses on complex societal phenomena and commonly results in a "co-production of knowledge among different disciplines and in collaboration with practice partners and experts in the field" (Mühlemeier, 2019, p. 17). As the researcher often becomes part of the research object through empirical investigations, the very presence of the researcher may impact the results throughout the investigations.

Various inter and transdisciplinary research approaches are applied within sustainability transition studies, often pushing the boundaries of classic scientific knowledge. In this line, Avelino (2011, p. 22) advocates for the need to "combine different epistemological paradigms and explore the whole spectrum of what was, what is, what seems to be, what people want, and what we think that will be or ought to be."

In this Ph.D. thesis, I place myself at the intersection of interpretive and critical research paradigms. To better understand the various contexts from the view of key agents in the systems, I aim to apply a neutral and interpretive perspective to the data collected and analysed. However, the work has a critical intend with the hope to motivate change toward more sustainable e-waste management systems. Combining the interpretive and critical paradigms opens for raising insights that can hopefully lead to transformations toward the desired transitions.

Within the various epistemologies, research can apply a qualitative and quantitative methodology. The difference between the two goes far beyond the emphasis on words or numbers, as qualitative research focuses on understanding the connections between human beings and the social world (Mason, 2002). Qualitative research investigates phenomena in their natural environment, often designed while conducted (Gephart, 2004). Therefore, it "is open to unanticipated events, and it offers holistic depictions of realities that cannot be reduced to a few variables" (Gephart, 2004, p. 455). This type of research provides contextual information, which assists in addressing complex phenomena (Guba and Lincoln, 1994). Intending to investigate various e-waste management practices in different settings, applying qualitative research to this Ph.D. thesis assists in providing such contextual information, which leads to several insights addressed in later chapters.

With the aim of providing new insights for improving global e-waste management, the work investigates challenges faced by various agents in locations that are among the most affected globally. In this context, the Global South is well-known to be the most impacted by global e-waste generation, and some countries in specific. Ghana, Brazil, and China are among the most impacted within their respective continents and are, therefore, significant locations for empirical research. By considering e-waste management systems in different countries, the Ph.D. thesis applies a multiple-case study methodology. Also addressed as a collective case study, this type of research aims at understanding a particular phenomenon, general condition, or population (Stake, 2005).

E-waste management in each country analysed is perceived as a system and represents the empirical context. Within each system, the Ph.D. thesis analyses different cases that are represented by specific sites and organizations. The individual cases "may be similar or dissimilar, with redundancy and variety each important. It is believed that examining such cases will lead to better understanding, and perhaps better theorizing, about a still larger collection of cases" (Stake, 2005, p. 446). A background of the cases is presented in detail in the following.

3.2 Case background and data collection

The work comprises empirical research in three countries. The various data sets represent different levels of analysis that are addressed in Chapter 5. The study in Ghana focuses on the activities performed by the informal sector, while the one in Brazil focuses on activities in the formal sector. The study in China combines both sectors.

The empirical research conducted in the three countries was analysed separately and resulted in independent publications. The empirical contexts, case studies, and related publications are illustrated in Figure 11.

Some data collected were not directly applied in the publications, for instance, data collected within the formal sector in Ghana. Nevertheless, all data collected are described in the following as the combination of various data sets assisted in building a better understanding of the empirical contexts.

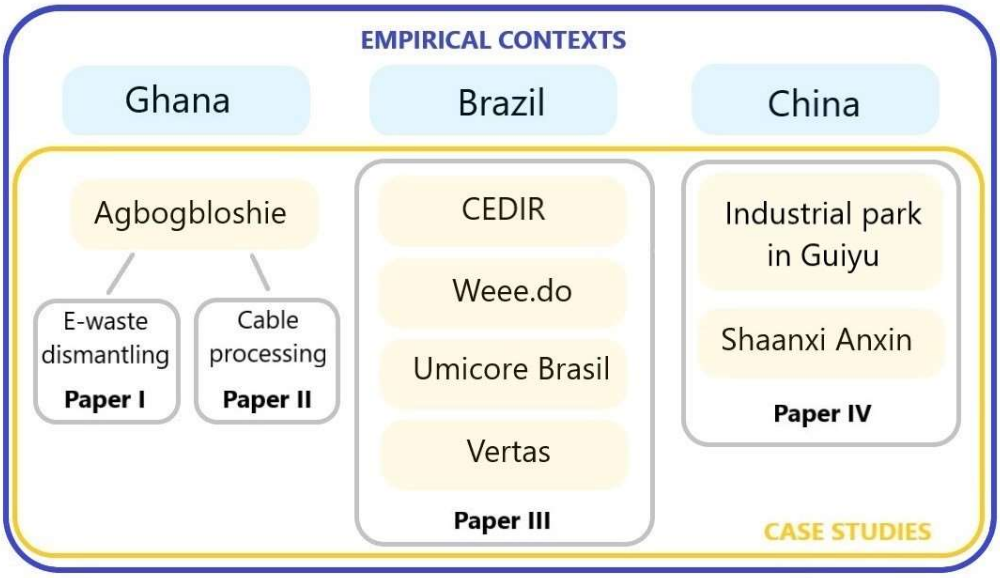

Figure 11. Connection of the empirical research with the publications.

3.2.1 Ghana

Ghana is a country in West Africa with almost 33 million inhabitants (World Bank, 2023). The country generated 1.8 kg of e-waste per capita in 2019, the equivalent of 53 Kt of e-waste generated in total (Forti et al., 2020). To put into context, the countries with the highest e-waste generation per capita in the world result in more than 20 kg per capita. Here, the amount referred to as e-waste generated refers to "the annual supply of domestically generated e-waste prior to collection without imports of externally generated e-waste" (Forti et al., 2020, p. 36).

The Hazardous and Electronic Waste Control and Management Act (Act 917) from 2016 (EPA, 2023) regulates the control and management of e-waste in Ghana, including import and final disposal. In addition, the Technical Guidelines on Environmentally Sound E-Waste Management for Collectors, Collection Centres, Transporters, Treatment Facilities and Final Disposal in Ghana was implemented in 2018 to support the Act by providing information on best practices for e-waste management in the country (EPA and SRI, 2018). However, enforcement of legislation remains a challenge.

Electronics commonly enter the country as second-hand goods (Grant and Oteng-Ababio, 2016), but estimates are that around 30-40% of the devices are not functional upon arrival (Daum et al., 2017). Although global shipments of electronics often enter Ghana through ports of neighbouring countries, the port in Tema represents the primary entry point of used electronics for shipments sent directly (Daum et al., 2017).

The informal sector plays an essential role in e-waste management in Ghana. Agbogbloshie is a scrap metal yard located in the capital Accra and a primary site for informal e-waste processing in the country. The site is well-known for the effects of improper e-waste processing, especially concerning environmental and social hazards. Based on a material flow analysis methodology, Owusu-Sekyere et al. (2022) estimate that Agbogbloshie processes around 39% of the e-waste generated in Ghana. The site comprehends an area of 31.3 ha (Amankwaa et al., 2017), where around 5000 individuals work on the processing of scrap metals (Forti et al., 2020). Agbogbloshie thus represents a significant case for investigating e-waste management practices within the informal sector.

It is relevant to mention that the site has changed considerably since the field studies in 2017. In July 2021, the government demolished the informal huts and built a wall around Agbogbloshie (Seidu and Kaifie, 2022). However, the informal e-waste processing activities continue as workers have been relocated to surrounding areas (Owusu-Sekyere et al., 2022).

In Ghana, I conducted field studies on several points of interest during a two-weeks period in September 2017. Figure 12 illustrates the country and highlights the main cities included in the empirical research.

Figure 12. Map of Ghana and specification of cities related to the empirical research.

Primary field studies focused on the informal sector, in specific the case-study of Agbogbloshie. Initially, I conducted a semi-structured interview with the chairman and board members of the Greater Accra Scrap Dealers Association in Agbogbloshie to gain access to the site and learn about the organization of activities. The interview was translated from Ashanti to English and vice versa, lasted around an hour, and was documented through audio recording. After getting access to the site, the follow-up visits were comprised of observations of various activities and groups. The activities were organized into groups that focused on the processing of various equipment. I visited the Agbogbloshie site seven times, and each visit lasted around half a day. During each visit, I would go around the area and engage in conversations with workers from various groups.

I conducted a semi-structured interview with the leader of one of the groups (composed of around 15 workers) responsible for dismantling various types of electronics in Agbogbloshie. The interview was conducted in English in their working space on the site, lasted about an hour, and was documented through audio recording. Subsequently, the data collection took place through on-site observations. I conducted interviews in the form of informal conversations with several workers performing various activities within this group. In addition, I engaged in conversations with a smaller group (which focused on mobile phones) and a worker that focused on laptops. Shorter conversations with other workers on the site took place while going around the area during the visits. I had a set of pre-established questions that assisted in guiding the conversations and interviews (cf. Appendix II). These were adapted though data collection.

The conversations varied in time and data collected, depending on the availability and willingness of the workers to participate. These were conducted while observing the workers' activities. I documented the observations in Agbogbloshie through field notes and, when authorized, also through photography and video recordings. Many of the notes were taken after the visits since I quickly realized that notetaking during the data collection could have a negative effect, potentially limiting the disclosure of information. Especially during the initial days, I felt that the respondents were very apprehensive in sharing any information. The trust increased by going to the site several times and engaging into conversations with some of the workers for several days and longer periods of time.

In addition, I visited a commercial area close to the port in Tema for about half a day. Here, I engaged in conversations with various sellers of electronics. These focused on the origins and state of the appliances, for instance, if the electronics required immediate repair. The conversations were documented through notes and, when possible, photography. In total, I recorded about 25 short videos that included the dismantling and sorting activities in Agbogbloshie and the surroundings of Agbogbloshie and Tema. I took more than 400 pictures focusing on e-waste processing in Agbogbloshie, as well as the commercialization of devices in Agbogbloshie and Tema.

Within the formal sector, I had the opportunity of visiting organizations working with varied focus. Here, I collected data through semi-structured interviews conducted in English and documented through audio recording. The interviews are described in Table 1.

Table 1. Interviews conducted in various formal organizations in Ghana.

INTERVIEWEE	ORGANIZATION	LOCATION	DURATION	FOCUS
Project Manager	Green Advocacy Ghana (GreenAd), an environmental NGO that conducts e-waste management research in Ghana	Sakumono	1h	Activities and related challenges in Agbogbloshie
Director of Standards Compliance & Enforcement	Ghana Environmental Protection Agency	Tema	1h30min	Challenges and opportunities related to e-waste management in the country and future plans
Manager	A company working with assembling, commercialization, and a take-back system (for repair and recycling) of ICT equipment	Accra	1h	Main activities conducted, challenges and opportunities
Manager	A company working with collection, repair, and recycling of ICT equipment	Accra	1h	Main activities conducted, challenges and opportunities
Manager	A scrap metal (including e-waste) recycling company working with initial processing and trade (local and international)*	Accra	30min	Main activities conducted, challenges and opportunities

* The interview was followed by a short visit to the facilities. Notes were taken to document the visit.

The diversity of data collection in various points of interest in Ghana provided insights from the perspective of different agents in the system, as well as a better understanding of the e-waste management activities performed in the country.

3.2.2 Brazil

Brazil is the largest country in South and Latin America, with a population of more than 214 million inhabitants (World Bank, 2023). The country generated 2.1 Mt of e-waste in 2019 (10.2 kg per capita) and represents the largest generator of e-waste in Latin America (Forti et al., 2020).

A national policy on solid waste from 2010 is the main legislative framework regulating e-waste management in the country (Brasil, 2022, 2010). As in most countries within the Global South, implementing e-waste management legislation remains challenging. According to Xavier et al. (2021), the country lacks an established system for collecting and recycling e-waste in most metropolitan regions.

E-waste management activities in Brazil are difficult to quantify due to a lack of data on the informal sector (Dias et al., 2018). The Global E-waste Monitor (Forti et al., 2020) estimates that less than 1% of the e-waste generated in 2019 in South America was collected and recycled through formal channels. A large portion of e-waste in Brazil is disposed of as household waste and often ends up in landfills or open dumpsites (Abbondanza and Souza, 2019; Xavier et al., 2021). Such sites represent a common collection point for workers in the informal sector (Mancini et al., 2021). Waste collectors play a vital role in waste management in the country, although commonly perform activities under vulnerable working conditions (Schneider et al., 2017).

Dias et al. (2018) have identified 134 organizations working with e-waste recycling and 13 with the export of e-waste. Most of these organizations are concentrated in the Southeast and South regions. The state of São Paulo in the Southeast region is the most populous in the country. Its capital city, also named São Paulo, is the most populous in the country and the Americas, with more than 12 million inhabitants (IBGE, 2023). The state thus represents a focal point for empirical research.

In the South region, the capital city of the State of Santa Catarina, Florianópolis, represents a technology hub in the country due to the growing concentration of companies in the information technology sector (Sabatini-Marques et al., 2020). Therefore, the state represents a focal point for empirical research in the South region.

In Brazil, I focused on the formal sector and conducted field studies in four organizations between June and July 2018. Figure 13 illustrates the country and highlights the municipalities in which the visited organizations are currently located. The organizations visited comprised the following: CEDIR, Weee.do, Umicore Brasil, and Vertas.

The first organization (CEDIR, 2023) is a university centre located in the city of São Paulo focusing on the reuse and disposal of electronics. It represents a pioneer project in the country. The second (Weee.do, 2023) relates to a reference company for e-waste management in Santa Catarina. The company works in cooperation with a non-governmental organization (NGO) and has an established structure for e-waste collection through several voluntary collection points.

The third organization (Umicore, 2023), located in the state of São Paulo, is a branch of one of the largest e-waste recycling companies worldwide, with headquarters in Belgium (Kaya, 2019). Finally, the fourth organization (Vertas, 2023) is also located in the state of São Paulo. The company presents an example of an innovative process for e-waste recycling within the Brazilian context. The four organizations represent varied case profiles within the formal sector of e-waste management and assist in building a better understanding of the current scenario in the country.

Figure 13. Map of Brazil and specification of cities related to the empirical research.

I conducted semi-structured interviews in Portuguese with the representatives of the recycling organizations. These were conducted in offices at the respective organizations and documented through audio recordings and field notes, using a predefined set of questions that helped guide the interviews (cf. Appendix III). These were adapted through data collection. During the interviews, I focused on topics such as the processes conducted by each organization and the main drivers and barriers to the growth of activities within the formal sector. Table 2 provides further details of the interviews.

Table 2. Interviews conducted in formal recycling organizations in Brazil.

INTERVIEWEE	ORGANIZATION	LOCATION	DURATION OF THE INTERVIEW	DURATION OF THE VISIT TO THE FACILITIES
Operations Technician	CEDIR	São Paulo	1h	30min
Chief Executive Officer	Weee.do	Palhoça	1h	1h
Commercial Manager	Umicore Brasil	Guarulhos*	1h	1h
Commercial Director	Vertas	Mauá	1h30min	1h30min

*Data collection took place in the facilities in Guarulhos, which were later relocated to Americana.

After the interviews, I visited the facilities of all organizations. During the visits, I documented data collection through field notes and photography. I took more than 100 pictures focusing on the recycling processes of various appliances. I contacted the organizations again in August and September 2022 to check for possible updates.

3.2.3 China

China is a country in East Asia and the most populous in the world, with more than 1.4 billion inhabitants (World Bank, 2023). The country is the largest generator of e-waste in the world. It generated 10.1 Mt of e-waste in 2019, equivalent to 7.2 kg per capita (Forti et al., 2020). Estimates show that the total generation can substantially increase to more than 28 Mt by 2040 (Zeng et al., 2020).

The country is well-known for its previous e-waste importation and unregulated recycling activities. Guiyu, in Guangdong Province, has been widely perceived as one of the largest informal e-waste processing sites in the world (Chi et al., 2011). With activities dating back to 1995, Guiyu commonly processed e-waste from abroad in its early years (Breivik et al., 2014). The site is known for the rudimentary processes performed, as well as detrimental impacts on the environment and society (Pérez-Belis et al., 2015). However, activities in Guiyu have changed after the implementation of an industrial in 2010 (Song et al., 2017). Guiyu represents a focal point for empirical research within the informal sector.

China has advanced significantly in terms of the implementation of legislation. The Administration Regulation for the Collection and Treatment of WEEE from 2011 (also referred to as the WEEE Regulation) is a primary legislative framework for e-waste management in the country (Zhu et al., 2012). The WEEE Regulation outlines the shared responsibilities of various agents in the system, including producers of electronics, consumers, and e-waste recycling organizations.

Through the Regulatory Measures for Collection and Disposal Fund of WEEE from 2012 (also referred to as the Fund policy), the government offers subsidies to a set of licensed companies in the country for dismantling certain appliances (Chen et al., 2018). The subsidies have strengthened the activities within the formal sector and led to the establishment of 109 licensed companies (Wang et al., 2022). To investigate the activities within the formal sector, the licensed companies are another focus point for empirical research.

The study of e-waste management in China combines data from the informal and formal sectors. Figure 14 highlights the main cities included in the empirical research. In August 2019, I conducted a field study together with the co-author of Paper IV at Shaanxi Anxin CRT Recycling Processing Applications Co. Ltd. (Shaanxi Anxin, 2023), an e-waste recycling company in Xizhangbu town, in Shaanxi Province. The company is hereinafter referred to as Shaanxi Anxin. Here, we conducted a semi-structured interview of around one hour with the general manager. The focus was on topics such as the main processes performed, the appliances covered, and the impact of policies on recycling activities. A set of preliminary questions (cf. Appendix IV) assisted in guiding the interview and was adapted as necessary. The interview was documented through field notes and translated from Chinese to English and vice versa. This was followed by a visit to the facilities, which lasted approximately one hour. The visit was documented through field notes, photography, and video.

In Paper IV, the above-mentioned data was complemented by data from my co-author, collected in April 2018 at an industrial park in Guiyu town in Guangdong Province. The dataset from my co-author formed the basis for the example case of e-waste recycling from the informal sector in China. Around eight semi-structured interviews were conducted in Chinese with managers and workers processing e-waste in Guiyu. The focus was on investigating changes to the work environment and processes after implementing an industrial park in the region. The observations were documented through field notes, photography, and video.

Figure 14. Map of China and specification of cities related to the empirical research.

In addition, I conducted a field study in Zhongguancun, Beijing, in September 2019. Zhongguancun is a major technology hub in the country, also known as China's Silicon Valley. The site consists of several stores with a primary focus on the repair and trade of second-hand electronics. I visited the site for around two hours with the assistance of a local student. Here, I engaged in conversations with repairers and sellers of electronics. The focus was on the main activities performed for repair and the destination of the components beyond repair. The conversations were translated from Chinese to English and vice versa. These were documented through field notes (after the visit) and photography. I took around 100 pictures and three short videos of the recycling company in Shaanxi and the market in Beijing.

3.3 Methods of data analysis

The work in this Ph.D. thesis combines the results from the empirical research conducted within different sectors of the economy in distinct countries of the Global South. Various theoretical and analytical lenses were applied throughout the research journey, reflected in the publications, and illustrated in Table 3.

The data collected in the three countries were analysed through thematic analysis. Braun and Clarke (2006) categorize two ways of identifying patterns within data through thematic analysis: the deductive and the inductive approaches.

Table 3. Description of the theoretical and analytical lenses applied through the research journey.

Year of data collection	2017	2018	2019
Empirical context	Ghana	Brazil	China
Sector of the economy	Informal sector	Formal sector	Informal and formal sectors
Theoretical framing	CAS theory	Transition management	Transition management
Analytical lens	CAS properties and the theory of constraints	MLP framework	X-curve of transition dynamics

The deductive (or theoretical thematic analysis) is a 'top down' way of analysing the collected data. The deductive approach is often "driven by the researcher's theoretical or analytic interest in the area, and is thus more explicitly analyst-driven" (Braun and Clarke, 2006, p. 84). Therefore, it requires from researcher an understanding of the related theoretical literature prior to the data analysis. In contrast, the inductive approach represents a 'bottom up' way of analysing the data collected:

> An inductive approach means the themes identified are strongly linked to the data themselves […]. In this approach, if the data have been collected specifically for the research (e.g., via interview or focus group), the themes identified may bear little relation to the specific questions that were asked of the participants. They would also not be driven by the researcher's theoretical interest in the area or topic. Inductive analysis is therefore a process of coding the data without trying to fit it into a preexisting coding frame, or the researcher's analytic preconceptions. In this sense, this form of thematic analysis is data-driven. (Braun and Clarke, 2006, p. 83)

The methods applied for data analysis in each country are described in the following.

3.3.1 Ghana

Data collected in Ghana were analysed through deductive and inductive approaches. The audio recordings were transcribed and analysed in combination with the notes and pictures from the empirical research. The results of the investigations in Ghana are presented in Paper I and in Paper II.

In Paper I, the deductive approach was applied to investigate the dismantling of e-waste (especially computers and mobile phones), as well as the environmental and social hazards associated, in Agbogbloshie. Here, CAS theory (as detailed in Chapter 2) was applied as an analytical tool to better understand the processing of e-waste. The results from the empirical research were manually processed and coded according to topics related to social, economic, and environmental aspects. In the second step of the analysis, data were categorized according to the following properties from CAS theory: adaptation, non-linearity, emergence, and feedback loops. The classification into properties from CAS theory are presented in the discussion section of Paper I.

In Paper II, I applied an inductive approach to analyse the data collected on the cable processing in Agbogbloshie. The data that emerged were categorized into three topics: the open-air burning activity to process cables, the process of implementing the wire stripping machines, and the challenges regarding the change in operations. Here, I applied the theory of constraints (TOC) in the analysis, specifically for exploring factors contributing to the prevalence of the open-air burning activities. The TOC focuses on addressing factors that limit the performance of a system in achieving its goals, referred to as the system's constraints (Goldratt, 1990). These are classified as market, resources, material, vendors or suppliers, financial, knowledge or competence, and policy constraints (Schragenheim and Dettmer, 2000). Accordingly, each type of constraint requires specific management approaches to be tackled. The TOC was applied exclusively in this paper to investigate possible reasons for the lack of use of wire stripping machines in Agbogbloshie. The application of the TOC to the case revealed managerial-policy constraints, many which unveiled significant challenges connected to implementing the wire-stripping machines in an international context.

3.3.2 Brazil

The analysis of data collected in Brazil was conducted through a deductive approach. The audio recordings were transcribed and analysed in combination with the field notes and pictures from the empirical research. Transition management was applied as the overarching theoretical lens in this study. The MLP framework (as presented in Chapter 2) was applied as an analytical tool. The objective was to investigate the main barriers to the growth of the formal sector in transitioning toward an established e-waste management system according to the perspective of varied recycling organizations in the country. The results from the empirical research were manually processed. Data identified as barriers were sorted into color-codes according to the organizations. The results comprised the identified barriers, categorized into the various regime dimensions.

In addition to the empirical research, the study in Brazil analysed advancements in the legislative framework for e-waste management in the country based on a review of legislation and other studies. This analysis assisted in building a better understanding of the current e-waste management situation in the country. The results of the investigations in Brazil are presented in Paper III.

3.3.3 China

The analysis of data collected in China was conducted through a deductive approach. The study applied transition management as the guiding theoretical lens. The x-curve of transition dynamics (as presented in Chapter 2) was applied when analysing the data to explore the co-existence of multiple regimes, in this case, the informal and formal sectors. The field notes, pictures, and videos from the industrial park in Guiyu and the Shaanxi Anxin company were analysed in combination. Data analysis focused on the following topics: motivations to focus on specific appliances and e-waste components, working conditions, and interconnections between the informal and formal sectors.

Like the study in Brazil, this study also analysed advancements in the legislative framework. This analysis was based on a review of publications addressing e-waste management legislation and provided an overview of significant policy advancements in the country. The results of the investigations in China are presented in Paper IV.

3.3.4 Combining the empirical contexts

This Ph.D. thesis combines core results from the empirical contexts and related publications while theoretically based on the research field of sustainability transitions, specifically on transition management.

The thesis applies the MLP framework (Geels, 2002) as a broad analytical tool to navigate through the various levels of complexity within e-waste management. More specifically, the analysis extends from the conceptual framework by van Welie et al. (2018) that proposes two analytical levels within the regime: the sectoral and the service regimes. Here, e-waste management is perceived as the sectoral regime.

The thesis considers two layers of abstraction in the analysis, namely the sectors of an economy and the stages of e-waste management. The e-waste management (sectoral) regime represents a system in each country, which is further divided into two sub-systems: the informal and the formal sectoral regimes. These relate to, respectively, the informal and formal sectors of the economy. Additionally, the various stages of e-waste management are categorized as: collection, pre-processing, and end-processing. Each sector of the economy provides various services at different stages of e-waste management, which are perceived as service regimes. Making the aforementioned distinctions assists in navigating through the complexities at various analytical levels in each system.

Table 4. Categorization and definition of the service regime dimensions applied in the Ph.D. thesis.

SERVICE REGIME DIMENSION	DEFINITION
Technologies & infrastructures	The physical structures available to the functioning of the service regime.
Organizational mode	The organizational structure, including the preconditions and strategies for providing the service.
Rationale & meaning	The values and beliefs guiding the provision of the service.
Internal coordination	The communication and interactions among agents within the service regime.
Legislation & public financing	The formal laws and regulations, including related funding allocated toward the service regime.

In this Ph.D. thesis, I have chosen to formulate an understanding of the service regime dimensions based on a combination of terminologies adopted in different studies as presented in Chapter 2 (van Welie et al., 2018; Schippl and Truffer, 2020; Helgegren et al., 2021) and the data collected through the empirical research. The categorization of the dimensions applied in this thesis is presented in column 1 of Table 4, and my definition of each service regime dimension is summarized in column 2.

3.4 Strengths and limitations of the empirical work

This Ph.D. thesis explores barriers and drivers in transitioning to more sustainable e-waste management systems based on the empirical contexts of Ghana, Brazil, and China. The following highlights some methodological strengths and limitations of the empirical work.

In the work, I take an international approach to e-waste management with a focus on the Global South. I provide various perspectives from agents located in countries within three different continents, therefore giving voice to a diversity of rationalities within e-waste management in the Global South. However, the study performed in each of the countries does not attempt to represent the reality of other countries within the same continent. The various locations in which this work took place have assisted me in providing insights into some similarities and differences within the Global South yet should not be seen as a definite picture of e-waste management in the Global South.

A limitation of this work comes from language challenges and the context of data collection. As Inhetveen (2012) points out, several challenges emerge from qualitative interviews that require translations. A primary challenge here refers to how the translator interprets the meanings of the information at hand. Some nuances and rationalities of the information can sometimes be lost through the translation process due to various aspects such as expressions and local language diversities. In Ghana, one interview was orally translated from Ashanti to English and vice versa. Similarly, information collected in China was translated from/to Chinese to/from English in the specific case of data collection in the formal sector. In the case of the activities in the industrial park in Guiyu, data collection was conducted by my co-author in Chinese. In Brazil, on the contrary, no translation was necessary during data collection.

Data have been collected differently within each of the three countries and resulted in various levels of data analysis. The study in Ghana focused only on the informal sector, and the study in Brazil was only on the formal sector. The China study, on the other hand, builds on one example case from each of the sectors. The reasoning behind the different datasets is the availability of data collection at the sites, which tends to be rather restricted. Unfortunately, it was not feasible to implement data collection integrating all sectors in the three countries or expanding it to more sites of interest within the limited time of this Ph.D. work. Therefore, this work does not present a comparative case study but rather a multiple-case study with datasets of various analytical levels. The work also does not represent a comprehensive study of e-waste management practices in each country analysed, as each of the three countries has the presence of e-waste management activities both in the formal and informal sectors. Instead, its goal is to shed light on some of the barriers and drivers for sustainability transitions in e-waste management by capturing primary challenges faced in various countries of the Global South.

In specific related to data collection within the formal sector, a challenge refers to obtaining access to relevant organizations. Before the start of data collection, I anticipated that some organizations might not be willing to participate in the work, which could potentially indicate a reluctance of being exposed if not operating according to legislation. Indeed, I was not granted access to some organizations that I contacted. Therefore, the results presented here are restricted to the organizations willing to disclose information on their activities, which may introduce biased results.

I also faced challenges with data collection within the informal sector, for instance, due to restricted access to data collection and the reluctance of workers to share information. In Ghana, for example, it was necessary to receive approval from the Association running the activities in Agbogbloshie before I could collect data on-site. Additionally, a reluctance of workers to share data became evident from the start of my investigations in Agbogbloshie. Fortunately, the reluctance could be mitigated by returning to the site and talking with the workers several times. In China, although I had aimed to collect primary data in Guiyu, it was unfortunately not feasible to access the site as it is highly restricted. Previous investigations by my co-author (cf. Paper IV) complemented the study in China. The aforementioned challenges illustrate the strength of this work as it is most often not trivial to get deeper insights into various sites in the context of e-waste management in the Global South.

As pointed out, only a few cases have been examined within the different sectors in each country. The study in China, for example, analysed one site within the formal sector and another within the informal sector (the latter of which relied on empirical research conducted by my co-author). The study in Brazil only examines data from four organizations in the country. The countries analysed have many other organizations present within the formal sector, as well as other sites within the informal sector. However, the cases in this work represent significant instances of e-waste management in their respective countries and provide important lessons toward sustainability transitions in the Global South. These involve, for instance, aspects that differ between the countries and sectors, as well as insights commonly found among the sectors and countries where data collection took place.

3.5 Ethical considerations

This Ph.D. work has included data collection with various agents in different environments. Therefore, it was necessary to consider several ethical aspects throughout the research process. The guidelines for research ethics by the National Committee for Research Ethics in Science and Technology (NENT, 2016) and by the National Committee for Research Ethics in Social Sciences and Humanities (NESH, 2021) have assisted in addressing some ethical challenges through the course of the work.

As mentioned in Chapter 1, a part of this work was connected to the SMART project (SMART, 2020). The research work package on “Policy coherence and the social and environmental externalities in the product life cycle of mobile phones (SMART | Phones)” of the SMART project was conducted according to ethical guidelines from the Norwegian Centre for Research Data (NSD) under project number 59894. In addition, this Ph.D. thesis has had its own NSD application. The application of this Ph.D. work was made before data collection in the three countries (i.e., Ghana, Brazil, and China) under project number 60582 and renewed in 2021 under project number 991635. The application gathered information regarding the project and how the data would be collected, stored, and used.

All the participants were informed about the research project, and informed consent was obtained before the start of data collection. “Informed consent means that researchers provide sufficient and clear information about what participation implies. The information should make clear to participants why they are asked to participate, what type of data is being collected, how it will be used, who will make use of the data, and for which purposes.” (NESH, 2021, p. 19)

Participation happened voluntarily, and the participants were informed that they could withdraw at any time from the project. Data collection of photos, videos, and audio recordings only took place with the explicit permission of the participants.

The specific case of data collection in the informal sector often involves young adults and people under vulnerable working conditions. Therefore, a focus here was on how the collected data would be used and published to preserve the privacy of the respondents.

In the case of data collection in the formal sector, some reluctance from organizations to share information that might affect their market strategy was anticipated. Therefore, the interviews were semi-structured, and the questions were adapted through each interview according to the information the respondents were comfortable in sharing.

Chapter 4

Summary of the papers

In this chapter, I provide a summary of the four papers included in the thesis. Each summary connects the paper to specific ROs of the thesis. Additionally, I present the motivation, the main research question, and the main results of each paper. An overview of the research objectives addressed by paper is illustrated at the end of this chapter.

4.1 Summary of Paper I

Schneider, A.F., 2019a. Informal processing of electronic waste in Agbogbloshie, Ghana: A complex adaptive systems perspective, in: *Proceedings of the 6th International Conference on ICT for Sustainability*. Presented at the ICT4S 2019, Lappeenranta, Finland, ISSN 1613-0073.2382, p. 8. (Best paper runner-up award)

Paper I addresses specific RO 1. The paper presents the results of field studies conducted in the metal scrap yard of Agbogbloshie, Ghana, in 2017. The focus was on the workers dismantling e-waste on the site, especially computers and mobile phones. The starting point for this study was to apply CAS theory as a tool to analyse the data collected in Agbogbloshie. Therefore, the main research question of Paper I was: How can CAS theory help in understanding the processing of e-waste in Agbogbloshie, Ghana?

The paper connected the findings with several properties present in CAS theory, specifically adaptation, non-linearity, emergence, and feedback loops. The property of adaptation was evidenced through the different ways in which e-waste was manually dismantled, depending on the design. For instance, mobile phones with screws in their composition, prevalent in older devices, were dismantled differently than the ones in which most internal components were assembled with glue. The property of non-linearity was identified through the regulation of activities according to changing circumstances in the system. Specifically, it was found that market prices had a strong effect on the input of devices and the output of components. The practice of targeting components with the highest value in the market, such as the PCBs, was a common practice.

The organization of activities on the site was connected to the property of emergence. As identified, activities in Agbogbloshie did not happen in isolation, but as a result of combined agents' behaviour. Workers performing the activities were members of an association, which functioned to self-organize the system. In addition, waves of rural and urban migration were connected to feedback loops, driving the system beyond its equilibrium state. The application of CAS theory as an analytical tool in this paper helped to explore several nuances present in the complex setting of Agbogbloshie. In addition, it gave insights into a more comprehensive understanding of the interactions among agents in e-waste management systems.

4.2 Summary of Paper II

Schneider, A.F., 2019b. Managing change in operations: The case of the wire stripping machine in Agbogbloshie, Ghana, in: *Proceedings of the 26th International EurOMA Conference: Operations Adding Value to Society*. Presented at the EurOMA 2019, Helsinki, Finland, pp. 1479–1488.

Paper II also presents results of field studies conducted in the metal scrap yard of Agbogbloshie, Ghana, in 2017. The paper also addresses specific RO 1 of the thesis. This time, the focus was on the workers processing cables on the site. A common practice for e-waste processing in Agbogbloshie was the open-air burning of cables, which causes substantial pollution and poses severe hazards to human health and the environment. Between 2014 and 2016, wire-stripping machines were installed on the site to stop the open-burning practice. The machines could process cables of different thicknesses and provide copper and plastic as the result. Nevertheless, the machines were not found in operation during the investigations in Agbogbloshie, but the open-air burning activities prevailed. Thus, the main research question for this paper was: What are the reasons for the lack of use of the wire stripping machines in Agbogbloshie, Ghana?

The interviews with workers in Agbogbloshie and with the NGO that assisted with installing the wire stripping machines provided several insights into the reasons for the prevalence of open-air burning activities. These were analysed through the lenses of the theory of constraints, a management theory that considers the performance of a system to be limited by one or more factors. This paper focused on identifying these factors, here denoted as constraints. Three reasons were identified for the non-use of the machines. The first relates to the cost of electricity involved in operating the machines. While no final cost was directly allocated from the workers to perform the open-air burning, they needed to pay for the electricity consumed when using the machines. The second reason is the long time required to strip the cables with the machines compared to the open-air burning activity. Third, a lack of trust in the copper yield was identified, specifically in the case of the machine for thin cables that delivered copper chopped into small pieces as the result. All reasons translate into managerial-policy constraints, namely financial, policy, and market constraints. The paper provides suggestions for further exploration, such as seeking to optimize the machines toward faster processing and promoting educational campaigns to explain the functioning of the wire-stripping machines.

Applying the theory of constraints as an analytical tool to this paper assisted in focusing on a specific process within e-waste management (in this case, cable processing) while maintaining a systemic perspective applied throughout the research. In addition, the theory helped to consider some challenges involved with operational change, especially concerning the transfer of technologies in an international context.

4.3 Summary of Paper III

Schneider, A.F., Aanestad, M., Carvalho, T.C. Exploring barriers in the transition toward an established e-waste management system in Brazil: A multiple-case study of the formal sector. Under revision for an international journal after first-round review.

Paper III addresses specific RO 2 of the thesis. The paper presents results of field studies conducted at four recycling organizations in Brazil, in 2018. Data were checked for updates with the organizations in 2022. The motivation for writing this paper was to investigate possible reasons for the low presence of e-waste management activities within the formal sector in the country. Therefore, the main research question of this paper was the following: What are the main barriers to the growth of the formal sector in the transition toward an established e-waste management system in Brazil?

The paper provided a perspective of organizations with diverse levels of e-waste management operations. Transition management was the main theoretical lens guiding this study. Specifically, the MLP (cf. Chapter 2) was applied as an analytical framework to identify the main perceived barriers from the four organizations. The paper took a larger scope of analysis than Paper I and Paper II. It addressed, for instance, the main aspects of the legal framework that regulates e-waste management in Brazil. In addition, it established connections among different levels within the MLP framework.

Data were analysed through thematic analysis and categorized into four regime dimensions, each presenting perceived barriers at the meso-level. Within the technology & infrastructure dimension, the following barriers were identified: a lack of comprehensive processing infrastructure, a lack of processes for the complete separation of metals, and a high recycling cost for certain e-waste types. In the dimension of economy & market, a high reverse logistics cost, a lack of knowledge from the suppliers in handling e-waste, and a lack of transparency throughout the supply chains were the barriers identified.

The results show a lack of environmental awareness for disposal, concern with data security, and cultural resistance to repaired and recycled products as the barriers within the society & culture dimension. Finally, the barriers identified in the policy dimension comprise a lack of financial incentives, lack of policy integration, high bureaucracy for governmental initiatives, and lack of standardization and labelling in the appliances.

At the micro-level, the paper highlights initiatives from the four organizations illustrating how some barriers may be tackled. A take-back initiative by a public university, a sampling process performed in the country, a planned collection through voluntary collection points, and a complete process resulting in alloys are discussed as positive examples in transitioning toward more sustainable practices. The application of the MLP framework to this paper assisted in establishing connections among different levels of analysis. In addition, it helped to provide new insights for future policy implementation to strengthen the formal sector in Brazil.

4.4 Summary of Paper IV

Schneider, A.F., Zeng, X., 2022. Investigations into the transition toward an established e-waste management system in China: Empirical evidence from Guangdong and Shaanxi. *Current Research in Environmental Sustainability.* Vol. 4, No. 100195, pp 1–10. https://doi.org/10.1016/j.crsust.2022.100195

Paper IV addresses specific RO 1 and 2. The paper presents results of field studies conducted in China, specifically at a recycling organization in Xizhangbu in Shaanxi province, and at the industrial park in Guiyu in Guangdong province. China is the largest generator of e-waste in the world and is among the countries affected the most by previous e-waste importation and unsustainable recycling practices conducted by the informal sector. Nevertheless, the country has had considerable advancements in e-waste management legislation. This paper started from the assumption that e-waste management in China is currently going through a transition and with the motivation of further exploring its direction and the ways in which this transition is taking place. Therefore, the main research question of Paper IV was: How has the implementation of policies impacted a transition toward an established e-waste management system in China?

The paper addresses the recycling activities conducted by both the informal sector (through the example case of Guangdong) and the formal sector (through the example case of Shaanxi). Transition management was the main theoretical lens guiding the study. Specifically, the x-curve of transition dynamics was applied as an analytical model to the development of e-waste management in China. Just as in the case of Paper III, this paper also takes a larger scope of analysis than Paper I and Paper II. The main advancements of legislation related to e-waste management in the country are presented and connected to the activities within the informal and formal sectors.

The results show that external forces, such as legislation and the market, have the power to shape the e-waste management system in China. The driving force of legislation is demonstrated through the implementation of industrial parks, as well as through the increase of recycling activities by the formal sector after subsidies allocated by the government to licensed companies took place. The market is also identified as a driver, for instance, through the focus on the recovery of certain metals. In addition, corporate social responsibility (CSR) strategies are shown to be fundamental for recycling specific appliances, as in the case of fluorescent lamps.

Despite the documented advancements, several challenges persist. For instance, certain appliances are not addressed by legislation or not incorporated in the policy that allocates subsidies to licensed recycling companies. Thus, these appliances are often not collected through formal channels. Another challenge identified is a disconnection between the policies and the activities of the informal sector. Further study on the viability of extending the coverage of subsidies to more e-waste categories is suggested, as well as the implementation of more inclusive approaches to include the knowledge of previous informal agents in the emerging regime.

Applying the x-curve model to this paper has assisted in exploring the nuances of transition dynamics, such as the co-existence of multiple regimes (in this case, the informal and formal sectors). As a result, the study provides insights into the importance to (and some possibilities for) considering both sectors in the transition toward an established e-waste management system.

4.5 Overview of research objectives addressed by each paper

As presented in Chapter 1, this Ph.D. thesis has the following specific ROs:

RO 1. To identify barriers and drivers experienced by the informal sector in transitioning to established e-waste management systems.

RO 2. To identify barriers and drivers to the growth of the formal sector in the transition toward established e-waste management systems.

The following Table 5 summarizes which of the research objectives are addressed in each of the four papers.

Table 5. Overview of the ROs addressed by paper.

PAPER	ADDRESSES
I	RO 1
II	RO 1
III	RO 2
IV	RO 1 and 2

The studies presented in the papers provide a wealth of insights that address the ROs of the thesis by identifying various barriers and drivers experienced by the informal and formal sectors. These are discussed in Chapter 6. The following Chapter 5 presents the analysis, which focuses on the identification of various service regimes in the two sectors of the economy, and misalignments across the three systems.

Chapter 5

Analysis

The combination of papers in this Ph.D. thesis provides several insights into e-waste management, specifically in Ghana, Brazil, and China. The work perceives e-waste management in each country as a system with different agents and multiple rationalities. In this chapter, I present core findings across the three systems by addressing multiple analytical levels.

According to the MLP framework (cf. Chapter 2), the macro-level relates to landscape developments that are external to but influence the e-waste management systems. More specifically, such developments pressure the existing regime practices, which, in turn, may create opportunities for the emergence of niche innovations (Geels, 2019). The widespread business models relying on elevated consumption of electronic products are one example that influences the generation of e-waste and, thus, impacts the e-waste management systems. Such business models are driven by strategies of obsolescence, such as planned obsolescence (e.g., a battery that significantly loses capacity after a short time) and perceived obsolescence (e.g., due to social norms, marketing of consumerism, and throwaway culture). These strategies motivate consumers to replace their electronics after short periods, increasing the amount of e-waste generated.

The design of electronics is another example at the macro-level that influences the e-waste management systems. More specifically, a manual dismantling process may vary depending on the design of the electronic device. As pointed out in Paper I, for example, the manual dismantling of mobile phones can better separate components assembled with screws than components assembled with glue, even though the first demands more time for the process.

The micro-level of the MLP framework relates to the niche. Innovations typically emerge within the niche, and often face a high degree of uncertainty and trial and error, in which only some successfully develop into regime practices (Geels, 2019). The installation of wire stripping machines in Agbogbloshie (as addressed in Paper II) is one example, which is here perceived as an unsuccessful innovation. The machines, capable of processing a wide range of cable sizes, were installed in Agbogbloshie to tackle the open-air burning of cables performed in the area. Nonetheless, the cable burning persisted by the time of the investigations on the site. Different pressures from the meso-level, which are addressed in the paper, have influenced the failure of this niche innovation.

The findings at the meso-level represent the regime and are the focus of the following analysis. First, I describe various service regimes in different analytical layers identified from the investigations in the three countries. Second, I identify misalignments present within and between service regimes.

The service regimes are categorized into five dimensions (as previously defined in Chapter 3): technologies & infrastructures, organizational mode, rationale & meaning, internal coordination, and legislation & public financing. These dimensions may represent barriers or drivers toward transitions and are discussed in Chapter 6.

5.1 Identification of service regimes in e-waste management

The conceptual framework proposed by van Welie et al. (2018) expands the traditional view of a socio-technical regime as strictly monolithic (i.e., a sectoral regime with one dominant service regime). Instead, the authors propose a more nuanced analysis in which multiple services can co-exist and interact within one sector.

This work applies the framework from van Welie et al. (2018) while considering the complexities inherent to e-waste management in the Global South. Here, two layers are included in the analysis: the sectors of an economy (i.e., the informal and formal sectors) and the stages of e-waste management (classified in this thesis as: collection, pre-processing, and end-processing).

Figure 15 illustrates the analytical layers included in the regime that are considered in this work. Following the framework presented in Chapter 2, the white circles represent the service regimes, the smaller inner circles the regime dimensions, and the lines between the various circles the alignments between dimensions.

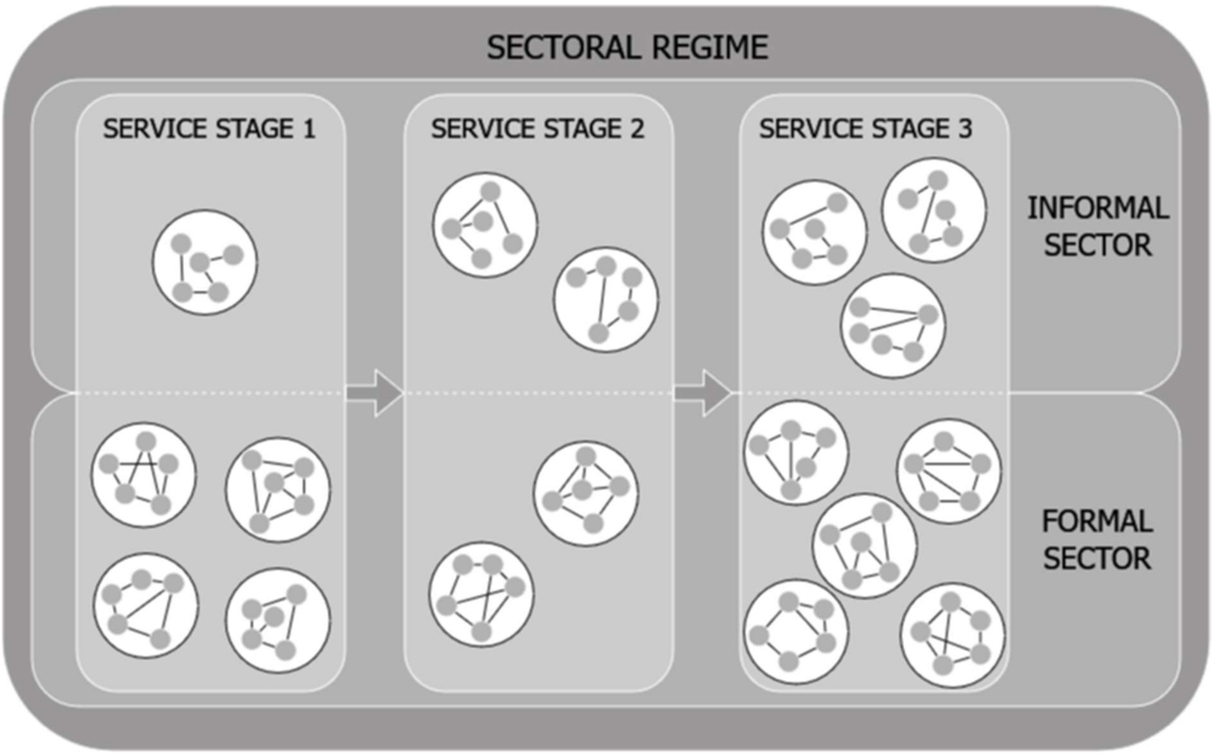

Figure 15. The various analytical layers identified within the e-waste management regime in the Global South (extended version based on van Welie et al., 2018). The three depicted service stages denote collection, pre-processing, and end-processing of e-waste.

The analysis that follows considers the e-waste management as the sectoral regime and identifies various service regimes included in the three stages, both in the informal and formal sectors. The service regimes identified represent various levels of institutionalization within the MLP framework. While some services seem better established within the sectoral regime, others are closer to being perceived as a niche innovation.

5.1.1 Collection

The first stage of e-waste management represents the collection of e-waste. Within the informal sector, a primary service regime identified in such a stage is the *individual collection*. Here, specific agents (also known as "scavengers") often perform the activity individually, collecting e-waste from various sources (e.g., households in the neighbourhood and repair markets).

Although with some variations in the service offer, the informal sector represents the predominant path for e-waste collection in several countries of the Global South, as evidenced in Ghana and China. In Ghana, for instance, e-waste collection by the informal sector was organized by an association (cf. Paper I), which divided the work hierarchically and pre-financed novice workers for collecting e-waste. This kind of self-organizing mechanism fostered a growth in the number of agents in the e-waste management system in the country (in this case, specifically on the number of workers focusing on various service stages in Agbogbloshie).

In the formal sector, one service regime relates to the *take-back schemes* from large electronic producers. Paper IV exemplifies this through a recycling company in Shaanxi that installed equipment to process EoL fluorescent lamps in 2016. The company receives financial incentives from certain producers, which makes it financially viable to recycle the appliances.

Another service regime in the formal sector is identified through the *business-to-business* (*B2B) collection* in Brazil (cf. Paper III). For example, an e-waste management company collects directly from organizations with EoL corporate equipment. Such collection service demands different arrangements, especially considering the amount of e-waste handled.

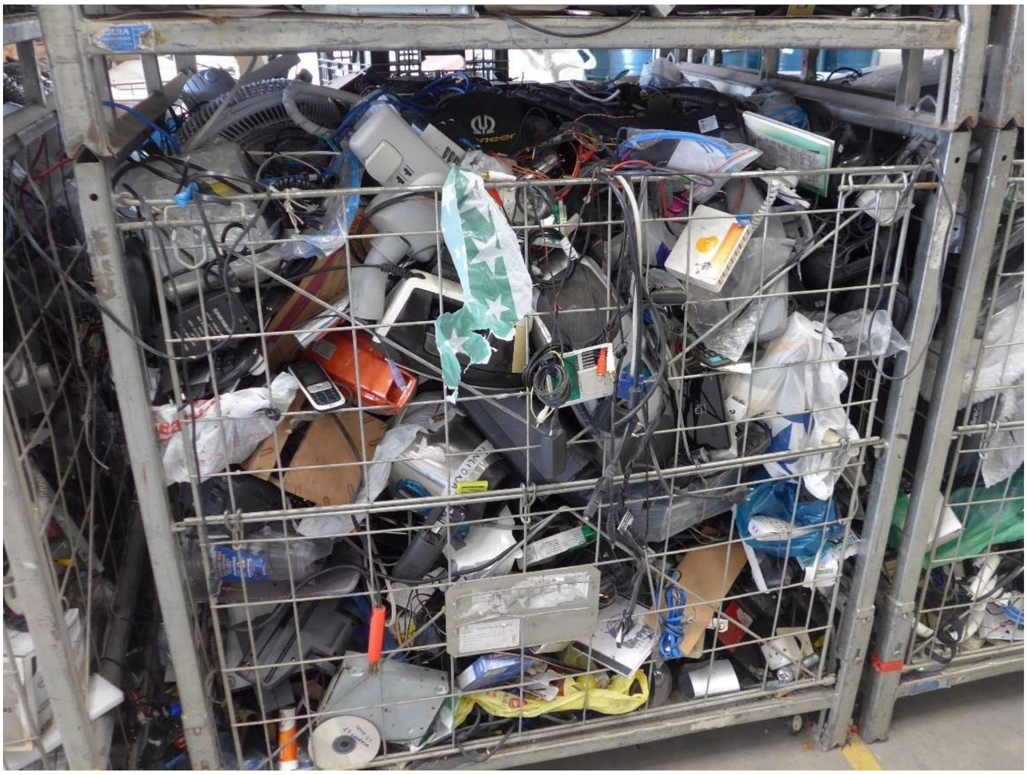

Figure 16. Unsorted batch from one of the voluntary collection points by a recycling company in Brazil.

Service regimes also appear as planned collection through *voluntary collection points*, as identified in another Brazilian company (cf. Figure 16). The collection points installed in several locations enable the company to have a cost-efficient collection. Specifically, the company can reach a wide collection area and reduce logistic costs by optimizing the pick-up routes.

Additionally, *collection centres* implemented specifically for e-waste represents another service regime. One example is an initiative performed by a centre that is part of a public university in Brazil. The centre has a partnership with recycling companies that support various social projects, such as training programs for low-income young adults. In return, the centre collects and forwards appliances to the aforementioned recycling companies.

5.1.2 Pre-processing

The second stage of e-waste management is the pre-processing. In the informal sector, one service regime identified refers to the *manual dismantling in the open air or adapted shelters*. As evidenced in Agbogbloshie, workers tend to prioritize the dismantling of the most valuable components and categorize the various types (cf. Figure 17). Here, it is worth highlighting an intersection between the informal and formal sectors, namely the intermediation through specific agents in the system (known as "middlemen") that forward the sorted PCBs to companies that export the material for the end-processing.

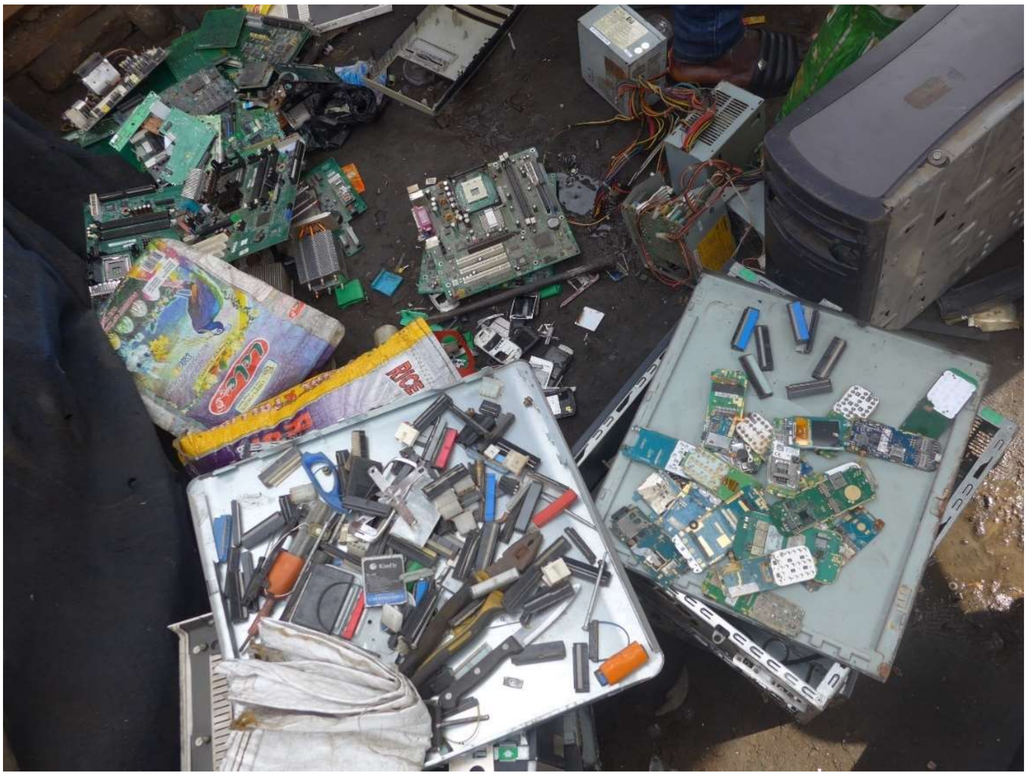

Figure 17. Separation of computer PCBs (in the back-left side) from mobile phone PCBs (in the front-right side) during the manual dismantling in Agbogbloshie, Ghana.

In Guiyu, the industrial park provides an intermediate solution for pre-processing e-waste by the informal sector, specifically through the *manual dismantling in workshops*. The park includes various connected workshops that each focus on specific activities for e-waste processing. The sorting of dismantled components is a common practice after the manual dismantling, as evidenced in Agbogbloshie and Guiyu.

In the formal sector, a *manual dismantling in facilities* represents a service regime. In such a setting, a sorting is usually performed prior and after the manual dismantling. However, some variations were highlighted by organizations in Brazil on whether and how performing a sorting and manual dismantling. Such can be due to various factors, for instance, market prices of specific components, labour costs, and the amount of e-waste received.

Figure 18. Variety of grained-material mixes obtained through shredding at a recycling company in Brazil.

Mechanical treatment appears as another service regime at the pre-processing stage performed by the formal sector and is often performed using a shredder. In Brazil, this was identified as part of different strategies. For instance, one company performs a sampling process of e-waste before exporting the material for end-processing. A part of the process involves a shredder that destroys the appliances. The company analyses the shredded material to quantify the presence of specific metals in each batch of e-waste and pay the suppliers accordingly. Another strategy identified relates to a company that processes the e-waste with a shredder and forwards the material (as shown in Figure 18) to foundry companies in the country for a smelting processing that results in alloys of different kinds. In the case of Shaanxi Anxin, cathode-ray tube (CRTs) are processed through mechanical treatment to refine the lead.

5.1.3 End-processing

The third stage of e-waste management (cf. Figure 15) represents the end-processing. In the informal sector, the *open-air burning of cables* is an example, as identified in Agbogbloshie (cf. Paper II). Like the case previously mentioned of PCBs dismantled in Agbogbloshie, the processing of cables is another example that illustrates an intersection of service regimes between the informal and formal sectors. Specifically, the copper extracted from the cables is forwarded by “middlemen” to smelters in the country, therefore entering the formal sector.

The installation of wire stripping machines in Agbogbloshie, perceived in this analysis as a niche innovation, has aimed at phasing out the hazardous open-air burning of cables. However, as the implementation was unsuccessful (by the time of the observations), the open-air burning persisted as a service for the processing of cables (cf. Paper II).

The *high-temperature separation of components from the PCBs in workshops*, as identified in Guiyu, represents another service regime as an intermediate solution for the informal sector. Here, a desoldering process removes the solder and separates some components from the PCBs before the end-processing stage.

The *open-air dumping* also represents a service regime within the informal sector. Components of inferior value are often discarded on-site, as illustrated by the example of computer chassis spread within the area of Agbogbloshie. While some components tend to be picked up by “scavengers”, others with insignificant value often remain in the scrap yard.

In the formal sector, a prevailing service regime in the Global South is the *export of specific components for end-processing*. This is exemplified through the export of PCBs by most Brazilian companies for recovering precious metals. However, an initiative worth highlighting is a *smelting process resulting in alloys*. This innovative approach addresses the lack of comprehensive national processing infrastructure. The process, entirely performed on national ground, does not separate all the metals but results in different alloys used for varied purposes.

In China, however, the usual is to recycle on national ground. In the case of Shaanxi Anxin, for example, a *high-temperature separation of components from the PCBs in facilities* is performed. With a similar aim as the separation mentioned earlier by the informal sector, this happens within a closed area. Additionally, *pyrometallurgy* is one of the processes adopted for further processing. Such a process chemically separates metals through high temperatures, allowing for the recovery of specific metals.

The *final disposal in industrial landfills* represents another service regime performed by the formal sector. For example, alkaline batteries, which have high recycling costs associated, are often sent to industrial landfills in Brazil instead of undergoing a recycling process.

5.2 Identification of misalignments

The conceptual framework from van Welie et al. (2018) allows for the identification of various service regimes within a sector. Furthermore, it provides a more nuanced analysis to explore misalignments at various levels. “Misalignments within service regimes cause ineffective ways of providing and accessing a service, while misalignments between service regimes are a result of a lack of coordination in the sector” (van Welie, 2019, p. 19).

This work has categorized various service regimes into two layers: stages of e-waste management and sectors of an economy (cf. Figure 15). Misalignments may appear in different combinations within and between such layers. The analysis that follows identifies misalignments between dimensions within a service regime, and between service regimes (in the same and between different stages of e-waste management). The following highlights examples of such misalignments in the informal sector, the formal sector, and in both sectors of the economy.

5.2.1 Misalignments within a service regime

“Alignments at the service regime level are determined by the complementarities between different service regime dimensions” (van Welie, 2019, p. 34). The lines between the small grey circles in Figure 15 illustrate such alignments. Misalignments within a service regime occur when specific dimensions in such a regime are not well-aligned.

An example of misalignment within a service regime in the informal sector is the common practice in which workers target specific components at the pre-processing stage. Here, the service provided, as evidenced through the manual dismantling in the open air or shelters in Agbogbloshie, often disregards less-valuable components. Specifically, this illustrates a misalignment between the *rationale & meaning* dimension (i.e., the values and beliefs guiding the provision of the service) and the *legislation & public financing* dimension.

Misalignments within a service regime also occur in the formal sector, for instance, at the collection stage when incorrect waste categories are disposed of at voluntary collection points for e-waste. This exemplifies a misalignment between the *organizational mode* dimension and the *internal coordination* dimension, in which the strategies for providing the service are not well communicated to the users. Such misalignment results in inefficiency reflected in extra financial costs for the service provision (e.g., transporting and sorting incorrect waste categories).

Figure 19. E-waste recycling in Agbogbloshie, Ghana. Left half: open-air burning of cables in the smoke plume. Right half: dismantling area.

Some specific misalignments within a service regime appear in both informal and formal sectors. Here, it is worth highlighting a misalignment at the end-processing stage of e-waste management, specifically between the *technologies & infrastructures* dimension and the *organizational mode* dimension. Such misalignment appears in different services within both sectors. In the informal sector, for example, the persistence of the open-air burning of cables (as shown in the left half of Figure 19 and in Paper II) illustrates an inefficient service provision with the recovery of copper and the loss of plastic material, which incurs significant environmental hazards. In the formal sector, the final disposal in industrial landfills for alkaline batteries also represents an inefficient service provision without recovering the materials from such batteries.

5.2.2 Misalignments between service regimes

Misalignments between service regimes result from an incoherent sectoral regime, in which alignments between different services are either weak or completely missing. According to van Welie (2019, p. 218), improving the "alignment between service regimes requires more coordination among different service providers, adequate sector planning, and optimization of the complementarities between different services." The following highlights examples of misalignment between service regimes in two layers: within the same stage and between different stages of e-waste management.

In the layer within the same stage of e-waste, an example from the informal sector is the difficulty of successfully implementing the wire stripping machines in Agbogbloshie. Here, the preconditions and strategies for providing the prevailing service of open-air burning of cables appear misaligned with the ones for providing the service with the machines. Aspects such as the costs of operating the machine and the time for processing cables play a decisive role in the reluctance to change processes (cf. Paper II).

Figure 20. Recycling of CRTs from televisions in a company in China. Left: Machine for the mechanical treatment. Right: Refining of lead from the recycling process.

In the formal sector, the policy in China that allocates financial incentives for dismantling specific appliances (e.g., CRT televisions, as shown in Figure 20) illustrates misalignments within the same stage. As some appliances are not yet covered by the subsidies, the service for dismantling and further processing such appliances falls short compared to the appliances covered by the policy.

Misalignments also occur within the same stage of e-waste management between the informal and formal sectors. For instance, the financial incentives in China are allocated only to licensed companies. This translates into extra costs for agents from the informal sector to perform their services compared to agents in the formal sector.

Various misalignments occur in the layer between service regimes of different stages of e-waste management. For instance, in the informal sector, the open-air dumping of less-valuable components evidenced in Agbogbloshie illustrates a misalignment between the stages of pre- and end-processing. Here, components with the highest value (e.g., PCBs) are often the target of manual dismantling in the open air or shelters before being sent to end-processing. However, components perceived as having insignificant value for the workers tend to remain in the scrap yard instead of being sent for end-processing.

In the formal sector, the lack of gold recovery in the case of Shaanxi Anxin evidences a misalignment between the collection and the end-processing stage. Here, the amounts of e-waste collected by the company are not significant enough to cover the elevated costs for extracting the gold in the end-processing.

Misalignments between stages of e-waste management also occur between the sectors of the economy. For instance, the resistance of companies in Brazil to collaborate with agents in the informal sector through the different stages of e-waste management demonstrates a misalignment of values guiding the provision of services between the two sectors.

Chapter 6

Discussion

In this chapter, I focus on the main contributions of this Ph.D. thesis. First, I link the main results to the research objectives of the work, as presented in Chapter 1. Second, I discuss possible transition pathways for e-waste management based on the results in the three countries. Finally, I present the main contributions of the work to the sustainability transitions research field.

6.1 Identification of barriers and drivers in e-waste management

The primary aim of this work was divided into two specific ROs. The first focused on identifying barriers and drivers experienced by the informal sector in transitioning to established e-waste management systems, and the second focuses on barriers and drivers to the growth of the formal sector in the transition toward established e-waste management systems. Paper I and Paper II address the specific RO 1, and Paper III is specifically targeted at RO 2. Paper IV addresses the combination of specific RO 1 and RO 2. This sub-chapter focuses on linking the main results to the ROs of this Ph.D. thesis, which are addressed together.

The referred barriers and drivers depict phenomena observed at the meso-level, that is, the regime practices as presented in the MLP framework (Geels, 2019). Here, the focus is on aspects that pressure the existing systems, acting either as drivers or barriers toward transitions. These are categorized into the following regime dimensions (as previously defined in Chapter 3): technologies & infrastructures, organizational mode, rationale & meaning, internal coordination, and legislation & public financing. It is worth highlighting that this categorization is to some extend subjective, as many of the findings have connections to more than one dimension.

The field studies in the three countries provided several insights into critical barriers and drivers for transitions in e-waste management. Through the investigations in Ghana, it was possible to highlight workers' perspectives within the informal sector, while the findings in Brazil illustrate perspectives from organizations within the formal sector. The results from China present a combination of the two sectors. The empirical findings comprise diverse insights from different service regimes (highlighted in italic in the following) as well as various realities and cultures, which guides and enriches the discussion.

6.1.1 Technologies & infrastructures

The studies in the three countries have shown that e-waste management is performed by various agents in the respective systems. Agents focus on different services and stages of e-waste management (e.g., collection, pre-processing, and end-processing). The result of an e-waste management system is, therefore, not the outcome of isolated behaviour, but of the several services performed in combination and their interaction. Therefore, the service regimes are highly influenced by the processing infrastructure available within the related sectoral regime.

Within the three countries analysed, it was found that none currently has a comprehensive infrastructure for e-waste processing. In this context, a comprehensive infrastructure is understood as one capable of conducting complete processing (i.e., pre- and end-processing) of e-waste at a level that balances with e-waste generation. This confirms previous studies showing that indeed, only few countries currently have such infrastructure for conducting complete processing of e-waste at high yields (Hagelüeken and Corti, 2010; Hewitt et al., 2015).

Service regimes such as the *open-air burning of cables* (cf. Paper II) and the *manual dismantling in the open air or shelters* performed in Ghana (cf. Paper I) illustrate the lack of a comprehensive processing infrastructure in the informal sector. Indeed, such rudimentary services are often identified as such in the literature also in other countries of the Global South (Awasthi and Li, 2017). Several challenges persist also in the e-waste processing infrastructure in China (as presented in Paper IV), specifically concerning the prevailing challenges associated with the activities in the informal sector.

The lack of a comprehensive processing infrastructure pressures the system and can represent a major barrier to sustainability transitions also in the formal sector. In Brazil, it was shown through Paper III that, overall, e-waste recycling continues to focus primarily on the pre-processing on national grounds and the *export of specific components for the end-processing*, which is in accordance with existing literature (de Albuquerque et al., 2020; Xavier et al., 2023).

At the same time, the lack of infrastructure can represent a driver once it opens for the emergence of niche innovations. Particularly through a transition period, innovative approaches – even if they present intermediate solutions – are extremely relevant to move the system beyond its equilibrium state, potentially in the direction of the desired transitions. One example is the implementation of a *smelting process resulting in alloys* from e-waste in Brazil (cf. Paper III). The findings from this study extend the overall existing literature by presenting an innovative approach in the country.

Manual processes tend to predominate in emerging economies due to several aspects, such as a lack of infrastructure and especially the low labour costs associated with manual processing in unregulated settings. Overall, the mechanization of processes for e-waste recycling is a common trend in countries that have substantially advanced the infrastructure for e-waste processing. This is addressed in the literature, for instance, by Schluep et al. (2009), as well as evidenced in Brazil (cf. Paper III) and China (cf. Paper IV). With the growth of regulated activities in the formal sector, both countries have undergone several transformations regarding e-waste management, specifically a gradual shift from manual to mechanical processes. This shift was evidenced, for instance, in organizations in Brazil that previously performed most processes manually and have either implemented a *mechanical treatment* or outsourced the service to organizations with the required machinery installed.

6.1.2 Organizational mode

The organizational mode includes the preconditions and strategies for providing the service. Within this dimension of the regime, certain aspects were identified as pressuring the existing e-waste management systems at different levels. Market prices of various CRMs obtained through e-waste recovery, for instance, seem to motivate the recycling of certain appliances and specific components.

Market prices can act as a barrier to sustainability transitions, especially in unregulated recycling settings as observed in the informal sector. As shown in Paper I, workers in Agbogbloshie (Ghana) would target specific components from e-waste through the *manual dismantling in the open air or shelters*, a practice commonly referred to as cherry-picking (Baldé et al., 2022). This practice encompasses several environmental hazards because the remaining components are often not given proper treatment and destination. Components that are often targeted in a cherry-picking practice include, for instance, the PCBs.

However, practices such as the so-called cherry-picking were found to be highly organized in Agbogbloshie. For example, PCBs were not only a primary focus of dismantling but also categorized according to type. The PCBs from computers, for example, were sold separately from the PCBs from mobile phones due to different market prices obtained for the various types of PCBs. Such manual dismantling and separation of various PCB types leads to higher quality of feedstock and levels of material recovery compared to processes solely relying on mechanical dismantling (Hagelüeken and Corti, 2010).

The *open-air burning of cables* in Agbogbloshie is another service regime exemplifying cherry-picking, in which market prices act as a barrier to sustainability transitions. Here, workers focus on obtaining the copper from the cables without accounting for the plastic material, as well as disregarding the environmental and health hazards associated with the open-air burning practice (as described in Paper II).

Market prices can also act as a driver for sustainability transitions. Especially in regulated recycling settings illustrated by the formal sector, market prices can motivate the emergence of specific agents, such as recycling companies focusing on pre- and end-processing. In this context, it is worth highlighting the complexity of market dynamics. As shown in Paper IV, for instance, one company in China would recover certain metals from PCBs having a lower market price (e.g., cobalt and copper) than other non-recovered metals (e.g., gold). In this concrete example, this was because gold is only present in small amounts in PCBs, as well as costly to recover. Therefore, recovering metals such as gold would be financially viable for the company only if large amounts of PCBs were recycled.

Paper III presents another example of a company in Brazil in which market prices determine how e-waste is processed. In this specific case, e-waste undergoes a *mechanical treatment* with a shredder, resulting in various grained-material mixes. The mixes are sent to foundry companies in the country, resulting in alloys of different kinds. The types of grained-material mix obtained (and, consequently, the types of alloys as end-product) directly reflect the components inserted in the shredder. The decision to invest in manual separation of specific components before shredding depends mainly on the costs associated with the entire process, including labour costs for manual pre-processing compared to the prices received for the resulting mixes.

The aforementioned examples illustrate how market prices can motivate the emergence of agents focusing on various levels of processing. Such initiatives, although not optimal for the recovery of various metals, are highly relevant in a period of transition. Nonetheless, they also evidence the importance of implementing large-scale recycling facilities in an established system, which would be capable of recovering various metals and achieving a high level of material recovery.

6.1.3 Rationale & meaning

The rationale & meaning dimension represent the values and beliefs guiding the provision of the service. These translate into, for instance, traditions, and habits undertaken by the various services identified. In some cases, these can be interlinked with regional differences and educational levels.

In the informal sector, certain factors such as the level of education and certain beliefs play a significant role in the context of the cable processing. More specifically, such factors seem to hinder the widespread use and development of wire stripping machines installed in Agbogbloshie, and instead influence the persistence of the *open-air burning of cables*. As observed in Paper II, one reason for the lack of use of the machines is a mistrust in the copper yield delivered by the machines. Ultimately, this contributes to the reluctance to adopt this technology. This example highlights the importance of accounting for regional and societal differences when transferring technologies (in this case, the wire stripping machine) to different geographical settings.

The CSR initiative for recycling fluorescent lamps in the Shaanxi province in China, as part of *take-back schemes* (cf. Paper IV), illustrates a driver connected to the rationale & meaning dimension in the formal sector. In this regard, it is worth highlighting that recycling fluorescent lamps is particularly challenging due to the high operational costs and the low market prices obtained for the recycled materials (Peng et al., 2014). Therefore, the integration of recycling costs by large production companies of fluorescent lamps as part of CSR strategies presents a strong driver for recycling such appliances.

6.1.4 Internal coordination

Several aspects related to the provision of services link to the dimension of internal coordination, which represents the communication and interactions among agents within the service regimes. A significant aspect worth highlighting here is the environmental awareness toward the disposal of devices once reaching the EoL phase. The behaviour of consumers directly reflects the possibilities for e-waste collection and, consequently, e-waste recycling. This aspect has strong connections with the landscape developments mentioned in the previous chapter, such as the prevailing business models motivating consumers to change their devices after a short time frame.

Improving e-waste collection is a critical aspect to address in the transition to established e-waste management systems. Indeed, previous studies such as Liu et al. (2019) have identified a tendency among consumers of storing devices that are no longer used at home. The incorrect sorting of e-waste is another practice that hinders efficient e-waste collection. The sorting of e-waste as regular recyclable household waste, for instance, is a common practice in Brazil, especially in the case of smaller devices (de Oliveira et al., 2020; Rodrigues et al., 2020; Santos and Ogunseitan, 2022). However, the system for regular recyclable household waste in the country does not include e-waste, which is managed through a separate collection system. These practices disrupt a crucial part in the lifecycle of electronics, namely, the collection phase, and consequently impede the recovery of CRMs. Moreover, they hinder the transition toward a circular economy, as discussed in Chapter 1.

As addressed in Paper III, a lack of environmental awareness for disposal is a major barrier identified in the formal sector, both in the B2B and in the business-to-consumer (B2C) market in Brazil. In the *B2B collection*, the lack of knowledge from supplying companies on how to properly store and handle e-waste before forwarding it for recycling is a concern. In addition, the B2C market poses several challenges for e-waste collection because it heavily depends on the willingness of consumers to sort and deliver the e-waste in designated services, such as the *voluntary collection points* and *collection centres*. Unfortunately, voluntary collection points for e-waste are often misused containing other types of waste. This incurs extra costs for agents focusing on collection.

A concern with data security is also identified as a barrier for collection. This represents a major reason for consumers to store small EoL appliances at home instead of disposing of them in the appropriate collection points in China, as addressed in Paper IV. In addition, it was mentioned by organizations in Brazil that many computers are collected without the hard disk drive, or with the component being destroyed (cf. Paper III). These insights may pave the way for improvements aimed at reducing such concerns related to data security. These could be tackled, for instance, through better communication from the service providers concerning data destruction methods.

An increase in environmental awareness can have direct implications for the behaviour of diverse agents in a specific system, which can act as a driver for sustainability transitions. For example, an increase in consumers' environmental awareness may reflect in consumers' choices through different life cycle phases of electronics (e.g., purchasing choices and consumption patterns). Specifically, consumers may deem it important to acquire electronics from producing companies that include the electronics EoL phase into their business model, and in a transparent way. This, in turn, might influence companies' strategies toward CSR initiatives. As shown in Paper IV, *take-back schemes* (which can be motivated by different reasons) seem to have a fundamental role in shaping the emerging system for certain appliances in China (in this case, fluorescent lamps).

6.1.5 Legislation & public financing

Within the legislation & public financing dimension, several aspects have been identified at the meso-level, which pressure the system, especially the micro-level, for the emergence of niche-innovations. These pressuring aspects can act either as drivers or barriers toward transitions. Some examples are discussed in the following.

Paper III and Paper IV have addressed the legislative framework for e-waste management in Brazil and China, respectively. In these papers, it was shown that recent advancements in legislation had a strong impact on fostering transitions toward more established e-waste management systems in both countries.

The implementation of a national initiative for managing the reverse logistics and recycling of certain e-waste categories in Brazil (cf. Paper III) represents a driver to strengthening the recycling services in the formal sector. This initiative seems particularly relevant for attending the B2C market through installing several *voluntary collection points* in the country. On the other hand, the lack of financial incentives for the recycling activity in Brazil, and the need for recycling companies to pay fees for transporting e-waste through different regions, represent a barrier for the current activities, as well as for the emergence of niche innovations within the formal sector in Brazil.

In China, legislation advancements have also shown significant results in strengthening recycling activities within the formal sector (cf. Paper IV). Specifically, the subsidies implemented through a Fund policy in the country appear to act as a driver for the growth of recycling companies focusing on appliances covered by the subsidies. The policy allocates financial incentives to licensed companies for the *manual dismantling in facilities* for certain appliances. This has resulted in the appearance of new agents in the e-waste management system of China, such as companies focusing on pre-processing that directly benefit from the subsidies. In addition, new companies have emerged that focus on the end-processing and treat the material received from companies focusing on pre-processing. Hence, these companies benefit indirectly from the subsidies.

Despite the advancements in legislation, a lack of integration between the informal and formal sectors remains. For instance, in Ghana, the recycling activities carried out by the informal sector in Agbogbloshie were found to be conducted without basic work standards. A precarious work environment, a lack of use of personal protective equipment, and long working hours are some of the aspects mentioned in Paper I.

In China, legislation has advanced significantly in strengthening activities within the formal sector (as shown in Paper IV). However, there seems to remain a disconnection between policies and the integration of the informal sector, which represents a barrier to sustainability transitions. The implementation of the industrial parks, particularly as shown in the case of Guiyu (in Guangdong province), represents efforts to regulate activities in the informal sector. Services such as the *manual dismantling in workshops* and the *high-temperature separation of components from the PCBs in workshops* are among the ones performed in the industrial parks. Nevertheless, several challenges remain to achieving effective integration of these agents in the emerging sectoral regime.

Integrating the informal and formal sectors remains a challenge also in Brazil. Paper III highlights that the presence of non-compliant cooperatives that operate without proper working conditions and correct documentation represents a barrier to collaborations with organizations within the formal sector. It is worth highlighting though that cooperatives complying with the norms represent a powerful driver for integrating informal agents into established e-waste management systems (ILO, 2014).

Many findings from this work reinforce results from previous transition studies within the Global South. Specifically, the work identifies a strong presence of the informal sector in e-waste management, often associated with complex power dynamics and social inequality. In aiming for just transitions within countries of the Global South, it is essential to consider both the informal and formal sectors (Ramos-Mejía et al., 2018; Swilling and Annecke, 2012) when tackling the policy dimension.

6.2 Transition pathways for e-waste management

Transitioning toward established e-waste management systems is critical to achieving more sustainable systems. These transitions are highly complex, as they depend on many agents with various rationalities. Identifying barriers and drivers as presented in the previous subchapter has a role in designing transition pathways. This subchapter focuses on critical aspects to consider when steering the desired transition in e-waste management in the Global South, specifically: integrating agents from the informal sector into the emerging regime, strengthening activities within the formal sector, advancing overall policies on the topic, and accounting for the diversity of service provision in the Global South.

6.2.1 Integrating agents from the informal sector

First, there is a need to integrate agents from the informal sector into the emerging regime. As addressed through the thesis, e-waste management in the Global South is primarily performed by the informal sector, especially in countries that lack proper infrastructure. Agents in this sector tend to contribute significantly to the economies of countries in the Global South. Therefore, finding options to integrate the informal sector is crucial for sustainability transitions in e-waste management.

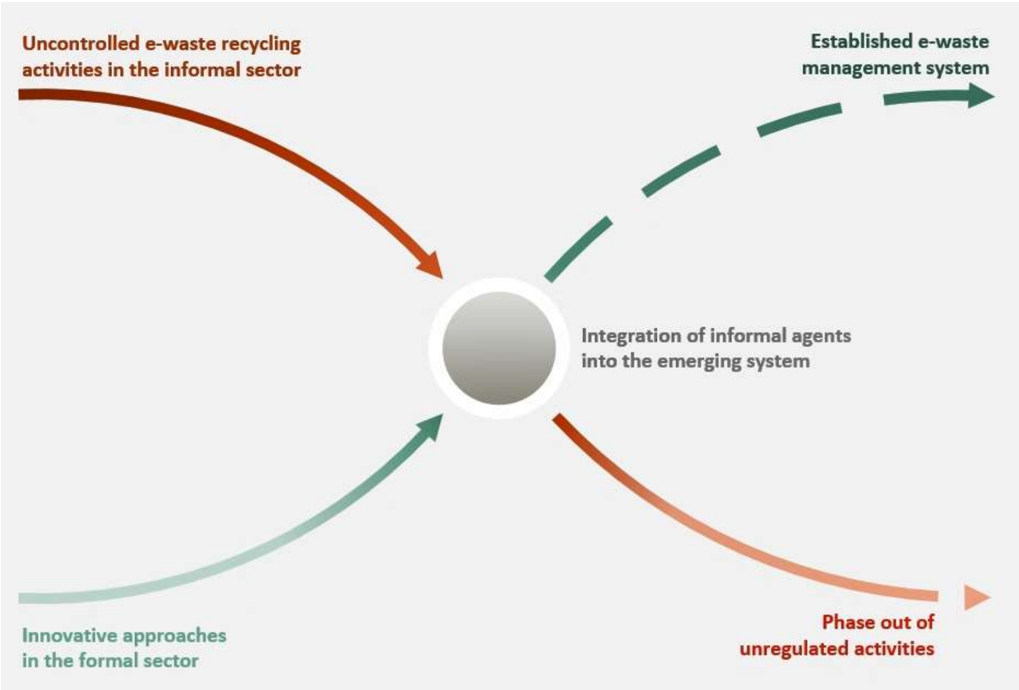

Figure 21. Transition dynamics of formal and informal sectors in e-waste management (based on Loorbach et al., 2017).

Through an x-curve of transition dynamics, Figure 21 illustrates the co-development of the informal and formal sectors suggested for transitioning to established e-waste management systems in the Global South. Applying the x-curve assists in considering the co-existence of the two sectors and possible transition pathways for both sectors.

6.2.2 Strengthening activities within the formal sector

Second, there is a need for strengthening activities within the formal sector, specifically at the end-processing stage. As highlighted through the work, recovering specific CRMs (e.g., gold) is only economically viable to recycling companies if considerable amounts of e-waste are processed. A complete transition to an established e-waste management system, thus, requires implementing large recycling facilities capable of recovering CRMs at high yields. Such facilities would be optimal for the end-processing. Yet, it is fundamental to consider alternative options while the implementation of such facilities is still not a reality. In a period of transition, fostering the emergence of innovative approaches at the niche level can provide significant results, even though they present intermediate solutions. An example here is a company in

Brazil (cf. Paper III) that currently focuses on processing on the national ground and obtains alloys of different kinds from e-waste.

Through field studies in recycling organizations, it was identified that a manual process is usually required in the initial stages of e-waste management. Among other aspects, this is due to a lack of a standard design in the appliances. Both on collection and pre-processing, there is no need for high investment in technology, thus neither for large recycling facilities. Therefore, it is relevant to foster the emergence of small-sized organizations that focus on the initial stages of e-waste management (in which manual processes are required).

6.2.3 Advancing policies on e-waste management

Third, the need to advance overall policies focused on e-waste management is of special relevance. This was evidenced, for instance, in the studies of the legal framework in Brazil and China. In Brazil, a lack of policy integration (e.g., divergent classifications of e-waste depending on regional policies) was identified as a barrier (as presented in Paper III). Fortunately, this is currently being mitigated by a national decree (from 2022) that applies a unified classification within the country.

The impact of certain taxes versus subsidies on e-waste recycling activities is also worth highlighting. In Brazil, for instance, the lack of financial incentives for recycling was mentioned by organizations as a barrier to the growth of the formal sector in the transition toward an established e-waste management system. In this case, organizations are, instead, required to pay certain taxes for transporting e-waste through different regions.

On the contrary, the subsidies offered through a Fund policy in China have shown significant results in motivating the growth of recycling activities within the formal sector (as addressed in Paper IV). Here, subsidies offered for recycling certain appliances by licensed companies have shown significant results in motivating the appearance of agents in the emerging system. Subsidies are, therefore, suggested to be analysed for implementation in other countries, especially for creating windows of opportunities toward sustainability transitions in e-waste management.

6.2.4 Accounting for the diversity of service provision

Lastly, an essential element to consider when designing e-waste management policies in the Global South is the diversity of service provision common in such geographies. This work has identified various service regimes in the three stages of e-waste management (i.e., collection, pre-processing, and end-processing) included in both sectors of the economy. In the same vein, it has pointed out alignments and misalignments at different levels, namely within and between service regimes, which translate into barriers and drivers. The development of e-waste management policies has a critical role in addressing misalignments at the various layers, and specifically in directing which services to phase out and which ones to prioritize.

Figure 22 illustrates a schematic proposition of a polycentric regime configuration within e-waste management based on the conceptual framework from van Welie et al. (2018) including the additional layers of the stages of e-waste management and the sectors of the economy, as designed in this work. The figure depicts a regime with various services that are well-aligned both on the service and sectoral levels. Furthermore, it highlights the alignments across the informal and formal sectors at various layers (i.e., within the service regimes, between service regimes in the same stage, and between service regimes of different stages of e-waste management) required for a complete harmonization in the system.

Intending to direct the transition, I emphasize the need to implement policies that focus on integrating agents from the informal sector in the initial stages of e-waste management. This is needed especially for the first two stages of collection and pre-processing, which currently reside largely within the informal sector. Integrating the expertise of agents from the informal sector into an emerging regime can be achieved through inclusive approaches, such as cooperatives (as addressed in Paper III and Paper IV).

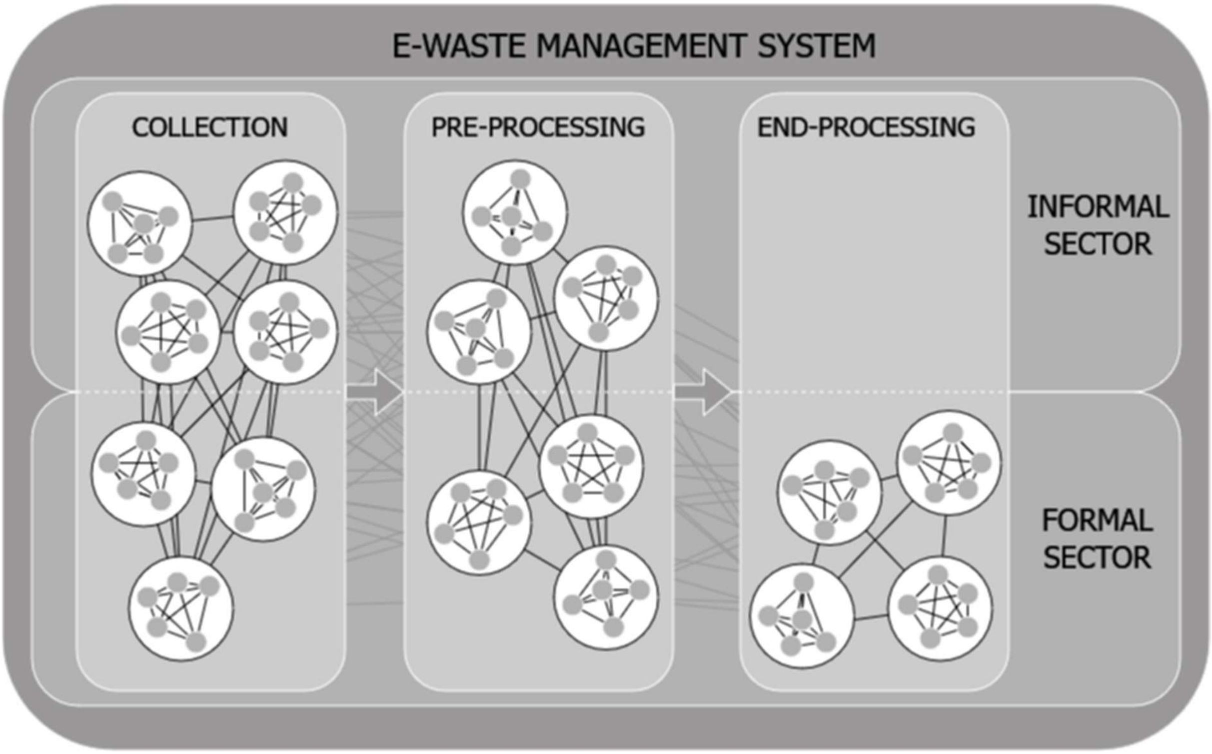

Figure 22. Proposition of a polycentric regime configuration as a transition pathway in e-waste management in the Global South (extended version based on van Welie et al., 2018).

In addition, it is essential to strengthen the growth of activities within the formal sector. This is especially important for the stages that require high investment in infrastructure and have a higher risk of environmental hazards (i.e., the end-processing). Finally, it is essential to align the regime dimensions within and between the various analytical layers, thus accounting for the variety of service regimes and promoting efficient service provision through all stages of the e-waste management system.

6.3 Contributions to the sustainability transitions research field

This Ph.D. thesis is focused on e-waste management and is theoretically framed within the research field of sustainability transitions, specifically on the transition management approach. This subchapter outlines the main contributions of the work to the research field.

Despite the increasing need to address the global e-waste challenge, current sustainability transitions literature on such a topic remains limited. I address this gap in this work by providing critical insights from the empirical investigations conducted on e-waste management. I apply the sustainability transitions framing to investigate diverse challenges in Ghana, Brazil, and China, countries significantly relevant to e-waste management in a global context. To the best of my knowledge, this is the first time a work combines empirical studies on e-waste management in these three countries.

The research field of sustainability transitions has been gaining strength recently. However, studies on the Global South are still emergent, and empirical work requires further expansion. Through this work, I provide empirical evidence on e-waste management that reinforces existing concepts and notions of the research field applied to the Global South. For instance, I highlight the prevalence of the informal sector, the diversity of development, and the presence of varied service provision in such geographies.

Studies in the research field often focus on the regime (i.e., the meso-level of the MLP framework). However, little has been investigated on the structuration of different combinations of regimes (Fuenfschilling and Truffer, 2014; van Welie, 2019). A growing body of knowledge argues for the need to adapt existing and develop new sustainability transition frameworks that focus on the Global South (Ramos-Mejía et al., 2018). In this thesis, I apply different frameworks that emerged from sustainability transitions research to the topic of e-waste management. For example, the adaptation of the x-curve of transition dynamics (Loorbach et al., 2017) applied to the sectors of the economy has assisted in analysing challenges related to the co-existence of the informal and formal sectors through diverse phases of transition.

Additionally, applying the conceptual framework proposed by van Welie et al. (2018) has helped me to explore the diversity of service provision within e-waste management in the Global South. Defining and applying specific adaptations to the conceptual framework has helped me to utilize the framework in an optimal way in the context of e-waste management in the Global South. Moreover, applying this adapted framework to the empirical observations conducted within this work has provided a concrete use case that allowed me to identify barriers and drivers of transitions in a real-world setting.

Specifically, these adaptations to the framework allow me to categorize the various service regimes identified within different processing stages (collection, pre-processing, end-processing) as well as the sectors of the economy (formal and informal) in a meaningful way. The separation of stages in e-waste management provides a more nuanced analysis to identify various types of alignments and misalignments. Such an adaptation in the application of the conceptual framework contributes to investigating the provision of more complex services than as applied by the original framework to basic services.

Finally, incorporating the sectors of the economy into the framework has assisted in visualizing alignments and misalignments between various analytical layers and considering possible transition pathways for e-waste management in the Global South. Overall, I believe that this adapted version of the framework from van Welie et al. (2018) allows the researcher to study transitions within this complex system in a structured way, especially because it is based on the actual evidence observed through the various observations within the three countries.

Chapter 7

Conclusion

The overarching aim of this Ph.D. thesis is to explore possible avenues for transitions toward more sustainable e-waste management systems in different countries of the Global South. In this context, a sustainable e-waste management system accounts for all aspects of sustainability, including the core pillars of social, economic, and environmental sustainability. Concepts such as the circular economy and life cycle thinking are central to guiding the broad understanding of the research.

The thesis is theoretically framed within the interdisciplinary research field of sustainability transitions and applies a transition management approach to e-waste management. Investigating central aspects that hinder or motivate transformations in the desired direction is crucial for providing insights for policy implementation. Therefore, the specific RO 1 of this thesis aims to identify barriers and drivers experienced by the informal sector in transitioning to established e-waste management systems, and specific RO 2 to identify barriers and drivers to the growth of the formal sector in the transition toward established e-waste management systems.

The Ph.D. thesis combines results from the empirical studies on e-waste management conducted in Ghana (2017), Brazil (2018), and China (2019). These countries are among the most impacted by e-waste generation and management in their respective continents and, therefore, are significantly relevant in the global context. To the best of the author's knowledge, this is the first time a work combines empirical studies on e-waste management in the aforementioned geographies.

Although the empirical studies in this thesis are in the Global South, the e-waste management challenge transcends borders. Managing e-waste in the Global South is intrinsically connected with the developments in the Global North, such as the high levels of production and consumption of electronic products and the export of used electronics to the Global South. The transplantation of the challenge to countries in the Global South – commonly known to have less infrastructure and regulations to address e-waste management – is of critical concern. Therefore, this thesis takes a broad perspective for perceiving e-waste management as a global challenge.

The work identifies various service regimes within the e-waste management systems in the Global South. It considers multiple layers of analysis, namely the varied stages of e-waste management (i.e., collection, pre-processing, and end-processing) within the informal and formal sectors of the economy. It identifies misalignments within and between service regimes. Many of such misalignments translate into barriers toward sustainability transitions. At the same time, some can represent drivers toward the appearance of niche innovations.

Considering various analytical layers provides a more nuanced analysis for identifying different misalignment types, such as within and between stages of e-waste management and at the interplay of informal and formal sectors. Identifying various service regimes and misalignments within various analytical layers opens for considering possible transition pathways for e-waste management in the Global South.

Applying the transition management approach illuminates some avenues to encourage the desired transitions. More specifically, the work highlights the need to integrate agents from the informal sector into the initial stages of e-waste management (i.e., collection and pre-processing). Additionally, it is critical to strengthen activities within the formal sector, specifically at the end-processing stage. Based on the studies of the legal frameworks in Brazil and China, the work points out relevant advancements on the topic and the relevance to further advance policies on e-waste management. Finally, the evidence suggests that it is essential to account for the diversity of service provision when steering the desired transitions in e-waste management in the Global South.

7.1 Limitations and suggestions for further work

This Ph.D. thesis is theoretically framed within the interdisciplinary research field of sustainability transitions to address the research topic of e-waste management. It combines the results of empirical investigations and identifies a diversity of service provision in three countries of the Global South. However, it does not map all service regimes within e-waste management in the countries analysed. In this context, it is suggested for future investigations to incorporate a larger sample of service regimes in e-waste management in specific countries. Comprehensive studies of service provision within e-waste management in specific geographies would assist in a more detailed identification of alignments and misalignments at the various levels, ultimately advancing sustainability transition studies on e-waste management and contributing to directing the desired transitions.

The work opens for the exploration of various aspects in further detail. For instance, future studies should explore the possibilities of integrating the informal sector into the emerging regime. Specifically, it is suggested to conduct studies on policy development that promote cooperation between the informal and formal sectors. Additionally, further studies on the possible implementation of subsidies for e-waste management in different geographies are suggested.

7.2 Final considerations

This work contributes to the research field of sustainability transitions within the topic of e-waste management by combining various perspectives of critical agents in the e-waste management systems in Ghana, Brazil, and China. The results reinforce existing sustainability transition studies that evidence the diversity of service provision in the Global South. The work highlights the need to incorporate the informal sector into the emerging regime, specifically in the initial stages of e-waste management (i.e., collection and pre-processing). In addition, the work evidences the impact of legislation and the need to strengthen end-processing within the formal sector. Hopefully, the contributions of this work can assist in guiding future studies and policy implementation for sustainability transitions in e-waste management in various countries of the Global South and ultimately help tackle the global e-waste challenge.

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Publications

Paper I

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Informal processing of electronic waste in Agbogbloshie, Ghana:

A complex adaptive systems perspective

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***Abstract*— Agbogbloshie is a scrap metal yard in Ghana that has achieved international notoriety for the improper manner in which electronic waste (e-waste) is processed. However, little is known about the reasons why this situation has not changed over the years. This paper focuses on the workers dismantling e-waste in Agbogbloshie; in particular, mobile phones and computers. By taking a *Complex Adaptive Systems* (CAS) approach to e-waste management in Ghana, I investigate the dismantling activity and the environmental and social hazards associated with it. Data have been collected through on-site interviews and observations. The analysis shows a dismantling process that is able to adapt to changing circumstances; the role of market prices in regulating the input of devices and output of components; and the organization of activities through diverse groups. The migration of workers from rural and urban areas functions as a kind of feedback loop into the system. Applying CAS as an analytical tool provides detailed insights and improved knowledge related to the characteristics and behaviours of the workers dismantling e-waste in Agbogbloshie, as well as their relations with other agents in the system. On a wider perspective, it enables a better understanding of the complexity in e-waste management systems.**

***Index Terms*— E-waste management system; manual dismantling; recycling; sustainability; waste electrical and electronic equipment.**

I. Introduction

In 2008, more than one billion personal computers (PC) were in use worldwide [1]. Only 7 years later, in 2015, this number had doubled, showing more than two billion operational PC's [1]. For mobile phones, the lifespan does not exceed an average of two years [2]. These are only two examples that demonstrate our strong and growing consumption of electronics. High levels of production and consumption have a direct impact on electronic waste (e-waste) generated, this latter pointed out by Hilty [3] as an emerging risk for society.

In 2016, 44.7 million tonnes (Mt) of e-waste were generated worldwide, corresponding to 6.1 kg per capita [4]. From this, 0.7 Mt corresponds to lamps, 3.9 Mt to Small IT (e.g. mobile phones, printers, desktop PCs), 6.6 Mt to screens and monitors (e.g. cathode ray tube monitors, flat display panel monitors), 7.6 Mt to temperature exchange equipment (e.g. fridges, air conditioners), 9.1 Mt to large equipment (e.g. dishwashers, washing machines), and 16.8 Mt to small equipment (e.g. headphones, cameras, speakers). For this same period, the United States and Canada produced about 20 kg of e-waste per capita, and Norway 28.5 kg – the highest quantity per capita in Europe. Although e-waste involves a multitude of devices, this paper focuses on mobile phones and computers.

Not surprisingly, the highest amounts of electronics are consumed in high-income countries, but many of these end up in emerging economies as second-hand goods [5]–[7]. When no longer used, these electronics stay in the country, shifting the e-waste problem to countries that do not have the capacity to properly recycle such devices [8]. Schluep et al. [9] discussed some of the challenges of e-waste recycling in emerging economies already in the first ICT4S Conference.

Agbogbloshie is a scrap metal yard – located in Accra, Ghana – that has achieved international notoriety for the manner in which e-waste is processed [5], [7], [10], [11]. The site is considered as one of the most polluted urban environments in the world due to the present informal processing practices and the lack of governmental regulation [5], [10].

Workers processing e-waste in Agbogbloshie are exposed to toxic gases and other dangerous species on a regular basis, which is reflected on their poor health status [7], [12]. The activity also affects the people living nearby, and furthermore, results in severe environmental impacts [13]–[15].

In this paper, I apply *Complex Adaptive Systems* (CAS) as an analytical tool to explore the complexity of informal e-waste processing. I address the following research question: How can CAS help in understanding the processing of e-waste in Agbogbloshie?

In CAS, a system consists of many agents that adapt or learn through interacting with others in the system [16]. This study focuses on agents dismantling e-waste in Agbogbloshie, and their interactions and interdependencies with other agents in the e-waste management system in Ghana.

Section two brings a short overview of research addressing CAS, and its applicability as an analytical tool to waste management. Sections three and four describe, respectively, the methods used and the organization of activities in Agbogbloshie. Section five presents detailed results of investigations into the informal processing of e-waste, with a focus on the dismantling activity. In section six, different CAS properties identified in this system are discussed. The last section concludes with some remarks on CAS as an analytical tool to understand the informal processing of e-waste in Agbogbloshie.

II. Complex Adaptive Systems

CAS analyse the interactions and interdependencies of various agents in a system, as well as the changes that occur due to such interactions [17]. In order to address sustainability in and by ICT, it is indispensable to explore the multitude of agents involved in each of the life cycle phases of such technologies (e.g. design, production, consumption, recycling).

This paper relies on the definitions adapted from Cohen and Axelrod [18]: *An agent* is an individual with the ability to interact and respond to events happening in its environment. Entities that lack qualities of agents – instead, being objects that are used by the latter – are defined as *artifacts*. Different *types of agents* form a *population of agents* when using similar strategies. The system is composed, thus, of "one or more populations of agents [...], all the strategies of all the agents [...], along with the relevant artifacts and environmental factors" [18, p. 6].

A. CAS Properties

A CAS has particular characteristics and properties that differentiate it from other systems [19]. In this section, I address some of these, which are later applied to the case study in the discussion section.

One of the main properties of a CAS is a high level of *adaptation*, which strengthens the system's resilience when a perturbation occurs. Usually, a large number of agents in the system interact and adapt over time to improve performance, learning from experience [16].

Another property of a CAS is its *non-linearity*. Since the relations among its agents are non-linear, the outcomes are to some extent unpredictable. This gives CAS the potential for chaotic behaviour and randomness [20].

The property of *emergence* means that the system's outcome is the result of combined agents' behaviour. Such an outcome cannot be achieved from the isolated behaviour of agents in the system [21]. Therefore, "the emergent properties of systems are lost when the system is broken down into parts and parts removed from the system lose the emergent properties they previously possessed" [20, p. 49]. A form of emergent behaviour is *self-organization*, in which new structures are developed without a central control [19], [20], [22].

An important feature of a CAS is that it can have both *negative* and *positive feedback loops*. In the negative feedback loop, the state of one type of agents affects the other in the opposite direction, keeping the system within its original boundaries. On the opposite, the positive feedback loop stimulates change by providing a source of instability, driving the system outside of its normal parameters. "The notion that equilibrium was the norm to which a system would return if there were a small deviation, via the mechanism of a negative feedback loop, is challenged by the discovery of positive feedback loops that drive a system forward beyond equilibrium" [23, p. 454]. The positive feedback loop, thus, enables a CAS to be in a state of change.

B. CAS in waste management research

Waste Management Systems (WMS) are highly complex systems that are often in a state of change. These systems receive information from the environment they operate, under a high level of unpredictability, and adapt accordingly. As a result, such adaptation leads to changes in the environment.

The application of CAS in waste management research has resulted in a better understanding of the complexity of WMS. Specifically, on improved knowledge of the characteristics and behaviours of the agents involved in these systems, and impacts in their environment.

Seadon [24] presents the study of waste management in New Zealand – including waste generation, collection, and disposal – as a CAS. "A WMS and its environment interact and create dynamic, emergent properties through quasi-equilibrium and state change, non-linear changes and non-random futures. The environment in which the WMS operates gives feedback to the system and changes the system" [24, p. 1645]. By exploring a series of links between the components of the system, the author justifies the application of an integrated approach to move towards more sustainable societies.

Ikhlayel [25] addresses the lack of integrative thinking in modern societies and applies such to e-waste management systems. Based on field trips to Vietnam and Jordan, the author proposes an integrated approach to improve e-waste management in developing countries. Both the composition of e-waste – with its associated environmental impacts – and the nature of e-waste management form the rationale for employing the proposed approach.

Agent-Based Modelling (ABM) is used in order to understand and model a CAS, through the identification of agents and their interactions in the system. In this regard, Bollinger et al. [26] apply an ABM of material flows connected to the production, consumption, and recycling of mobile phones. In their analysis, they focus on the interaction among agents trading metals. The authors conclude that the implementation of combined interventions shows more potential to promote a shift to closed-loop flow systems than single interventions.

III. Research design and context

This paper is part of a larger research project that analyses e-waste management systems in different countries. The project explores the multitude of agents and processes involved, as well as their interconnections, in each of the studied systems.

The e-waste management in Ghana is understood as a CAS that involves several *types of agents*. These include producers of electronics with take-back systems; government; *Non-Governmental Organizations* (NGOs); consumers of electronics at the disposal stage; and companies with intermediate processing. Other types of agents in this CAS – here understood as a *population of agents* for having similar strategies – include the ones in Agbogbloshie: the scavengers collecting e-waste; the workers dismantling e-waste; the workers burning cables; the "middlemen" intermediating the scrap from Agbogbloshie to the recycling facilities; and the board members of the *Greater Accra Scrap Dealers Association* (GASDA).

From the multitude of agents involved in the e-waste management system in Ghana, this paper brings a detailed study of one *type of agents*: the workers dismantling electronics in Agbogbloshie. The focus on their activity enables to establish connections with other agents in the system and to understand the informal processing of e-waste from a CAS perspective.

Data were collected in a continuous two-week period in September of 2017 and included visits to several points of interest and organizations, both in the capital (Accra) and adjacent cities. Data were collected through a mixed methods approach that combined observations, interviews, photography and videos on the e-waste management in Ghana. For this paper, the focus is on the data collected about the activity of dismantling e-waste in Agbogbloshie, particularly mobile phones and computers.

I visited the Agbogbloshie site seven times during the stay and engaged in conversations with 10-15 workers. The conversations were conducted while observing their activities. Data collection was strengthened through observation on the e-waste processing performed by various workers on the site.

Semi-structured interviews were conducted with organizations connected to e-waste management in Ghana. This paper brings data collected through interviews with the GASDA in Agbogbloshie, as well as with the NGO *Green Advocacy Ghana* (GreenAd) in Sakumono.

IV. The organization of activities

Agbogbloshie receives high amounts of e-waste and is regarded as one of the most toxic sites in the world [5], [10]. Although an open-air site with informal activity, it relies on the GASDA to organize the workers allowed on site, the activities performed, and the access of visitors. Interviews – translated from Ashanti – with the chairman of the association and main members of the board were conducted to receive permission to visit the site and to collect data.

According to information obtained through the interviews, the GASDA was registered with only 11 members in 1979, which has later grown to 3000-4000 members. Everyone working in Agbogbloshie must be a member before starting with their activities. The work is hierarchically divided, based on experience: the highest positions often belong to the ones working on the site for longer. The ones with the highest positions coordinate around 10-20 newer members and teach them how to dismantle different devices.

New members usually start at the GASDA by burning the cables [27] or as scavengers [15]. The scavengers go around the neighbourhood – and sometimes beyond the city – to collect metal scrap. In order to buy it, the novices are pre-financed by their leaders. The e-waste processing in Agbogbloshie is male-dominated [28], and women are found in the area selling water and food, often accompanied by children.

Adjacent to Agbogbloshie is Old Fadama: a large urban slum, separated from the scrap yard by a few hundred meters, with the Abose-Okai Road and the Odaw River. Both work as an extended community, with workers in Agbogbloshie often living at Old Fadama and markets such as the onion and the yam market located in between. The slum grew in the 1990s due to waves of migration, with refugees coming from the north of the country due to a combination of intertribal conflicts and decline in agricultural opportunities [29].

GreenAd is an environmental NGO that conducts research and initiatives on e-waste management in the country. In an interview, the NGO explained that workers have increasingly regarded Agbogbloshie as a possibility to increase their income. For this reason, the area has received rural and urban migration from different parts of Ghana. In addition, some come from neighbouring countries, particularly Nigeria, with a similar purpose.

V. The dismantling of electronics

The activity for dismantling electronics in Agbogbloshie happens most often in groups spread across the scrap yard. I have conducted visits to one of the biggest groups – denoted as *big group* in the following – dismantling various types of electronics on the site, with around 15 workers. A *small group* that focuses on mobile phones, and an *individual worker* who dismantles mainly laptops, have further complemented data collection.

The activity of dismantling, and especially the prior scavenging, demands time. The leader of the *big group* mentioned that, during the first years of activity, there was not a large number of electronics to work with. As a result, their income had to be complemented with other activities. With the passing years and a growing amount of e-waste arriving in Agbogbloshie, their whole livelihoods started depending on the dismantling of electronics. In the case of the *small group*, the number of devices is considerably less, and they complement their income by selling clothes in the same place where the dismantling is performed.

The *big group* dismantles various types of electronics, mainly mobile phones, desktops, and laptops. Each member of the group scavenges the electronics during the afternoon and dismantles them in the next morning. There is no clear division of work: they all scavenge, and they all dismantle the various types of devices they have each collected. Working hours vary depending on the amount gathered but mostly comprehend long journeys. In the case of the *small group*, workers dismantle electronics that they have most frequently bought from the scavengers in advance.

Workers in Agbogbloshie have direct contact with the ground, often muddy due to rain. The working environment is very precarious, which reflects in ergonomic problems. Workers often turn computer towers into benches to have a place to sit while dismantling electronics (see Fig. 1) or work in a crouching position for long periods of time.

The workers do not use any *Personal Protective Equipment* (PPE) in their activity, even though dealing with devices that release toxic substances. During an interview, the chairman of the GASDA highlighted that NGOs often come to provide workers with PPE and information, but that the workers most often do not follow advices, and do not use the PPE provided.

Fig. 1. Dismantling of electronics

The tools used to dismantle electronics are simple, such as scissors, pliers, screwdrivers, hammers, and cold chisels (see Fig. 1). Scissors are mainly used to separate cables from other components. The other tools are used interchangeably, depending on the design of the electronics and the availability of tools.

For the processing of cables, workers look mainly for copper. After the separation, cables are put together in a separate pile to be further assessed: This most often includes an open-air burning process, performed in an area away from the dismantling.

For mobile phones, different models demand different tools: devices that have screws are dismantled with screwdrivers; while the ones with glue are dismantled with hammers. Screws make it possible to better separate the components, but the workers in Agbogbloshie prefer the glued mobile phones because it takes less time to open them. Pliers and the cold chisels are mainly used to assist in separating the components of various electronics, including laptops and desktops.

Printed Circuit Boards (PCBs) contain precious metals, resulting in a high value if gathered in large amounts. Therefore, workers in Agbogbloshie look mainly for these components when dismantling electronics. This strategy is known as *cherry picking* [6], in which only a few components are targeted throughout the process.

The PCBs have different market prices depending on the electronics (e.g. computers, mobile phones). For this reason, they are stored separately, according to type. After a considerable amount is gathered, the PCBs are sold per kilo to middlemen. Following, they are sent abroad for further processing, because Ghana does not have the infrastructure to properly extract and separate the related metals.

The working environment in Agbogbloshie is mostly open-air. The *big group* has a shipping container to store the PCBs after dismantling the devices (see Fig. 2), and a simple roof to protect themselves from rain and direct sun. The *small group* works open-air – at the border of the Odaw River – and stores the PCBs on rice sacks. The *individual worker* has a small container, which he uses both for storing the materials, and as a working place.

The workers dismantling electronics often dispose of other components with inferior value. For instance, it is common to see computer chassis spread out over the area of Agbogbloshie (see Fig. 3). Eventually, some components are picked up by scavengers to be locally recycled. Others, of insignificant value for the workers, remain in the scrap yard. Components are targeted based on their profitability and on market demand – if workers do not have a buyer for the specific component, this is thrown away.

Fig. 2. Storage of PCBs

Fig. 3. Disposing of computer chassis

The mobile phone batteries have most often a different route than the rest of the devices: These often recirculate several times in second-hand markets in the city. As a result, the majority of mobile phones that reach Agbogbloshie no longer have batteries, and workers dismantling the devices do not have regular buyers for the batteries. Thus, the few mobile phone batteries that get to Agbogbloshie are usually thrown away in the scrap yard. These can later be picked up by scavengers to be resold in second-hand markets. Otherwise, they remain in the area, falling out of the recycling system.

The lack of proper tools and PPE – combined with an improper working environment – leads to a series of health risks. The chairman of the GASDA explained that work injuries are common in Agbogbloshie: he gave the example of a worker who, when dismantling a device, lost vision on one eye due to a sharp piece of iron. As one of the workers in Agbogbloshie pointed out, the constant loud noises also have effects on their wellbeing:

"Sometimes, because of the hammer, at the end of the day, we have a headache."

The workers have also mentioned other incidences: for instance, injuries arising from falling tools or materials. According to the workers, these incidences are mostly due to a lack of attention and hence, usually happen after long hours of work. The use of improper tools for the activity is also a concern, as it poses challenges – and often makes it unfeasible – to properly dismantle certain components of electronics.

Health hazards arising from the processing of e-waste in Agbogbloshie go further than the localized and individual issues discussed above, as GreenAd explains:

"In 2010, we did a health survey of the people there to see what they've been exposing themselves to […]. We saw that in their blood there's a high level of led, cadmium, arsenic. There's cancer growing, they're not safe. They get the led from the [car] batteries they work on, they break it apart and they pour the acid out, they use their bare hand to break it up, to load up trucks, and from the cars they just pour the oil out."

Workers dismantling fridges, air conditioners, and car batteries work in the same environment as the ones dismantling mobile phones and computers. With such a multitude of devices handled in the same area, the complexity of hazards is high. Workers dismantling mobile phones and computers in Agbogbloshie are thus exposed to the direct risks of their activity, in addition to the indirect risks of other activities conducted in the scrap yard.

VI. Discussion

Above, I presented results from my investigations related to the dismantling of electronics in the scrap metal site of Agbogbloshie, Ghana. In this section, I connect my main results to the CAS properties of *adaptation, non-linearity,* and *emergence*. Further, I discuss the migration of workers from urban and rural areas to Agbogbloshie as a *feedback loop*. The properties, as well as the related examples that emerged from this study, have strong interconnections. The examples are discussed according to a specific CAS property, even though they could be sometimes connected to more than one.

It is worth to highlight that the analysis is based on data collected in a period of 2 weeks in Ghana. Even though Agbogbloshie was visited several times, the time framework represents a limitation. The analysis of one *type of agents* in this CAS is not meant to be taken as exhaustive and further data collection (e.g. ethnographic research) is suggested to complement this study.

A. Adaptation

In CAS, equilibrium is rare and temporary. Therefore, the agents in the system must constantly innovate to be able to adapt to new scenarios and changing circumstances. Here, adaptation can be connected to the design of electronics and the associated dismantling processes.

In section five, it was shown that design plays an important role in the manual dismantling of electronics: the various kinds of devices and models demand a constant adaptation of the workers to the changing circumstances.

In the case of mobile phones, I observed that devices were dismantled in different ways depending on their design. For devices that had screws – prevailing in older devices – workers used a screwdriver to assess and separate the PCB from the rest of the device. In more recent models, however, many internal components are assembled with glue. For these types of phones, the dismantling is done by using a hammer rather than a screwdriver, which is considerably faster and depicts one example of *adaptation* in the system.

I did not observe the dismantling process of any modular phone during my investigations in Agbogbloshie. However, one aspect to question in this regard is whether modular designed phones would entail a new level of adaptation from the agents, to maintain themselves in this system.

Adaptation is strongly connected to other CAS properties, which are discussed in the following. For instance, workers adapt their processes depending on the components that have the most value, which leads to non-linear behaviour in the system.

B. Non-linearity

The relations among agents in a CAS are often non-linear. This makes it difficult to predict how the system – as well as its individual agents – will react to changing circumstances, external and internal ones. As will be shown below, the sum of agents in Agbogbloshie can react in non-linear – and hence, unpredictable – ways to changing circumstances, such as variations in market prices. Such prices act as a regulator in the system: for the input of devices, for the processes performed, and for the output of components.

Concerning the number of devices entering Agbogbloshie, there has been a steady increase over the years, which also has its effects in the area itself. In the first years of e-waste activities in Agbogbloshie, workers had to rely on other activities to complement their income. However, with the increase of e-waste in the area, the *big group* now relies on the dismantling activity as its single way of subsistence. It is thus possible to establish a strong relationship between the intensity of e-waste processing in Agbogbloshie and the number of electronics discarded in the area.

Market prices affect which processes are actually performed in Agbogbloshie. For instance, PCBs are stored according to different kinds because they vary in price. In turn, the workers' income in Agbogbloshie is dependent on the number of devices dismantled and on the prices obtained for the targeted PCBs. Thus, the workers' income, as well as the material flow, are directly interlinked with the market prices. This results in a non-linear behaviour. The lack of regulations also leads to such behaviour: For instance, the *cherry picking* practices are common, in which the PCBs are targeted due to their high value on the market.

Another example that adds non-linearity to this complex system is related to the components and materials leaving Agbogbloshie. Mobile phone batteries, for instance, usually recirculate in second-hand markets and indeed, the vast majority of mobile phones arriving in Agbogbloshie no longer contains the batteries. As a result, the common practices for the dismantling of mobile phones do not involve the extraction and monetization of the batteries, since the workers do not have regular buyers for them. Thus, whenever a mobile phone arrives with a battery, it is often simply discarded on the site and falls out of the system. This exhibits another potential chaotic behaviour in the CAS. The connection with the market is clear: if there are no defined buyers, the components remain in the scrap yard.

Computer chassis are another example that illustrates how the market prices act as a regulator in the CAS. Computer chassis have low prices in comparison with PCBs and thus, often remain in the scrap yard because of the lack of buyers. This leads to uncontrolled accumulation of materials in the system, which adds an additional component of unpredictability to the system, as there are no defined input/output pathways for these materials.

The discussed examples demonstrate clearly that market prices act as a regulator in the dismantling of electronics in Agbogbloshie, both for the input of devices and the output of components and materials. The amount of electronics arriving at the site directly affects the behaviour of agents in the system. The buyers interested in specific components determine what goes out of Agbogbloshie via "semi-controlled" pathways. Everything in between (e.g. the accumulation of materials that is not of interest for the market) adds unpredictability to the system, which may lead to further instability and chaos.

C. Emergence

The outcome of a CAS is the result of the combined agents' behaviour, resulting in its emergent property. In Agbogbloshie, this became clear in the way each activity is organized, and its connection to other activities in the e-waste management system.

The activity of dismantling electronics does not happen in isolation. Instead, workers organize themselves mostly through groups to conduct their work, such as the mentioned *big group* and *small group*. In addition, the GASDA represents a kind of self-organization mechanism in the system, because workers need to be members of it in order to be able to work in Agbogbloshie.

Activities within the same group often do not have a clear division of tasks: all workers can scavenge and dismantle the several kinds of electronics they find. Therefore, there is no real control of the activities performed, and the workers dismantling e-waste are in a constant state of self-organization and emergence.

A further aspect of emergence in the system is represented by the way the agents that dismantle e-waste interact with other agents. Since the activity does not happen in isolation, the workers performing the dismantling interact with other agents that are directly related to their work (e.g. consumers of electronics at the disposal stage, companies performing further processing). These, in turn, interact with agents that are directly related to them, creating a chain in this CAS. Thus, the e-waste management system emerges and is maintained by the connection among several agents, and their respective activities.

D. Feedback loops

A CAS exhibits two kinds of feedback loops: negative and positive ones. A negative feedback loop refers to a mechanism that corresponds to a certain deviation in the system to bring it back to, or towards, its equilibrium. A positive feedback loop, on the opposite, denotes a disturbance that drives the system beyond the initial state of equilibrium [23].

Defining an initial state of equilibrium for the e-waste management system in Ghana is difficult, and it is hard to assess whether the system has ever been in such a state. However, on first order, one could define a state of equilibrium by requiring that the number of materials and agents in the system were constant. More specifically, for a given time, the amount of e-waste entering the system would have to be equivalent to the amount of materials leaving it (either as recycled materials or as components forwarded to be recycled outside of the system). In addition, the amount of agents would have to remain constant, which means that the number of agents coming into the system would have to be the same as the number of agents that leave the system.

By applying this simplified definition of an equilibrium state to my investigations on the e-waste dismantling in Agbogbloshie, it becomes clear that the system is currently not in equilibrium. This is valid for both the flow of materials and the number of agents involved.

The flow of materials in Agbogbloshie is an example of a positive feedback loop. This can be seen, for instance, by the fact that the most profitable components (PCBs) are primarily targeted, while others are often inappropriately disposed of as waste. This drives the system away from a state of equilibrium since certain materials tend to accumulate in the system.

The amount of agents entering Agbogbloshie is another example of a positive feedback loop, which is manifested by an increasing population density in the area, through waves of rural and urban migration. Such growth in the number of workers drive the system beyond its normal operating parameters and represents a source of instability.

In this regard, it is worth to highlight that the concept of equilibrium is solely stating that the parameters (here agents) that determine the state of a system are interacting in such way, that the system remains in the same state over time. Equilibrium does not mean that a system is not imposing negative impacts on itself or on connected systems. As such, it is possible to have a system that is in equilibrium, yet generating significant environmental and social impacts. Nonetheless, a state of equilibrium is usually preferable to a state of non-equilibrium, since such systems are easier to be managed and improved because the outcomes are to some extent more predictable.

VII. Concluding remarks

The e-waste management in Ghana is a system with a variety of agents involved. These adapt according to the circumstances and interact with one another in complex ways. In this paper, I have focused on one of the involved activities, namely the dismantling of electronics. Based on empirical data collected in Agbogbloshie, I showed that the system faces a series of challenges that go beyond technical ones.

The activity of dismantling e-waste in Agbogbloshie is associated with severe environmental and social hazards. Workers are faced with very poor working conditions: lack of ergonomics, proper tools, and PPE have been evidenced. In addition, they have direct contact with dangerous chemicals on a daily basis, which imposes serious health risks. The improper processing of e-waste results in the release of toxins and pollutants, and causes significant environmental hazards in the air, soil, and water streams.

In addition, the collected data gives insights into the connection of the e-waste management system in the end-of-life phase with respect to other product life cycle phases. For instance, it was shown that the design of devices directly influences the way electronics are dismantled. This demands from the agents the ability to *adapt* to changing circumstances.

Market prices for devices and components play an important role in regulating activities in Agbogbloshie. As such, market prices are connected to the *non-linearity* property in this system: both related to the input of devices and to the output of materials and components.

Further, the e-waste processing in Agbogbloshie is directly connected to the consumption phase, since the amount of electronics consumed has a direct impact on the number of devices that enter Agbogbloshie. This, in turn, impacts the intensity of the dismantling activities. In the same line, the recycling phase is also affected by the market prices: the interest of buyers in specific components for material recovery impacts on the output of materials from the scrap yard.

The organization of activities through diverse groups represents a property of *emergence* in this CAS. The flow of materials, as well as the migration of workers from rural and urban areas to Agbogbloshie, functions as a kind of *positive feedback loop*, driving the system beyond equilibrium.

Based on these findings, I argue that it is of crucial importance to further explore the complex behaviour of agents in Agbogbloshie – as well as the interactions and interdependencies among them – in order to improve the e-waste management in Ghana.

E-waste management varies considerably, depending on a multitude of aspects – such as economy, environmental awareness, consumption patterns, etc. – and cannot be fully understood by focusing on only one aspect. The CAS theory considers the diversity of activities and behaviours of agents in a system, as well as their interconnections. It is, therefore, a powerful tool to target different settings such as the one of this study.

The application of the theory of CAS as an analytical tool has revealed unprecedented and detailed insights into the characteristics and behaviours of workers dismantling e-waste in Agbogbloshie. In addition, it has resulted in improved knowledge of their relations with other agents in the system.

My findings show that the dismantling of electronics in Agbogbloshie is part of a complex system, with agents interacting in a variety of ways. This system has several properties associated with CAS, such as *adaptation*, *non-linearity*, and *emergence*. Understanding these properties – and their connections – is indispensable when aiming for improvements in the system.

The challenges of e-waste management in Ghana have deep roots on social injustices and underlying causes. Nevertheless, the CAS theory has enabled me to explore the present scenario and brought further knowledge on why the situation has not improved over the years.

I argue that the aim of an e-waste management system should be to achieve a sustainable equilibrium: one in which the input of devices is equivalent to the output of recycled materials, with minimum socio-environmental impact. Nevertheless, my findings indicate that the system in Ghana is not in equilibrium: Instead, it is in a state of constant adaptation to the changing circumstances.

In order to move towards a sustainable equilibrium in such a system, efforts should first tackle its most unstable and chaotic components. In Agbogbloshie, one of the most pressing issues identified was, that the workers dismantling electronics primarily focus on the most valuable materials, while the least valuable are often ignored. The application of CAS has helped to identify some of the crucial issues related to the processing of e-waste in Agbogbloshie. Furthermore, it has enabled to explore the complexities among agents involved in the e-waste management system in Ghana. These results will be useful for future investigations and should be helpful to find solutions that lead to a more sustainable and balanced environment, which will ultimately improve the socio-environmental and socio-economic circumstances in Agbogbloshie.

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Paper II

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Paper III

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Investigations into the transition toward an established e-waste management system in China: Empirical evidence from Guangdong and Shaanxi

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China

ABSTRACT

China not only is the largest generator of electrical and electronic waste (e-waste) in the world but is among the countries affected the most by previous importation and informal recycling. In this paper, we explore how the implementation of policies has impacted a transition toward an established e-waste management system. We combine a brief review of the main advancements of e-waste management legislation in the country with field observations at two e-waste recycling sites. Informed by transition management, we investigate interconnections between the informal and formal sectors, and motivations to focus on certain appliances. Our findings suggest that the strongest drivers of change toward sustainability transitions are external, such as legislation and market. The remaining challenges include policy gaps for specific appliances and the disconnection between policies and the informal sector. This study provides scientific insights into transition possibilities for more established e-waste practices and contributes to advancements toward a circular economy.

1. Introduction

Waste from electrical and electronic equipment, known as e-waste or WEEE, currently represents a global challenge (Althaf et al., 2021; Tong and Yan, 2013). Increasing amounts of e-waste generated over the last decades, combined with improper management practices, result in severe environmental and social hazards. In 2019, 53.6 million metric tons (Mt) of e-waste were generated worldwide, of which less than 20% were reported to be recycled through formal channels (Forti et al., 2020).

The basic steps in a formal e-waste recycling chain consist of collection, pre-processing (i.e., sorting, dismantling, and mechanical treatment), and end-processing (i.e., refining (through methods such as pyrometallurgy, hydrometallurgy, and/or electrometallurgy) and disposal) (Schluep et al., 2009). In informal sites, e-waste recycling is commonly associated with severe environmental pollution (Parajuly et al., 2019; Zeng et al., 2017). Without control of activities, workers often favor components that are the most valuable in the market, such as printed circuit boards (PCBs), while others tend to be improperly discarded and fall out of the recycling process (Schneider, 2019a).

To provide a blueprint for the most pressing global challenges to be addressed by 2030, the United Nations Member States adopted the Sustainable Development Goals (SDGs) in 2015 (United Nations, 2022). Improving e-waste management is strongly connected to the achievement of the SDGs and a more sustainable future. Furthermore, it contributes to climate change mitigation by enabling the circularity of resources, which ultimately decreases the demand for virgin materials (Hertwich et al., 2020; IPCC, 2014).

Secondary raw minerals obtained through e-waste recycling also present significant economic opportunities. This is especially the case for minerals found progressively less in nature and that are required for the manufacturing of electronics. For instance, indium and silver are among the minerals with predicted global shortage within the next few years. Metals such as indium are characterized by low recycling rates (e.g., due to products' design and recycling infrastructure). Nevertheless, the focus on resource recovery presents great opportunities for countries to mitigate environmental impacts while strengthening a domestic supply chain (Althaf et al., 2021).

China is the largest e-waste generator in the world. In 2020, 14 Mt of e-waste were generated, an amount predicted to grow to more than 28 Mt by 2040 (Zeng et al., 2020). Especially within the last decade, the country underwent substantial changes as a result of several initiatives and the establishment of national legislation for e-waste management

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(Awasthi et al., 2019; Chen et al., 2018). These efforts have brought significant improvements, which led the United Nations Environment Assembly to promote China as a model for e-waste management in 2016 and to consider its several lessons for international replication (Chen et al., 2018). In the period from 2012 to 2020, a total of 21.9 billion Chinese Yuan (CNY) was delivered in subsidies to e-waste recycling companies, and around 600 million units (including televisions, refrigerators, washing machines, air conditioners, and personal computers) entered the formal recycling channel (MEESCC, 2021).

In this paper, we start from the assumption that e-waste management in China is currently going through a transition. The direction of this transition, though, is not so clear. The establishment of policies has the potential to highly impact transitions to more sustainable systems but might as well lead to unintended consequences. For instance, Kirby and Lora-Wainwright (2015a, 2015b) explore some of the complexity involved in the transboundary trade of e-waste and discuss shortcomings of the Basel Convention to regulate the movement of hazardous wastes. To achieve the desired results, a detailed understanding of diverse rationalities, bottlenecks, and interconnections among subjects in such a system (hereinafter referred to as agents) provides valuable knowledge and perspectives to assist in potential policymaking. Informed by transition management (Loorbach, 2007; Rotmans et al., 2001), this work explores how the implementation of policies has impacted a transition toward an established e-waste management system in China.

This paper is organized as follows: in Section 2, we introduce sustainability transitions as a research field and, more specifically, transition management as our chosen lens. In Section 3, we present a review of literature related to the main advancements in e-waste management in China. In Section 4, we present two case studies on e-waste recycling, based both on results from field observations and on an analysis of literature. While the first case focuses on the informal sector, the second is an example from the formal sector. We discuss our results in Section 5, with a focus on some of the driving factors identified, as well as on the current direction of the transition. Lastly, we present our final considerations in Section 6.

2. Sustainability transitions

The field of sustainability transitions research addresses the large-scale transformations required to tackle grand societal challenges (Loorbach et al., 2017). To move away from unsustainable societal structures that prevail in current systems, radical shifts are necessary: the so-called 'sustainability transitions' (Köhler et al., 2019).

With an interdisciplinary nature, transitions research varies according to the angle that is taken on a specific societal problem. Loorbach et al. (2017) categorize three broad perspectives: socio-technical, socio-ecological, and socio-institutional. The socio-technical is at the origins of transitions research and has gained attention, especially, through the multi-level perspective (MLP) (Geels, 2002). The MLP has been applied in several studies, for instance, in the establishment and evolution of an extended producer responsibility (EPR) system for e-waste in China (Tong and Yan, 2013). The socio-ecological perspective focuses on the transformative capacity of a system and is often applied to topics such as climate resilience, nature, and biodiversity. The socio-institutional perspective, applied in this paper, takes a reflexive stand toward the role of governance and agency in sustainability transitions (Loorbach et al., 2017). One of its main analytical lenses is transition management, detailed in the following.

2.1. Transition management

Transition management (Loorbach, 2007; Rotmans et al., 2001) is a policy-oriented approach to persistent societal problems. The understanding of the dynamics of a societal system as a complex adaptive system forms the basis for new insights and for developing governance strategies (Loorbach, 2007). Grounded in governance and complex systems theory (Loorbach, 2010), the approach addresses several domains, agents, and scale levels (Rotmans et al., 2001). It is based on key notions from complex systems, such as emergence, self-organization, and co-evolution (Rotmans and Loorbach, 2009).

Due to the long-term nature of societal transitions, studies often include a historical analysis (e.g., through a period of decades). The approach recognizes the importance of the state, market, and society in driving transitions for sustainable development, and proposes a combination of top-down and bottom-up strategies for policymaking (Loorbach, 2010).

The x-curve of transition dynamics (Loorbach et al., 2017) is an analytical model to identify patterns that drive structural change. It combines two s-curves, one downwards that represents the breakdown of the established regime, and another upwards on the emergence of a transformative regime. Each curve is represented through five stages of transition. The established (old) regime develops from optimization to destabilization, chaos, breakdown, and lastly, phase out. The transformative (new) regime starts with the experimentation from niches and goes through the stages of acceleration and emergence until it replaces the old regime through the stages of institutionalization and stabilization. Fig. 1 illustrates this model.

The real process is far more complex and less clear than the model represents. For instance, agents move in different directions through the transition pathways and are not necessarily aware that a transition is taking place (Loorbach et al., 2020). The model helps to explore the nuances of transition dynamics, as well as to better understand the development and the co-existence of multiple regimes.

3. E-waste management advancements in China

Based on a historical analysis, Zeng et al. (2013) categorized the development of e-waste management in China into four phases (cf. Fig. 2). In the following, we explore the main advancements with a focus on legislation.

The processing of e-waste in China was highly dependent on the informal sector in its early years and was associated with severe environmental pollution (Chen et al., 2018). This was characterized by a lack of control over how the activities were performed, as well as a lack of knowledge regarding the origins of appliances and the destination of the recycled materials (Breivik et al., 2014).

Since 1990, China has been a signatory to the Basel Convention, a multilateral environmental agreement on the control of transboundary movements of hazardous wastes and their disposal (Ghosh et al., 2016). In 1999, the country ratified the Ban Amendment by banning the import and export of hazardous waste, with few exceptions (Basel Convention, 2022; Ghosh et al., 2016). Despite the ban, the country continued to be seriously impacted by the importation of e-waste (Kirby and Lora-Wainwright, 2015a). Estimates point out that approximately 33 million tons of e-waste were illegally imported to Asia in 2004, and that China was one of the main destinations (BCRC, 2005). Especially in the early 2000s, environmental and social impacts from unregulated trade and recycling of e-waste in the Chinese context gained international attention through reports and documentaries, such as the one from Puckett et al. (2002).

In 2007, the Ordinance on Management of Prevention and Control of Pollution from Electronic and Information Products came into force, also known as the China RoHS. This restricted the use of certain toxic and hazardous substances, stipulated the labeling, as well as information disclosure on hazardous substances and recycling as mandatory, and promoted green product design (Zhu et al., 2012). In 2008, the Administrative Measure on Pollution Prevention of WEEE was adopted, which aimed at reducing pollution caused by previous activities within the informal sector (Zeng et al., 2013).

A temporary management policy was implemented in 2009, the "Old-for-New" Implementation Measures for Household Appliances. This policy focused on establishing a collection and treatment system for

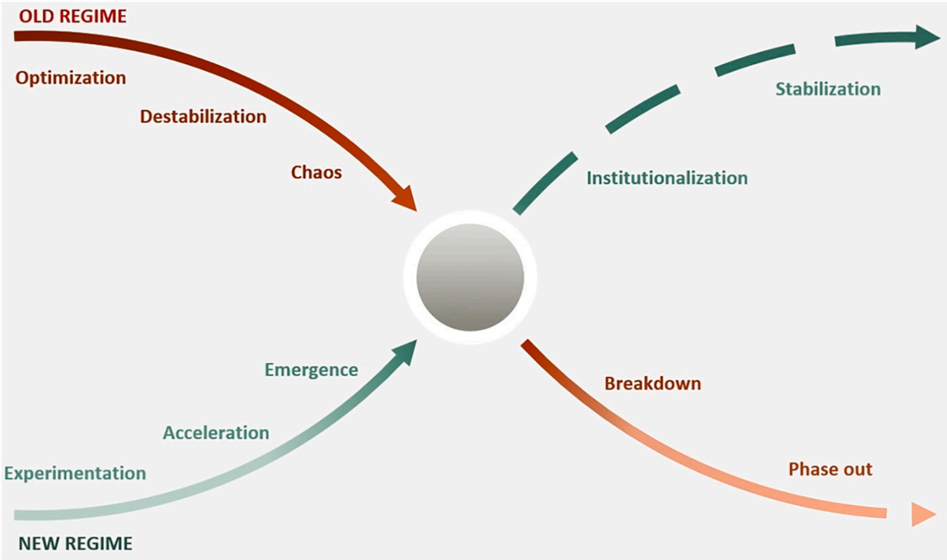

Fig. 1. The x-curve of transition dynamics (adapted from Loorbach et al., 2017).

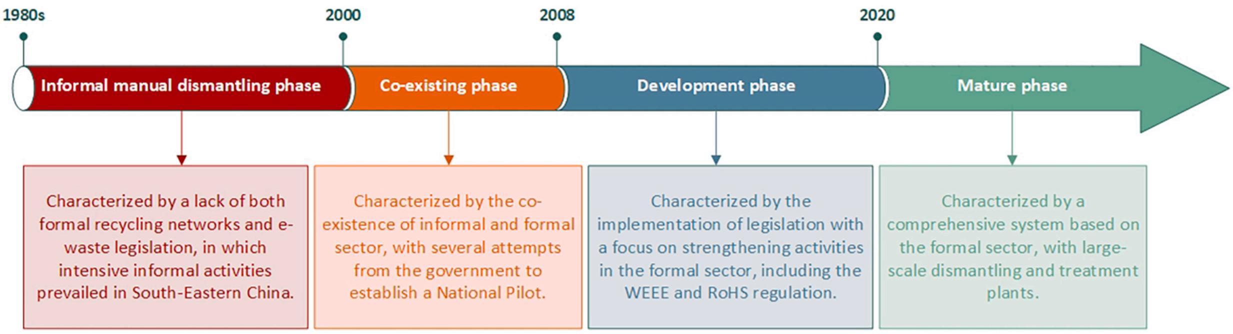

Fig. 2. Development of e-waste management in China (adapted from Zeng et al., 2013).

the end-of-life (EoL) appliances identified in the First Catalog of WEEE Recycling, which includes televisions, refrigerators, washing machines, air conditioners, and computers (Qi et al., 2022). The policy was initially implemented in nine provinces and cities and was gradually extended until covering the whole country (Zhu et al., 2012). Despite the more than 57 million appliances collected, the significant financial costs for the government resulted in the policy's interruption in 2011 (Chen et al., 2018). In total, more than 2,000 companies participated, including electronic retail, collection, and dismantling companies (Zhu et al., 2012).

The Administration Regulation for the Collection and Treatment of WEEE, also known as the WEEE Regulation, was implemented in 2011 with assistance from the Basel Convention Regional Centre for the Asia Pacific. The WEEE Regulation establishes requirements for the monitoring of environmental performance in recycling companies, sets out shared responsibility among different stakeholders throughout the electronics' life cycle, and promotes partnerships for e-waste recycling, among other contents (Zhu et al., 2012).

The Regulatory Measures for Collection and Disposal Fund of WEEE was issued in 2012, hereinafter referred to as the Fund policy (Chen et al., 2018). The Fund policy has common points with the European Union's EPR policy and offers subsidies to licensed companies. Listed appliances that enter the Chinese market are taxed (either toward the producer or the importer), and the funds are allocated for the dismantling. Appliances that are covered by the Fund policy include the ones identified in the First Catalog of WEEE Recycling. For example, the producer/importer pays 10 CNY (equivalent to approximately 1.6 USD in 2022) for every computer that enters the market, while the Ministry of Finance allocates 85 CNY for each computer dismantled at a licensed company (Zeng et al., 2013). The policy results in a negative balance for the central government. For instance, there was a deficit of approximately 2.6 billion CNY in 2015, as a result of the difference between the amount paid by the producers and the subsidy provided to the licensed companies (Chen et al., 2018).

In 2015, a new catalog of WEEE Recycling was issued, which increased the types of appliances covered by the regulations from five to fourteen. However, the new catalog has not yet been incorporated into the Fund Policy (WEF, 2018). For example, subsidies from the government to licensed companies for the dismantling of computers (listed in the First Catalog) are in place, but subsidies for mobile phones (introduced in the new catalog) have not yet been implemented (Liu et al., 2019; Zeng et al., 2017).

The advancements in e-waste management legislation in China have been considerable, and recent plans from the Chinese State Council indicate the continuation of improvements with a focus on resource circularity (Kanwal et al., 2022). However, both the collection and the recycling of e-waste remain a challenge, especially for small devices. For instance, a study that analyzed behavioral trends in China identified a preference of consumers to keep EoL mobile phones at home instead of recycling them (Liu et al., 2019). Some of the main reasons identified in the study involve concerns related to data security and residual value combined with the ease to store small equipment. The informal sector continues to be the prevailing channel for e-waste collection in China (CHEARI, 2019; Chi et al., 2011), and studies indicate that this is likely also the case for e-waste recycling (WEF, 2018). In the following, we explore how the development of policies impacts, in practice, a transition in both the informal and formal sectors.

4. Case studies

In this section, we present two case studies on e-waste recycling practices in different regions of China. These are presented through a combination of an analysis of literature with the results of our field observations. Case 1 is related to the informal sector and focuses on the recycling activities performed at the industrial park in the town of Guiyu, in which data were collected through field studies in April 2018. Case 2 is related to the formal sector, and data were gathered at a recycling facility at the industrial park in Xizhangbu town, in August 2019.

The data from the field observations were collected through a mixed-method approach including interviews, direct observations, and documentation (with photography, video, and field notes). To obtain information on the history and progress of activities in case 1, around eight semi-structured interviews were conducted with workers processing e-waste and managers in Guiyu. In case 2, a semi-structured interview was conducted with the general manager of the company. The focus of the data analysis for both case studies was on motivations to focus on specific appliances and e-waste components, working conditions, as well as interconnections between the informal and formal sectors.

4.1. Incorporating the informal sector? The case of e-waste recycling in Guangdong

China has been historically known for the e-waste processing activities conducted by the informal sector. These play an important role in the country's economy even though are often associated with severe environmental hazards (Zhu et al., 2012). Activities are mostly concentrated in specific regions. Guiyu, in Guangdong Province, South-Eastern China, has for long been perceived as one of the largest e-waste recycling hubs in the world (Chi et al., 2011), with documented informal activities dating back to 1995 (Breivik et al., 2014; Song et al., 2017).

Guiyu is a well-documented example of the substantial impacts associated with previous informal e-waste recycling due to the rudimentary processes performed (Pérez-Belis et al., 2015). E-waste was mainly processed in open-air backyards in its early years, and methods such as the open burning of cables and the open acid baths of PCBs used to be among the common practices for metal recovery (Terazono et al., 2004; Zeng et al., 2013). These methods are associated with severe environmental and occupational hazards and are often reported to be performed by the informal sector also in other countries (e.g., in Ghana (Schneider, 2019b), and India (Awasthi et al., 2018)).

The site has historically processed e-waste from abroad, including from the United States, Europe, Japan, and South Korea (Chi et al., 2011; Terazono et al., 2004). Without control of activities, it is difficult to precisely estimate the total amount of e-waste that has been processed in Guiyu, as well as the extent of how this has changed over time: results of studies range from hundreds to several thousands of kilotons per year (Breivik et al., 2014). Despite the restrictions of importation implemented through the Basel Convention, an amount of up to 0.5 Mt of e-waste is estimated to continue to enter China illegally every year (WEF, 2018).

Places of informal activity such as Guiyu have undergone intensive transformations with the legislative reforms. As part of a governmental project, the National Circular Economy Pilot Industrial Park was set up in Guiyu in 2010 (Song et al., 2017). According to several on-site investigations made by Schulz and Lora-Wainwright (2019) in the period from 2012 to 2018, it was only in their latest visit that they found the park in full operation.

The town of Guiyu has a population of about 200,000 habitants, of which around half were estimated to be involved with informal e-waste recycling before the installation of the park (Wang et al., 2020). Activities were mostly performed by local families, and organized in about 5,000 – 6,000 small workshops (Awasthi et al., 2019; Wang et al., 2021), which illustrates the importance of such activities for the local economy.

With the emergence of the industrial park, workers that previously conducted open-air activities were required to move inside and to comply with basic standards, including the payment of certain fees, such as rent and electricity (Wang et al., 2021). Workshops were merged into up to about 50 integrated business operations within the limits of the park (Awasthi et al., 2019; Schulz and Lora-Wainwright, 2019). The current scenario is somehow blurred: Although the official figures are that most of the previous workshops were moved into the park, studies indicate that many of the smaller workshops have seized to exist due to the high operational costs and that only the largest workshops were able to make the move (Schulz and Lora-Wainwright, 2019; Wang et al., 2021).

During our field observations, we documented that the current practices in Guiyu remain far from optimal. *E*-waste was observed to be transported by tricycles and stored in open-air areas when arriving at the park. Workers dismantled PCBs from computers while sitting on the floor (cf. Fig. 3 left) or in crouching positions. The high-temperature separation of components from the PCBs was performed on chairs that were not adapted for the activity, and without an adequate ventilation system (cf. Fig. 3 right). Instead, a simple fan was used to renovate the air in the workshops visited. Some workers used simple tools (e.g., electrical screwdrivers and hammers) to dismantle PCBs and sort their components, while others did not use any tool to dismantle the devices. Most workers in the visited workshops performed the activity without any personal protective equipment.

According to our observations, activities in the park are organized in different workshops (e.g., dismantling is performed in a separate workshop from the high-temperature separation). We found different kinds of PCBs that were sorted according to type, and specific components that were organized in separate batches in the manual dismantling. Schulz and Lora-Wainwright (2019) state that appliances that are out of the scope of the First Catalog were also found to be processed in the park (e.g., printers, CD and DVD players, and photocopiers).

As observed in the visit, the industrial park has an integrated system for the treatment of air pollution and sewage from the recycling process. However, concerns about the reliability of this system are raised by Schulz and Lora-Wainwright (2019). Our observations suggest that e-waste recycling in Guiyu continues to pose several environmental hazards. As evidenced in Fig. 3, the applied methods appear non-optimal to prevent the release of toxins. This goes in line with several studies that document the continued high concentrations of heavy metals and toxic chemicals in the region, such as from Vaccari et al. (2019) and K. Wang et al. (2020). In addition, the pollution that was generated before the implementation of the park can impose long-term effects on the ecosystem (Forti et al., 2020; Heacock et al., 2018).

Despite the challenges that remain, several improvements are evidenced in the region. For instance, local inhabitants could directly see some of the environmental improvements, such as the return of fish in the waterways, and plants in their banks (Schulz and Lora-Wainwright, 2019). The installations observed in the visit, although still far from ideal, provide a more suitable working environment than in the early years of activities in Guiyu. The scenario provides us with several insights into the e-waste management transition. In specific, it illustrates the efforts taken to improve the situation in Guiyu, as well as some of the challenges related to regulating informal e-waste activities.

Fig. 3. Recycling of PCBs in Guiyu. Left: Manual dismantling. Right: High-temperature separation of components.

4.2. Strengthening the formal sector: The case of a licensed e-waste recycling company in Shaanxi

The several initiatives to improve e-waste management in China have led to significant changes, especially in the formal sector, which showed a marked increase in the number of industrial recycling parks (Awasthi et al., 2019). The number of licensed e-waste recycling companies that were established grew from 36 in 2012 to 109 in 2017 (WEF, 2018), an amount that currently remains in operation (Wang et al., 2022). Their annual dismantling capacity ranges from 5,000 to 135,000 tons, and most companies are at the lower end (WEF, 2018).

Despite the increase in the number of licensed companies, the formal sector is still far from achieving the full capacity to recycle the e-waste generated in the country, and most of the e-waste is estimated to be processed by the informal sector. In 2016, the licensed companies had a dismantling capacity of 4.2 Mt per year, in contrast to the estimated 11 Mt of e-waste generated (WEF, 2018).

The licensed companies are distributed in different provinces in China, according to the mapping provided by Awasthi and Li (2017). Most are located in the east, which has a higher gross domestic product measure than other regions in the country (WEF, 2018). Those that perform the dismantling of appliances that are listed in the First Catalog receive financial incentives from the Fund Policy. Such incentives have pushed pre-processing activities, consequently strengthening the supply to companies that perform the end-processing.

Shaanxi Anxin CRT Recycling Processing Applications Co. Ltd. (hereinafter referred to as Shaanxi Anxin) is one of the 109 licensed companies. Established in 2010, the company is located at the Scrap Recycling Industrial Park in Xizhangbu town, Shaanxi Province. It is one of the earliest companies in the country to specialize in the recycling, disposal, and resource utilization of e-waste (Shaanxi Anxin, 2022). Shaanxi Anxin processes different appliances and e-waste components, which include cathode-ray tubes (CRTs) from televisions, PCBs from computers, and fluorescent lamps. Televisions and computers are listed in the First Catalog, whereas fluorescent lamps are not. Based on the information provided during the visit, the main processes for appliances that are covered by the company are illustrated in Fig. 4.

According to the interview, CRT televisions are manually dismantled at designated companies that receive the financial incentive from the Fund Policy, and their tubes are forwarded to Shaanxi Anxin where the

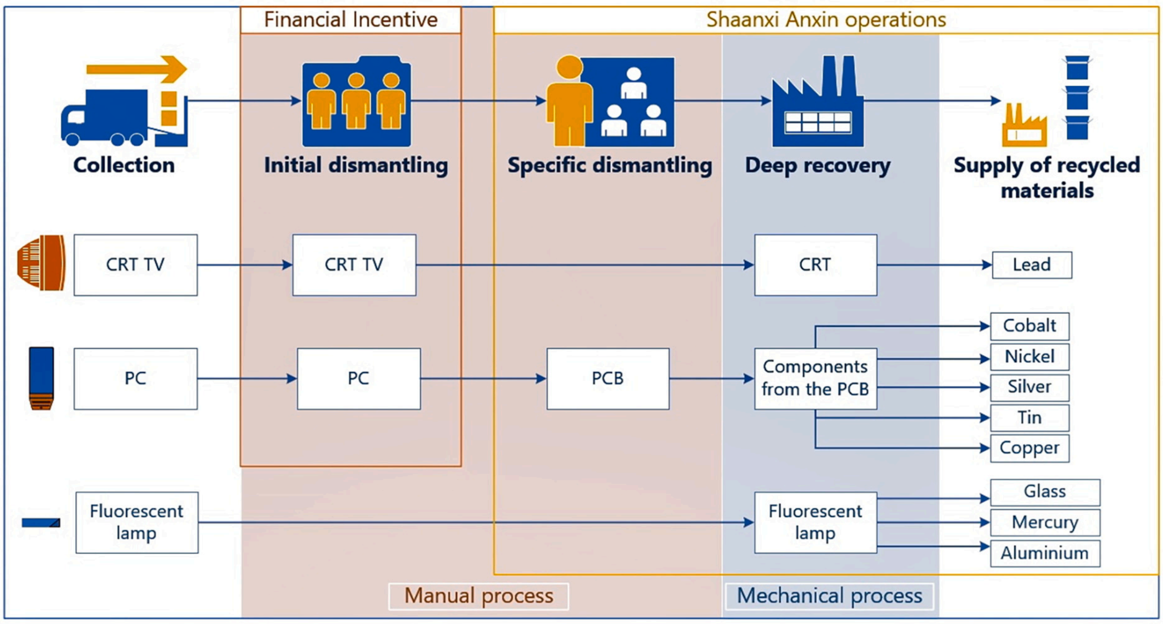

Fig. 4. E-waste management processes for appliances covered by Shaanxi Anxin.

CRTs are processed through mechanical treatment for the refining of lead. Further processing (e.g., pyrometallurgy) is completed in other metal mining companies.

The company has more than 30 employees that process around 3,000 tons of PCBs annually. According to information from the interview, these are recycled only from computers due to a lack of supply from other appliances that contain PCBs (e.g., mobile phones). Shaanxi Anxin receives the PCBs (cf. Fig. 5 left) from pre-processing companies that perform the manual dismantling of computers. First, some of the components are manually separated from the boards (cf. Fig. 5 right) with the use of simple tools (e.g., pliers, scissors, and electrical screwdrivers). Second, PCBs are processed at a high temperature within a closed area (cf. Fig. 5 left). This process melts the solder that is used to connect components to the board and allows for the separation of the remaining components.

Several metals are extracted from the PCBs (mainly cobalt, nickel, silver, tin, and copper). According to information provided by the company, gold is not refined due to the elevated processing costs compared to the small quantity of the precious metal obtained per board. As pointed out in the literature, gold is among the metals that are found in low concentrations in electronics (Li and Achal, 2020), and that require highly specialized metallurgical processes to be recovered appropriately (Hagelüeken and Corti, 2010). This process is not always economically feasible for recycling companies.

The recycling rate of fluorescent lamps through formal channels in China is estimated to be as little as 1% (Peng et al., 2014). Indeed, Shaanxi Anxin is one of the few companies that receives and processes this appliance (cf. Fig. 6 left). With the introduction of specialized equipment in 2016, the company became the first in Northwest China to focus on the recycling of mercury-containing lamps. The recycling process separates the glass (cf. Fig. 6 right) from the metallic components and stores the mercury vapor. The recycling of fluorescent lamps represents a challenge due to the high operational costs, in combination with the low market prices of the recycled materials (Peng et al., 2014). Nevertheless, the company highlighted that this process is financially viable because large production companies have started to integrate the recycling costs of their products as part of Corporate Social Responsibility (CSR) strategies. Therefore, Shaanxi Anxin receives financial incentives from certain producers, and in return performs the recycling of their EoL appliances.

The scenario evidenced in Shaanxi Anxin provides us with several insights into the e-waste management transition within the formal sector. Even though the company focuses on three types of appliances, the reasoning for such and the processes performed illuminate some of the challenges faced, as well as avenues of opportunities.

5. Transition analysis

In this section, we discuss our results from the case studies. In the first subsection, we focus on the identification of some of the driving factors, as well as on a reflection of their impact on the system. In the second subsection, we discuss the direction of the current transition and alternative pathways to consider.

5.1. Identifying driving factors

A system in transition moves from one relatively stable state to another through a co-evolution of different structures (Loorbach, 2007). These structures (e.g., market and legislation) can act either as drivers or barriers to change. Particularly in countries with a predominant political culture, the legislation seems to have a strong potential to act as a driver for transitions.

Through the analysis of the case studies, we find that legislation presents several opportunities for the e-waste management system in China. For instance, the subsidies offered through the Fund Policy led to the appearance of new agents (e.g., pre-processing and end-processing companies). A pattern of organization appeared through the industrial parks as an outcome of several governmental initiatives, as evidenced in both sites. In addition, environmental and occupational improvements were observed in Guiyu.

Our case studies show that legislation appears to have an impact on which appliances are recycled the most. The Fund Policy currently covers only the appliances identified in the First Catalog of WEEE Recycling (e.g., computers). For appliances that either appear in the New Catalog (e.g., mobile phones) or are not identified in any, there is no financial incentive. While computers are included in the financial incentives allocated from the producers to companies that perform the dismantling, mobile phones are not. This impacts the whole supply of e-waste for recycling within the formal sector. For instance, the lack of companies focusing on the dismantling of mobile phones impacts the supply of PCBs from mobile phones to companies that perform further processing (e.g., Shaanxi Anxin). Consequently, appliances that are not covered by the Fund Policy tend to be recycled by the informal sector, such as presented in case 1 (see Section 4.1).

The results from case 2 (see Section 4.2) show that a multitude of factors influences the recovery of certain materials by the formal sector. This is exemplified through the recycling of gold from PCBs, a metal that has a clear demand and high price in the market. Nevertheless, gold is among the unrecovered materials at Shaanxi Anxin because of the elevated costs involved in its recovery. Instead, the company recovers other metals from the PCBs that are found in larger amounts and do not demand such a costly process. Examples such as the recycling of gold explain the need for e-waste recycling to occur on a large scale to

Fig. 5. Recycling of PCBs from computers. Left: Storage on the right and high-temperature separation area on the left. Right: Manual dismantling.

Fig. 6. Recycling of fluorescent lamps. Left: Insertion of lamps into the machine. Right: Extraction of glass from the recycling process.

achieve an optimal level of material recovery.

In the case of fluorescent lamps, there is no financial incentive from the Fund Policy, and the recycling costs are high. Thus, neither legislation nor market prices appear to motivate the recycling of such appliances. However, the example in Shaanxi Anxin demonstrates that certain agents in the system (in this case, large international producers of fluorescent lamps) impact the e-waste management system by creating new market opportunities: once large companies integrate the recycling costs of fluorescent lamps as part of CSR strategies, it becomes financially viable for recycling companies to include such appliances in their portfolio. In this case, there is evidence that CSR initiatives have a fundamental role in shaping the emerging system.

5.2. Rethinking the direction

Implementation and enforcement of legislation on e-waste management have resulted in several transformations, especially in places with previous informal activities and no environmental control. Nevertheless, challenges remain at the intersection of the informal and formal sectors. In the following, we apply a transition perspective to e-waste management in China (cf. Fig. 7) by combining the x-curve model (Loorbach et al., 2017) and our adaptation of the categorization by Zeng et al. (2013) on the development of e-waste management in the country.

Managing transitions is inherently complex and far from a straightforward process (Loorbach et al., 2020). The model presented here is a simplification, as transition stages often happen simultaneously, and

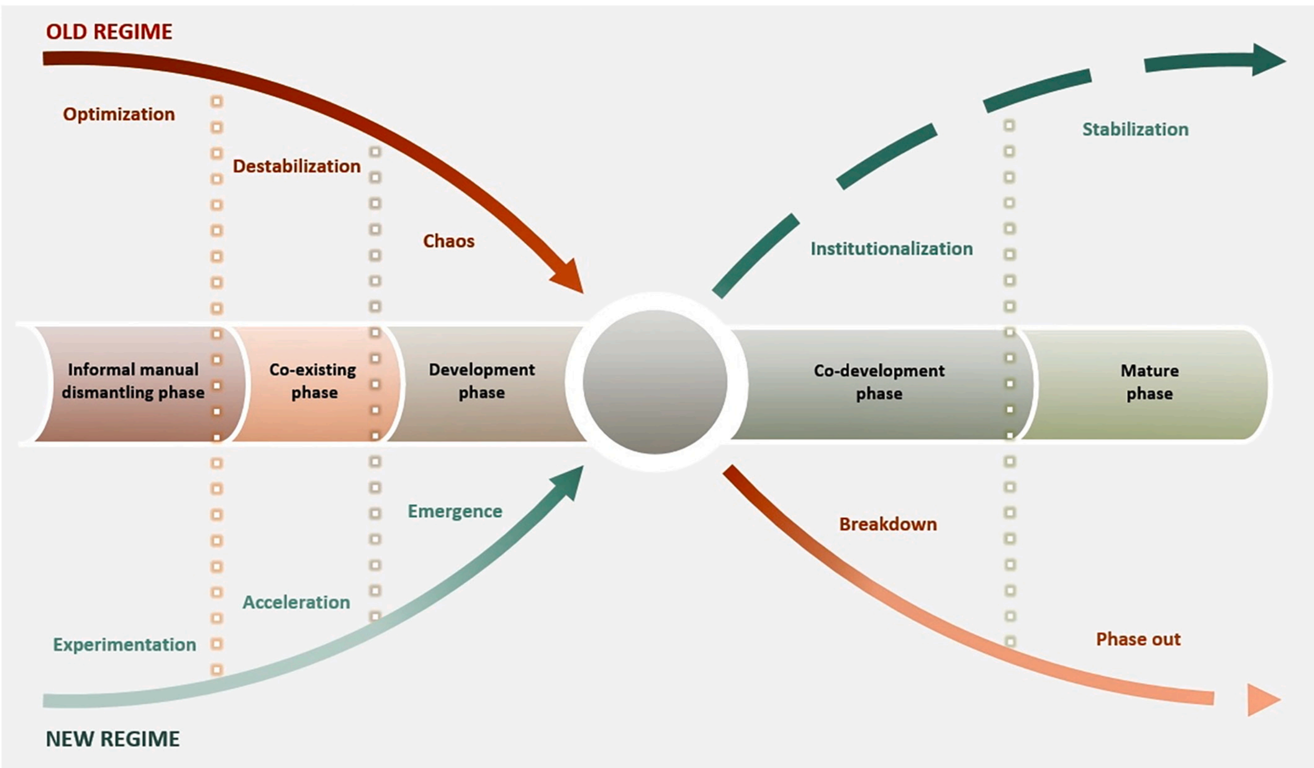

Fig. 7. Transition dynamics in the e-waste management system in China.

agents evolve at different points in time along the curve. Similarly, the categorization of the e-waste management developments in China is to some extent fluid: The phases overlap, and the e-waste management scenario is far more complex than such a model could depict.

We find that the introduction of e-waste management legislation in China has accelerated the transition toward formalization and has led to the destabilization of the previous regime, in which unregulated activities prevailed. With the continued development of legislation, such as the Fund policy, several agents have emerged in the new regime, while others had to adapt their activities. For instance, in the example case of Guangdong where an industrial park was implemented in 2010, workers that previously performed their labor independently were required to move to the park and adapt their operations according to the facility requirements.

Despite the several advancements achieved through the establishment of licensed companies, the informal sector remains the predominant path for e-waste collection in China, performed by individual collectors (CHEARI, 2019). Factors such as policy gaps (e.g., financial incentives that only cover certain appliances), as well as the country's social reality, influence its predominance.

Informal e-waste recycling has often been associated with severe environmental and social hazards. At the same time, it makes important contributions to a country's economy (Chi et al., 2011). The establishment of initiatives that address both sectors is key to enabling sustainability transitions. Although we observed improvements in Guiyu with the installation of the park, several challenges remain for including previous informal agents in the emerging regime. Therefore, we propose the implementation of a "co-development phase" (cf. Fig. 7) with a focus on knowledge and capacity building. This could be facilitated, for example, through the creation of cooperatives to gradually integrate informal agents into an established system. Studies with a focus on the implementation of cooperatives within e-waste management have shown great potential, such as for increased work recognition and job security (Ignatuschtschenko, 2017; ILO, 2014).

The integration of subsidies is suggested to be allocated also to the cooperatives. The subsidies would assist workers to cover some of the costs (e.g., rent) associated with the migration to the park, and potentially allow for the incorporation of a wider number of workshops. The co-development pathway here suggested would alter the direction of the transition, and ultimately the definition of the "mature phase" previously proposed by Zeng et al. (2013). Accordingly, the proposed mature phase would include both small organizations (e.g., cooperatives) and large-scale plants.

6. Final considerations

In this work, we have explored how the implementation of policies impacts a transition toward an established e-waste management system in China. We have presented the main advancements of legislation related to e-waste management in the country, in combination with two case studies on e-waste recycling. While the case study in Guangdong represents ongoing efforts to regulate the activities within the informal sector, the case study in Shaanxi is an example of the formal sector. Informed by transition management, we have applied the x-curve model of transition dynamics to the development of e-waste management in China to discuss the direction of the current transition, as well as to consider alternative pathways.

The analysis shows that external forces have the power to shape the e-waste management system in China through structures such as legislation and market. Overall, our observations suggest that legislation has the largest impact on the system, as well as the potential of driving sustainability transitions. For instance, the development and implementation of several policies in the country indicate a power for systemic transformation by enabling initiatives from the industry toward more sustainable e-waste recycling. This is demonstrated by the increased capacities within the formal sector after the financial incentives took place, as well as the implementation of several industrial parks.

The market is also identified as an external force that influences the e-waste management system in China. The focus on recovering certain metals from the PCBs (e.g., cobalt and copper) while others (e.g., gold) are not recovered is an example of the complexity of market dynamics, as well as how market prices (dependent on the amount of the recovered metal) can regulate e-waste recycling. In addition, market initiatives such as CSR strategies appear to be fundamental for the recycling of certain appliances, as shown in the case of fluorescent lamps.

However, despite the documented advancements, several challenges persist. For instance, many appliances are either not mentioned by legislation or not yet incorporated as part of the subsidies allocated from the government to licensed companies. Often, these appliances are not collected for recycling through the formal channels and are processed through the informal sector. Thus, we suggest further study on the viability to extend the coverage of financial incentives to more e-waste categories than the five identified in the First Catalog of WEEE Recycling.

Furthermore, we find evidence of a disconnection between legislation and the informal sector. Even though this sector continues to be the major pathway for e-waste collection in China and plays a crucial role in recycling, current policies focus on strengthening the formal sector. Especially in countries where the informal sector is predominant, we believe that it is fundamental to account for both sectors to establish plans for sustainability transitions in e-waste management. Therefore, we propose the implementation of more inclusive approaches (e.g., through the organization of cooperatives) that include the expertise of informal agents in the new regime.

The data from our field observations are constrained to short visits at two recycling sites, which focused on the broad picture through interviews and qualitative observations of processes. To establish a more comprehensive picture of the system, further research is suggested that incorporates data from more recycling sites and that includes long-term observations.

In our view, the opportunities created through the recovery of scarce minerals represent an important economic motivation for the continued implementation of legislation on e-waste management toward circularity. A national strategy toward resource recovery has the potential to minimize external dependence and assist in the future of electronics manufacturing while contributing to sustainability transitions. Through the case studies in Guangdong and Shaanxi, we have evidenced practical implications of the evolution of e-waste management legislation in both the informal and formal sectors in China. The cases have provided us with several examples of the importance to include both sectors in transitioning toward a more sustainable and established system.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

I. Poster

Schneider, A.F., Zeng, X., 2020. Towards more sustainable electronic waste management systems. Presented at the ICT4S 2020. Bristol (online), England.

TOWARDS MORE SUSTAINABLE ELECTRONIC WASTE MANAGEMENT SYSTEMS

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MOTIVATION

Worldwide, 44.7 Mt of e-waste were generated in 2016, with only 20% reported to be recycled through formal channels [1]. Here, we present results from field studies in three different settings.

BRAZIL

- The largest generator of e-waste in Latin America, equivalent to 1.5 Mt in 2016, 7.4 kg per capita [1].
- Combination of manual and mechanical e-waste processing.
- PCBs are mostly sent abroad for recycling.
- Innovative processing methods from formal companies have been emerging.

GHANA

- 1.4 kg per capita of e-waste generated in 2016, 39 Kt in total [1].
- Manual processes prevail.
- PCBs are sent abroad for recycling.
- Informal activities are predominant, with several social and environmental hazards associated (e.g., open-air burning of cables) [2].

MAIN CHALLENGES IDENTIFIED FROM THE STUDY

- High costs involved for an environmentally sound e-waste recycling.
- Lack of financial incentives.
- Insufficient connection between formal and informal activities.
- Little integration and high diversity among agents in the systems.
- Emerging understanding of the value of e-waste.

CHINA

- The largest generator of e-waste in the world, equivalent to 7.2 Mt in 2016, 5.2 kg per capita [1].
- Combination of manual and mechanical processes.
- All recycling processes are performed in the country.
- Development and implementation of the legislation has significantly changed the scenario, bringing an increase in formal activities [3].

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II. Interview guide for the informal sector in Ghana

1. What are the activities you perform? How long does each of them take?
2. What are the main challenges you face in each of these activities?
3. What do you believe to be the main opportunities/positive aspects involved in each of the activities?
4. Is the whole recycling process performed manually or is there any sort of mechanization?
5. Do different types of electronics impact the way the recycling process occurs?
6. Which is the most difficult process? Why?
7. Which is the process that takes the longest? Why?
8. Which are the most profitable components when recycling?
9. Do you recycle all the components? If not:
    a. Which components are not recycled?
    b. Why? (Lack of technology/not profitable?)
    c. What happens with these components?
10. What happens with the recycled materials?
11. Do you follow any regulations or need any approval to perform this activity? If so, of which kind?

III. Interview guide for the recycling organizations in Brazil

1. Informações gerais: (Overall information)
    a. Ano de criação da empresa: *(Year the company was funded)*
    b. Natureza da empresa: *(Type of company)*
    c. Território que abrange: *(Regions covered)*
    d. Tipos de eletroeletrônicos que recebe: *(Types of electronics received)*
    e. Número total de funcionários: *(Total number of employees)*
    f. Número de funcionários na linha operacional de reciclagem: *(Number of employees in the operational recycling line)*
    g. Quantidade média de eletroeletrônicos que recebe: *(Average amount of electronics received)*
    h. Quantidade média por categoria (e.g., computadores, celulares): *(Average amount per category (e.g., computers, mobile phones))*
2. Como ocorre a chegada dos aparelhos? Realiza coleta?

    (How do the devices arrive? Do you collect them?)
3. Atua geralmente em sua capacidade máxima?

    (Does the organization usually work at the maximum capacity?)
4. Como lida com a segurança de dados dos equipamentos descartados?

    (How do you handle data security concerns of discarded equipment?)
5. Como é feita a separação dos equipamentos na fase inicial (e.g., computadores x celulares x impressoras)?

    (How is the equipment separated in the initial phase (e.g., computers x cell phones x printers)?)
6. Quais os processos aqui realizados para a reciclagem de celulares e computadores?

    (What processes are carried out here for recycling mobile phones and computers?)
7. Quais os principais desafios / aspectos negativos em tais processos?

    (What are the main challenges / negative aspects in such processes?)
8. Quais as principais oportunidades / aspectos positivos em tais processos?

    (What are the main opportunities / positive aspects in such processes?)
9. Quais processos são realizados manualmente e quais mecanicamente?

    (Which processes are performed manually and which mechanically?)
10. Quais ferramentas são utilizadas?

    (Which tools are used?)
11. O processo de reciclagem difere de acordo com os modelos e o estado (e.g., dispositivo inteiro versus apenas PCB ou bateria) dos eletroeletrônicos?

(Does the recycling process differ according to the type of electronics and their state (e.g., entire device versus only PCB or battery)?)

12. Todos os componentes dos eletroeletrônicos são reciclados aqui?

(Are all the components from electronics recycled here?)

13. Em caso negativo, quais componentes / materiais não são reciclados?

(If not, which components / materials are not recycled?)

i. Por quê? (e.g., falta de tecnologia / não rentável?)

(Why? (e.g., lack of technology / not profitable?))

j. O que acontece com esses materiais?

(What happens to these materials?)

14. Como ocorre o manejo das baterias?

(How are the batteries handled?)

15. O que acontece com os materiais reciclados?

(What happens to the recycled materials?)

16. Quais regulamentações precisam ser seguidas para poder atuar no Brasil? E para exportar componentes?

(Which regulations need to be followed to run the activities in Brazil? And to export components?)

17. Há algum incentivo governamental para a atividade no Brasil?

(Is there any governmental incentive for the activity in Brazil?)

18. Em relação à Política Nacional de Resíduos Sólidos (PNRS), tem alguma crítica e/ou sugestão do que poderia ser melhorado?

(Regarding the National Solid Waste Policy (PNRS), do you have any criticism and/or suggestion of what could be improved?)

19. Quais você considera os principais gargalos no processo de reciclagem de eletroeletrônicos no Brasil?

(What do you consider the main bottlenecks in the process of recycling electronics in Brazil?)

20. Há cooperação direta com empresas produtoras de eletroeletrônicos?

(Do you have direct cooperation with manufacturing companies of electronics?)

21. Existe cooperação com outras instituições (e.g., setor público e/ou privado)?

(Do you cooperate with other institutions (e.g., public and/or private sector)?)

22. Como comunica suas atividades aos clientes?

(How do you communicate your activities to the customers?)

IV. Interview guide for the recycling organization in China

2. When was the company created?

3. What is the current recycling capacity?

4. Which kinds of e-waste the company receives and process?

5. What are the main activities performed by your company?

6. Who are your main suppliers (e.g., companies, individual collectors, etc.)?

7. Is there any initiative towards reuse and/or repair in your company?

8. Which processes are performed manually and which mechanically?

9. Do different models of electronics impact the way recycling occurs?

10. Do you recycle all the components of e-waste? If not:

   a. Which components/materials are not recycled in the company?

   b. Why? (Lack of technology/not profitable?)

   c. What is the destination of the non-recycled materials?

11. What happens with the recycled materials?

12. Do you have any cooperation with other organizations or the informal sector?

13. Do you receive any subsidy for the activity?

14. What do you believe to be the main challenges and opportunities for e-waste recycling?