Informal processing of electronic waste in Agbogbloshie, Ghana:

A complex adaptive systems perspective

Alice Frantz Schneider
Dept. of Informatics
University of Oslo
Oslo, Norway
alicefr@ifi.uio.no

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.

ACKNOWLEDGMENTS

This paper is written as part of Sustainable Market Actors for Responsible Trade (SMART), a HORIZON2020-financed research project (grant agreement No. 693642). Sincere thanks to Prof. Dr. Martin Oteng-Ababio, Louis Kusi Frimpong, and Alexander Buertey of the University of Ghana, for their support in my data collection. In addition, I would like to thank the workers in Agbogbloshie, the organizations that participated in this research, and Dr. Maja van der Velden and Dr. Hanne Cecilie Geirbo of the University of Oslo for sharing their time and knowledge.

REFERENCES

[1] Worldometers, "Computers sold in the world this year." [Online]. Available: http://www.worldometers.info/computers/. [Accessed: 15-Mar-2019].

[2] Kantar Worldpanel, "An incredible decade for the smartphone: What's next? The Future of Mobile is in Combining Devices, Content, and Services," 2017.

[3] L. M. Hilty, "Electronic waste—an emerging risk?," *Environ. Impact Assess. Rev.*, vol. 25, no. 5, pp. 431–435, Jul. 2005.

[4] C. P. Balde, V. Forti, V. Gray, R. Kuehr, and P. Stegmann, "The Global E-waste Monitor 2017: Quantities, Flows and Resources," United Nations University, International Telecommunication Union, and International Solid Waste Association, Bonn/Geneva/Vienna, 2017.

[5] K. Daum, J. Stoler, and R. J. Grant, "Toward a More Sustainable Trajectory for E-Waste Policy: A Review of a Decade of E-Waste Research in Accra, Ghana," *Int. J. Environ. Res. Public. Health*, vol. 14, no. 2, p. 135, Jan. 2017.

[6] T. Feldt *et al.*, "High levels of PAH-metabolites in urine of e-waste recycling workers from Agbogbloshie, Ghana," *Sci. Total Environ.*, vol. 466–467, pp. 369–376, Jan. 2014.

[7] M. Akormedi, E. Asampong, and J. N. Fobil, "Working conditions and environmental exposures among electronic waste workers in Ghana," *Int. J. Occup. Environ. Health*, Dec. 2013.

[8] E. M. Huang and K. N. Truong, "Breaking the Disposable Technology Paradigm: Opportunities for Sustainable Interaction Design for Mobile Phones," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2008, pp. 323–332.

[9] M. Schluep, E. Müller, L. Hilty, D. Ott, R. Widmer, and H. Böni, "Insights from a decade of development cooperation in e-waste management," presented at the ICT4S – First International Conference on Information and Communication Technologies for Sustainability, Zürich, 2013, pp. 223–230.

[10] R. J. Grant and M. Oteng-Ababio, "The Global Transformation of Materials and the Emergence of Informal Urban Mining in Accra, Ghana," *Afr. Today*, vol. 62, no. 4, pp. 2–20, Jun. 2016.

[11] J.-M. Davis, G. Akese, and Y. Garb, "Beyond the pollution haven hypothesis: Where and why do e-waste hubs emerge and what does this mean for policies and interventions?," *Geoforum*, Oct. 2018.

[12] K. A. Asante *et al.*, "Multi-trace element levels and arsenic speciation in urine of e-waste recycling workers from Agbogbloshie, Accra in Ghana," *Sci. Total Environ.*, vol. 424, pp. 63–73, May 2012.

[13] T. Itai *et al.*, "Variation and distribution of metals and metalloids in soil/ash mixtures from Agbogbloshie e-waste recycling site in Accra, Ghana," *Sci. Total Environ.*, vol. 470–471, pp. 707–716, Feb. 2014.

[14] N. M. Tue *et al.*, "Release of chlorinated, brominated and mixed halogenated dioxin-related compounds to soils from open burning of e-waste in Agbogbloshie (Accra, Ghana)," *J. Hazard. Mater.*, vol. 302, pp. 151–157, Jan. 2016.

[15] E. F. Amankwaa, "Livelihoods in risk: exploring health and environmental implications of e-waste recycling as a livelihood strategy in Ghana," *J. Mod. Afr. Stud.*, vol. 51, no. 4, pp. 551–575, Dec. 2013.

[16] J. H. Holland, "Studying Complex Adaptive Systems," *J. Syst. Sci. Complex.*, vol. 19, no. 1, pp. 1–8, Mar. 2006.

[17] R. Abbott and M. Hadžikadić, "Complex Adaptive Systems, Systems Thinking, and Agent-Based Modeling," in *Advanced Technologies, Systems, and Applications*, Springer, Cham, 2017, pp. 1–8.

[18] M. D. Cohen and R. Axelrod, *Harnessing Complexity: Organizational Implications of a Scientific Frontier*. Simon and Schuster, 2000.

[19] A. Fereidunian, H. Lesani, M. A. Zamani, M. A. S. Kolarijani, N. Hassanpour, and S. S. Mansouri, "A Complex Adaptive System of Systems Approach to Human–Automation Interaction in Smart Grid," in *Contemporary Issues in Systems Science and Engineering*, M. Zhou, H.-X. Li, and rgot Weijnen, Eds. John Wiley & Sons, Inc., 2015, pp. 425–500.

[20] I. Nikolic and J. Kasmire, "Theory," in *Agent-Based Modelling of Socio-Technical Systems*, Springer, Dordrecht, 2013, pp. 11–71.

[21] J. H. Holland, *Emergence: From Chaos To Order*. Cambridge, Mass: Basic Books, 1999.

[22] T. Y. Choi, K. J. Dooley, and M. Rungtusanatham, "Supply networks and complex adaptive systems: control versus emergence," *J. Oper. Manag.*, vol. 19, no. 3, pp. 351–366, May 2001.

[23] S. Walby, "Complexity theory, systems theory, and multiple intersecting social inequalities," *Philos. Soc. Sci.*, vol. 37, no. 4, pp. 449–470, Dec. 2007.

[24] J. K. Seadon, "Sustainable waste management systems," *J. Clean. Prod.*, vol. 18, no. 16, pp. 1639–1651, Nov. 2010.

[25] M. Ikhlayel, "An integrated approach to establish e-waste management systems for developing countries," *J. Clean. Prod.*, vol. 170, pp. 119–130, Jan. 2018.

[26] L. A. Bollinger, C. B. Davis, and I. Nikolic, "An Agent-Based Model of a Mobile Phone Production, Consumption and Recycling Network," in *Agent-Based Modelling of Socio-Technical Systems*, Springer, Dordrecht, 2013, pp. 221–243.

[27] D. Amuzu, "Environmental injustice of informal e-waste recycling in Agbogbloshie-Accra: urban political ecology perspective," *Local Environ.*, vol. 23, no. 6, pp. 603–618, Jun. 2018.

[28] E. F. Amankwaa, "E-Waste Livelihoods, Environment and Health Risks: Unpacking the Connections in Ghana," *West Afr. J. Appl. Ecol.*, vol. 22, pp. 1–15, 2014.

[29] G. A. Akese and P. C. Little, "Electronic Waste and the Environmental Justice Challenge in Agbogbloshie," *Environ. Justice*, vol. 11, no. 2, pp. 77–83, Mar. 2018.