Miller, Elizabeth M.

No rest for the complex: Information flows, adaptation, and emergence in circular supply systems

Published in:
Circular Economy Supply Chains

DOI:
10.1108/978-1-83982-544-620221003

Published: 19/04/2022

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Miller, E. M. (2022). No rest for the complex: Information flows, adaptation, and emergence in circular supply systems. In *Circular Economy Supply Chains: From Chains to Systems* (pp. 49-65). Emerald. https://doi.org/10.1108/978-1-83982-544-620221003

Miller, E. M. (2022). No Rest for the Complex: Information Flows, Adaptation, and Emergence in Circular Supply Systems. In L. Bals, W. L. Tate, & L. M. Ellram (Eds.), *Circular Economy Supply Chains: From Chains to Systems* (pp. 49–65). Emerald Publishing Limited. DOI: 10.1108/9781839825446

No Rest for the Complex: Information Flows, Adaptation, and Emergence in Circular Supply Systems

Elizabeth M. Miller

Abstract

To create circular economies, we need supply systems to convey materials between their use lives. Often, though, it is not possible to control an entire supply network. Without a coordinator to implement circular economy principles, how can circular supply systems come to be? This chapter sets out to build on complex adaptive systems (CAS) theory and circular economy research to conceptualize how information flows between actors can facilitate the emergence of a circular supply system. It begins by outlining why a supply network can be considered a CAS, as well as the CAS progression from information to adaptation to emergence. Next, it argues that information on local supply networks, extended supply systems, and biosphere impacts is particularly important for circular production. Finally, it concludes with two potential types of emergence that can stem from these information flows: (1) new actor roles and networks and (2) new spatial and temporal patterns. Ultimately, this conceptual overview aims to give researchers and practitioners a CAS frame for thinking about how continual adaptation to information flows can enable change toward circular supply systems.

Introduction

It is 1820, and there is a knock on your door. You are expecting him, the traveling salesman bringing tinware to exchange for your time-worn rags. Your scraps would be sold on to the paper industry that depended on household rags in places like the United States, where paper's necessary fiber inputs were near impossible to find outside of the home (Strasser, 2000). From scarcity emerged symbiosis.

Fast forward to today, and there are calls to return to such symbiosis – though probably with a lot less door knocking – under the umbrella of *circular economy*. The concept of circular economy is both popular and contested (Korhonen et al., 2018; Merli et al., 2018), with one study identifying 95 different definitions in scholarly literature (Kirchherr et al., 2017). To put it succinctly, circular economy means keeping materials circulating through strategies like reuse, remanufacturing, and recycling (de Jesus & Mendonça, 2018; Manninen et al., 2018; Urbinati et al., 2017). At its most ambitious, the circular economy ideal aims for a whole new paradigm in how we make, use, and dispose of goods (Genovese et al., 2017; Prieto-Sandoval et al., 2018) to ultimately "maximize ecosystem functioning and human well-being" (Murray et al., 2017, p. 377).

Unlike nineteenth-century rag collection, the current call for circularity in industrialized economies is driven not by scarcity but excess. On the surface, this may seem counterintuitive. Scarcity is an acute problem, while the perils of excess may stay long hidden. Waste is hauled far from residential areas, and natural resource overextraction (and the resulting ecological damage) takes place even further away. Yet some mature industrialized economies are investing in circular solutions to problems that are largely "out of sight, out of mind." Why?

If we start from the premise that each of our lives takes place amid myriad, intertwined *complex adaptive systems* (CAS) – which give us stocked supermarkets (Choi et al., 2001) and democratic governance (Wiesner et al., 2019) and even our bodies' development (Levin, 1998), among many other things – then we can start to understand that this investment in circularity comes as an adaptive response to something communicated through information signals. Signals that may have come from faraway places and times. Perhaps a future projection about plastic in the ocean, or the destruction of a distant jungle, or the potential cash that burns up in trash incinerators. Or a variety of information signals that have accumulated over time, from which action eventually emerged.

For these information signals to lead to the emergence of a circular economy, it is clear that change within supply networks is necessary (Farooque et al., 2019; Genovese et al., 2017; Parida et al., 2019). Much like how the early nineteenth-century American paper industries depended on interactions between traveling salesmen and the (usually) women who saved scraps of household fabric, modern firms generally depend on others if they want to engage in circular production. The question, then, is how new patterns and structures can emerge among supply networks in the current push for circularity.

In this chapter, we will look at the kinds of information that can help trigger the emergence of circular supply systems. I begin by outlining why supply networks can be considered CAS, as well as the CAS progression from information to adaptation to emergence. Next, I argue that information on local supply networks, extended supply systems, and biosphere impacts is particularly important for circular production. Finally, I conclude with different types of emergence that could potentially stem from these information flows.

How New System Configurations Emerge

To understand how information can help facilitate a shift toward circular supply systems, we first need to understand how new configurations emerge in complex adaptive supply systems more generally. In this chapter, the broader system including relevant environmental actors is referred to as a "supply system," whereas the direct chain of actors that interact to produce material goods is referred to as a "supply network," in a similar vein to Tate, Bals, Bals, and Foerstl (2019).

Supply Chains as CAS

Modern supply chains have the structure and behaviors of CAS (Choi et al., 2001; Pathak et al., 2007; Surana et al., 2005). CAS are “systems that have a large number of components, often called agents, that interact and adapt or learn” (Holland, 2006, p. 1). On the structure side, supply systems fit this definition since they are comprised of large numbers of interconnected actors (Choi et al., 2001; Pathak et al., 2007; Surana et al., 2005). Large may be an understatement: Choi et al. (2001, p. 357) refer to supply networks as “enormously large, complex, and fluid,” and Surana et al. (2005, p. 4235) likewise refer to the “overwhelming number of interactions and inter-dependencies” that they contain.

A large number of components do not automatically make a CAS, however. There is a difference between complicated and complex. That which is *complicated* “can be taken apart into its bits and reassembled from those bits,” while that which is *complex* cannot (Byrne & Callaghan, 2014, p. 4). In a complex system, there are nonlinear dynamics between the components (Pathak et al., 2007). System patterns can emerge that are different from the sums of their component parts.

How does this happen? The actors in a CAS work in parallel, each carrying out their own agendas and emitting their own information signals (Holland, 2006; Levin, 1998). Importantly, these actors have agency, meaning that they are able to influence the systems of which they are part rather than only being influenced by them (Choi et al., 2001). Collectively, their independent, parallel actions can lead to the emergence of new patterns, which are only visible through the interactions between actors in a system (Monat & Gannon, 2015). Put another way, when individual actors independently interact, without any central authority telling them what to do (*self-organization*, in systems parlance), tacit structures emerge that guide future behavior.

Supply systems are complex, not merely complicated, and thus have the behavior of CAS. These behaviors include adaptive capacity, interconnectivity (both within and between supply networks), emergent behavior, and co-evolution with the external environment (Pathak et al., 2007). For example, in a large supply network, individual companies may not be able to identify all of the firms in the network. They make decisions based on the information they have from their own first-tier (and maybe also second-tier) suppliers and their direct buyers, and the interaction of all of these decisions eventually makes it possible to produce, say, a car (Choi et al., 2001). No one company, even the final assembler, has authority over the whole network. Instead, they each have autonomy to make decisions but become interdependent when, for example, "improving due date performance, increasing quality or reducing costs" (Surana et al., 2005, p. 4240). The supply network is also impacted by the external operating environment, such as changes in consumer demand (Choi et al., 2001; Pathak et al., 2007).

Thus, supply systems have both the structure and the behavior of CAS. From this foundation, we can open up the dynamics of how adaptation and emergence come about.

Information Needed for Supply Chain Adaptation

Adaptations are often the result of conditional actions in response to information, another central characteristic of a CAS (Holland, 2006). Conditional action is the result of a classic "if/then" sequence of decision making, in which circumstance A (identified via an information signal) leads to action B (Holland, 2006). This is how interconnected actors in a system can change one another: the decision of one, once transmitted as information, then triggers a conditional decision in another. Over time, these decisions add up, forming a dynamic structure that can change as actors and circumstances do. Of course, incorrect or delayed information can result in suboptimal actions (Surana et al., 2005) – misunderstanding the “if” condition can lead to the wrong “then.”

These information flows can create interdependencies between actors in a CAS that ultimately lead to co-adaptation. For each conditional action, actors strive to learn the optimal “then” for each “if,” though it may take some time to figure out which actions caused a desirable outcome and what the underlying behavioral pattern looks like (Holland, 2006). The interdependencies can extend beyond just the direct chain(s) of interactions in a system. Actors in the broader environment, a higher-level system, can also impact and be impacted by the choices of the actors within it (Choi et al., 2001; Levin, 1998).

In supply networks, information flows are essential to the self-organized adaptation that makes and moves all the pieces of a car or a computer; they are no less critical than the flows of goods and money. Surana et al. (2005, p. 4239) give them equal weight, defining supply networks as “transfer[ing] information, products and finances between various suppliers, manufacturers, distributors, retailers and customers.” The information flows – which are mediated in supply networks through interfirm connections built on physical infrastructure like “telephone lines, fax numbers, electronic data interchange systems” (Pathak et al., 2007, p. 552) – may be localized and incomplete, but firms nonetheless adapt their decisions to them (Choi et al., 2001; Pathak et al., 2007; Surana et al., 2005). Success in a supply network depends on information that is as up-to-date and accurate as possible (Surana et al., 2005). As firms learn from the others in the network, the schemas on which they base their decisions may evolve accordingly (Pathak et al., 2007).

From Adaptation to Emergence

As components in a CAS adapt to one another, higher-order patterns and structures eventually emerge (Levin, 1998), and this is true in supply networks as well. Since it is rare for any actor to have control over all suppliers, the function of a complex supply network emerges from concurrent adaptations to local information (Choi et al., 2001; Surana et al., 2005). Firms that do the final assembly of products usually only choose their first-tier and possibly second-tier suppliers, which go on to choose their suppliers, and so on throughout the network. A product's supply network emerges from this self-organized adaptation (Choi et al., 2001), as does the network's ability to fulfill orders without any central coordinator (Surana et al., 2005). Not all emergence is desirable, though. As example frequently mentioned in complex adaptive supply network literature is the *bullwhip effect*, in which small changes in demand can lead to majorly disproportionate reactions upstream (Choi et al., 2001; Pathak et al., 2007; Surana et al., 2005). Ultimately, managers of firms within supply networks have to balance controlling what they can and adapting to new patterns as they emerge (Choi et al., 2001; Surana et al., 2005).

Information Flows for Circular Production

These CAS dynamics can help us understand the kinds of information needed for circular supply systems to emerge. Specifically, actors need information from (1) local supply networks, (2) extended supply systems, and ideally also (3) the biosphere, in keeping with Murray et al.'s (2017, p. 377) definition of circular economy as "maximiz[ing] ecosystem functioning." They continually need such information flows and adaptive capacity to react, as there is no single equilibrium in any CAS. Instead, systems are continually evolving, meaning that actors need to learn and adapt to changing conditions as they come (Gunderson & Holling, 2002). The circular economy is no exception. The ecological world is an open system, with energy coming in from the sun and matter lost to entropy (Korhonen, Honkasalo, & Seppala, 2018; Skene, 2018), so we can never reach an equilibrium of perfect circularity. We therefore need information to continually adapt.

Local Supply Networks

Modern supply chains often traverse the globe, but circular supply networks may include re-localizing production. Local circular supply networks reduce energy consumption needed for transportation and make it easier to monitor systemic impacts, so it should be a priority to develop circular supply networks within a relatively limited geographic scope (Korhonen, 2020). Thus, the local information discussed below is meant to be truly, spatially local.

Two key types of local information are necessary in a circular supply network: what waste materials are available, and what can be done with them. These information flows are put into action by the two new actor roles in circular supply networks identified by Tate et al. (2019), scavengers and decomposers. *Scavengers* are defined as “companies that feed off the waste resources of other companies in the system, redistributing resources […] back into the system to companies that can reuse the materials” (Tate et al., 2019, p. 117). *Decomposers*, on the other hand, are “companies that use waste resources from the producers, consumers and scavengers” (Tate et al., 2019, p. 117).

One source of waste materials for scavengers is local manufacturers, which may have side stream waste that other firms could use (Wells & Seitz, 2005). Companies that use post-business waste sources need to set up information flows to understand what materials are available, as well as the quantities and rhythms with which that waste is produced. The latter two are especially important, as limited quantities can impact companies’ ability to scale circular production (Patala et al., 2018; Sprecher et al., 2017). In some cases, the most promising local opportunities could require aggregating waste streams from competitors to create value from waste flows. A representative from Finnish pulp and paper company UPM commented on its industry competitors' matching side stream wastes, saying that "we have a lot [of side stream waste] together, but not enough alone" (Miller, 2018, p. 51).

However, companies traditionally do not share information on their waste streams with one another, out of fear of revealing sensitive information (Patala et al., 2018). Close geographic proximity can facilitate collaboration (Prendeville et al., 2018) and even potentially alleviate some of the trust issues around waste information sharing, as companies can directly but informally share information with one another (Patala et al., 2018). This is especially possible in tightly coupled industrial symbiosis systems. Industrial symbiosis systems, which are typically geographically bound sets of firms that input one another's waste as feedstocks to their own processes (Chertow, 2000), can facilitate stronger trust, integration, and information sharing between firms (Lopes de Sousa Jabbour et al., 2019). Even in more loosely coupled supply relationships, a sense of collaboration "is a prerequisite to information sharing" (Surana et al., 2005, p. 4262).

The question of waste availability and forecasting is even more difficult for companies using post-consumer waste, since there is little information on specific post-consumer waste flows, aside from flows like cardboard and metal that may be collected by municipal waste management services. Without data on quantities of waste available, companies might end up with either too little or too much of the material they need. An example of this is the Finnish home textile company Finlayson, which has run collection drives in its retail locations for customers' old bedsheets to make into traditional Finnish rag rugs to sell. In their early collection drives, the company received far more sheets than they had expected. Luckily, they were able to use their existing warehouse space and personnel to sort the several tons of sheets that they collected (Miller, 2018). There are no data sources on how many old linens are collecting dust in people's closets, but a hypothetical future circular supply network could have platforms for entering such data to help companies like Finlayson that want to take on the role of scavenger.

The scavengers in a circular supply system can also help overcome one of the key barriers to shifting toward circularity: reverse logistics to get waste materials back to a centralized place for processing (Farooque et al., 2019). While this role is typically played by municipal waste management organizations, the shift to circular supply systems is opening up new avenues for other firms to begin taking on this role as well through new recycling business models (Lüdeke-Freund et al., 2019; Patala et al., 2018). There is room for scavengers to get creative about how they handle reverse logistics. One example is geographically decentralized waste collection systems, such as point-of-sale bottle return programs that use scanners and product data to make it convenient for customers to bring their waste to scavengers (Miller, 2018).

In places without well-developed waste management infrastructure, the scavenger role may also be played by individuals who sell collected waste on to centralized facilities (Troschinetz & Mihelcic, 2009). For example, the Shanghai-based decomposer Waste2Wear, which creates textiles from plastic waste, has a collaboration with local actors to pay former fishermen affected by Yangtze River fishing bans to collect and sell plastic removed from waterways (Waste2Wear, 2020). However, in these kinds of partnerships, companies must take care not to perpetuate the poor working conditions and minimal incomes of independent waste scavengers (Troschinetz & Mihelcic, 2009).

To put scavenged materials to use, decomposers first need information on what is in them. In the case of remanufacturing, they also need information about the use life to help assess the condition of the product (Laubscher & Marinelli, 2014). Producers can help scavengers and decomposers by making product information available, which makes collecting, sorting, and secondary production more feasible (Jabbour et al., 2017; Laubscher

& Marinelli, 2014). This can be done, for example, through material passports, which travel with a product and contain full information on the component materials (Tate et al., 2019). A solution like material passports decouples these materials' secondary use from the actors that produced them, ensuring that this information still gets passed along even if the producing company goes out of business or otherwise falls out of the circular supply network. New technologies like radio-frequency identification (RFID) scanning and blockchain are promising for enabling ideas like material passports (Garcia-Torres et al., 2019; Tate et al., 2019). These technologies can help enable the volume, variety, velocity, and/or veracity of data needed to optimize information flows throughout the product's life cycle (Jabbour et al., 2017).

It is not enough, however, to only share information on the products themselves – decomposers also need to have information about what they can do with waste materials. Although modern recycling practices for some materials have been around for decades, material scientists are still studying how to give new life to other materials, particularly those with a mix of component materials. One such example is cotton-polyester blends, which are extremely difficult to separate (Haslinger et al., 2019). Various research projects are underway to uncover methods for recycling cotton-polyester blends (for example, Haslinger et al., 2019; Zou et al., 2011). Likewise, material scientists can also develop new material alternatives that are more conducive to circularity. Eventually, the findings of these research projects can be passed on to decomposers, who can bring the resulting technologies to the market. Decomposers also need to understand the potential challenges of their secondary production, from the risks of refurbishing plastics (Winans et al., 2017) to material degradation over time (Zink & Geyer, 2017).

Extended Supply Systems

Information on material properties and availability are not the only important information flows in a circular supply system. Information from the broader system of related actors is essential as well. One critical flow is information from governments to supply networks on their circular initiatives. Governments can play an important role in incentivizing the emergence of circular supply networks through circular-friendly policies, funding, research, partnership development, and/or public procurement standards (de Jesus & Mendonça, 2018; Masi et al., 2017; Patala et al., 2018; Prendeville et al., 2018; Winans et al., 2017). They could go even further in proactively facilitating circular economy through product standards, such as for ease of disassembly (Vanegas et al., 2017), or by launching city-level circular experimentation (Prendeville et al., 2018). Regulations and government-imposed reporting requirements can also aid in the development of circular finance products that are not simply exercises in greenwashing (Dewick et al., 2020). Conversely, regulations, such as what is legally considered waste and what can be done with it, and rescinding financing previously offered can be barriers to the emergence of circular supply networks (de Jesus & Mendonça, 2018; Winans et al., 2017). Governments need to clearly communicate all of this so that firms can adapt.

Another relevant information flow is on projected critical material shortages, which could potentially be a driver toward circularity. These shortages can be driven by diminishing supplies to be extracted or temporary disruptions to supply chains (Gaustad et al., 2018). While material shortages seem like an intuitive driver of circularity, short supply disruptions may not be enough to trigger a shift toward circular supply chain configurations, as companies can take easier steps to build their supply resilience (Sprecher et al., 2017). However, information on long-term supply issues could be more likely to induce scavengers to prioritize materials that may eventually become scarce.

Finally, retailers looking to go circular also need to understand consumers' willingness to buy in to their circular visions, whether that means buying circular products or bringing in their own waste to be remade. One of the key issues is the perception that products made from waste materials are of lower quality (Wang et al., 2018), which can prevent circular goods from displacing noncircular ones. This would simply "grow the 'pie'" of total goods available on the market (Zink & Geyer, 2017, p. 600), negating the capacity of circular economy to reduce resource use. Promisingly, though, it appears that the demand for circular products has been improving (Winans et al., 2017), which could mitigate the risk of this kind of "circular economy rebound" (Zink & Geyer, 2017). Information to consumers on circular product quality is therefore key.

In some circular systems, consumers do more than play the role of buyer – they can also be the source of waste materials for scavengers. Post-consumer waste is "the most difficult [material flow] to put into operation" (Wells & Seitz, 2005, p. 250), and that difficulty stems in large part due to the lack of education about circular behaviors (de Jesus & Mendonca, 2018). Consumers need to understand where to find scavengers – or how to become scavengers themselves, as discussed in the chapter by Hazen et al. – as well as any material requirements, such as whether materials need to be cleaned or taken apart before bringing them to a scavenger. Post-consumer flows also bring scavengers the challenge of identifying what is in materials, as consumers generally do not have this information the way industrial actors do (Singh & Ordoñez, 2016). However, despite the challenges, there are benefits to pursuing post-consumer flows, which can be facilitated by properly educating consumers. These flows can provide a domestic source of rare critical materials (Gaustad et al., 2018), as we saw with the nineteenth-century rag collectors and the paper industry. Additionally, getting consumers on board with circular initiatives could potentially make a more favorable policy environment, at least in democratic systems.

Biosphere Impacts

Finally, circular supply systems should ideally have information flows that allow them to understand and adapt to humanity's impacts on the biosphere. For supply systems to be truly sustainable, firms need to shift to a new logic that centers long-term ecological sustainability in their decision making (Montabon et al., 2016). To have biosphere benefits, firms in a circular supply network need information flows on biophysical indicators at multiple scales and the capacity to make decisions based on them. This necessitates actors translating global- or regional-scale indicators, such as the planetary boundaries, into information on the firm or industry level (Whiteman et al., 2013). The *planetary boundaries* are targets setting the "safe operating space" in nine planetary systems, beyond which these life-sustaining systems may become critically destabilized (Steffen et al., 2015, p. 736). One way to operationalize them for business planning is to incorporate planetary boundary indicators into lifecycle assessments or new tools "to facilitate predictive assessment" (Clift et al., 2017, p. 4).

For circular supply systems specifically, actors need to understand how to work within biosphere-appropriate quantities and rates of resource extraction and discarding. This could mean implementing material footprint frameworks tracking inputs and outputs (Helander et al., 2019) or translating biophysical limits into firm-level resource budgets, ideally using conservative estimates for resource use (Desing et al., 2020). Information that allows syncing production and disposal to the regenerative and absorptive rhythms of ecological systems would also be beneficial (Suárez-Eiroa et al., 2019). This is important for the management of both biological and technological resources, as even biological resources "will seriously disrupt our ecosystems" if they are not released "carefully, at a tempo in resonance with the natural order" (Skene, 2018, p. 485). Technologies like remote sensing already exist to monitor distant changes (Skene, 2018), and we need actors with the resources, capabilities, and motivation to use these technologies.

To put information flows on biophysical limits to use in decision making, it is necessary to have organizations in the broader circular supply systems that can track and operationalize information at different scales. Data from outside of an organization's scale of focus can end up as invisible "masked feedback" that is missed because human and ecological systems often operate on different temporal and/or spatial scales (Sundkvist et al., 2005, p. 228). Partnering with other organizations that are attuned to different scales can help broaden the scales that organizations take into account (Bansal et al., 2018). Governmental actors monitoring broader temporal and spatial scales can incorporate data on those scales into incentives and policies, and organizations monitoring local, faster changes can likewise report impacts on the ground.

Potential Emergence in Circular Supply Systems

From these information flows, new patterns and structures may emerge if actors choose to adapt accordingly. Two types of emergence in particular may emerge, as shown in Table 3.1: (1) new actor roles and networks and (2) new spatial and temporal patterns.

Table 3.1. Key Information Flows on Local Supply Networks, Extended Supply Systems, and Biosphere Impacts That Can Contribute to the Emergence of Circular Supply Systems.

Category	Type of information needed	What could emerge
Local supply networks	• What waste materials are available in local area • Quantities and rhythm of waste production • How to collect waste materials • Waste material properties • What can be done with waste materials • Subjective foundations of trust between actors	• New actor roles and networks ○ The actor roles of scavenger and decomposer ○ Supply networks for circular products • New spatial and temporal patterns ○ Local supply networks and industrial symbiosis ○ Increased length of time materials can be re-produced when material information is embedded in the products

Extended supply systems	• Governmental incentives for circular production • Regulative restrictions on how waste is used • Projections on critical material shortages • Consumer demand for circular products • How consumers can participate in post-consumer waste collection	• New actor roles and networks o New circular practices in response to governmental incentives and/or constraints o New customer segments due to increased perception of circular products' value o Two-way material flows between producers and consumers • New spatial and temporal patterns o Local resilience to critical material shortages
Biosphere impacts	• Firm- or industry-level translations of larger-scale goals, like planetary boundaries or resource budgets • Regenerative and absorptive rhythms of ecological systems • Monitoring data on biosphere changes	• New actor roles and networks o Partnerships between organizations that monitor different scales • New spatial and temporal patterns o Efforts to sync material flows with regenerative and/or absorptive cycles o Consideration of longer time horizons and/or broader spatial scales in organizational planning

New Actor Roles and Networks

When the kinds of information signals discussed above are received by actors with the capacity, autonomy, and will to react to them, new circular production actor roles and networks can emerge. Through the lens of conditional action (and put oversimply), that process would start from information like this:

- *if* waste material X can be remade into something of value, and
- *if* it is available in sufficient qualities and quantities, and
- *if* the external environment is conducive to such initiatives, and
- *if* we have the means to find out this information,
- *then* we need the capacity either ourselves or through partners we trust to create value from that waste material.

From there, supply relationships can emerge, each self-organizing the resources and capabilities they need to deliver their part of the production process. The actor roles of scavenger and decomposer will need to be fulfilled, sometimes by producers themselves, if no one else (Tate et al., 2019). The emerging circular supply networks also depend on and co-evolve with environmental conditions, such as government policies.

To illustrate this, we can return to the case of home textile company Finlayson's production of rag rugs from customers' old sheets:

> Rag rugs are a traditional Finnish handicraft, one that has largely died out over the years […] Finlayson wanted to revive this tradition, and at the same time the CEO learned about the problem of textile waste in Europe and felt the company had to do something. He realized that these two things would work well together […] They held the first collection in the spring of 2016 and received 11 tonnes of old sheets from customers […] In exchange for the sheets, customers were given discounts on their next purchases, as it was important to the company to show that "the old sheets have value" (Finlayson Interview, 2018) […] Because rag rugs had waned in popularity, it was no longer common for rag rugs to be industrially made at that point. They thought about purchasing the machinery themselves, but they ended up finding a supplier in western Finland. It was a small company run by a couple that had a half day's work at best on most days because rag rugs were such an "unpopular thing to make" (Finlayson Interview, 2018). Now, because of the Finlayson contract, the company is working full time and has hired new employees. (Miller, 2018, pp. 44–45)

In this example, the supply network for the rag rugs emerged through self-organization. Finlayson put out information on the sheet collection and incentives to the customers within their extended supply system. The customers that adapted to that information by bringing in their sheets then became part of the direct supply network. On the manufacturing side, Finlayson found, via some sort of information signals, one of the last remaining industrial producers of rag rugs in Finland. Thanks to the Finlayson contract, new temporal patterns (working full time) and resource structures (employing more personnel) emerged within that supplier. The whole rag rug initiative was kicked off by two pieces of information from the extended supply system: (1) Europe's textile waste problem and (2) the at least implicit information that there would be a market for reviving traditional Finnish rag rugs.

New Spatial and Temporal Patterns

As actors self-organize into circular supply systems, new spatial and temporal patterns can also emerge. Spatial scales of focus can both shrink and expand, and temporal scales can extend into the distant future.

Spatially, geographically close supply systems can emerge. This happens because actors in a local setting can monitor, react to, and build trust among one another more easily. Actors may even choose to co-locate in an industrial symbiosis system. Additionally, local circular production can help build local resilience to critical material shortages, especially when they can intake post-consumer waste flows of materials under threat.

Temporally, circular supply systems can also expand time horizons across which product and material information can travel. Technologies like blockchain that enable material passports can act as a bridge to the distant future, encouraging present-day actors to think about how to talk to circular supply systems in that faraway time. This could mean communicating to the company’s own future in an extended producer responsibility regime, which could incentivize companies to both design products to be more easily remade and plan information flows for the distant future.

The help of partners monitoring various scales can also extend the spatial and temporal horizons taken into account. Actors could be more likely to take distant biosphere impacts and critical material shortages into account if that information is monitored and scaled down into indicators useful to firm-level decision making. They could additionally have the information needed to better sync their material flows with the biosphere’s regenerative and/or absorptive cycles.

Information Alone Is Not Enough

While information flows are necessary for circular supply networks and systems to emerge, information alone is not enough. Actors need to be able to emit and receive these information signals, as well as possess the resources and capabilities to adapt to them. This requires physical resources – like production machines, information technology systems, and transport vehicles – to give materials new life, as well as personnel with the capabilities to put those physical resources to use. Of course, they also need the financial resources to pay for it all. Perhaps most important is the will to constructively adapt to the information signals received, which may require new institutional logics and incentives.

Conclusion

This chapter set out to build on CAS theory and circular supply network research to conceptualize how autonomous adaptation to information signals can lead to the emergence of circular supply systems. I argued that information on local supply networks, extended supply systems, and biosphere impacts is particularly important for circular production. From local supply networks, actors playing the roles of scavenger and decomposer need to know what waste materials are available and what can be done with them. From extended supply systems, information is needed from governments on their initiatives and regulations, as well as from analysts on potential critical material shortages. Additionally, information needs to flow to consumers on circular product quality and how to participate in post-consumer waste collection. Finally, information from the biosphere should ideally be collected and translated into a form useful for individual actors. From these information flows, new actor roles and networks, as well as new spatial and temporal patterns, can potentially emerge.

However, some limitations need to be considered. Being a conceptual paper, the argument was grounded in prior literature rather than new empirical work. Additionally, the focus was on information flows with little discussion of costs, which may be prohibitively expensive, thus negating their catalyzing potential. Likewise, since the focus was on the content of information flows, the technological systems that enable them were discussed only briefly.

In the future, it would be valuable to empirically study how social, political, institutional, and/or financial dynamics impact adaptive capacity in a (potential) circular supply system. Likewise, future empirical research could compare the ways different power dynamics in circular supply networks impact adaptive capacity. Another useful future research direction would be the role of positive and negative feedback loops in the information–adaptation–emergence progression. Finally, longitudinal studies of how circular supply systems emerge and co-adapt over time would offer empirically grounded perspectives on the specific mechanisms of circular systemic change.

References

Bansal, P., Kim, A., & Wood, M. O. (2018). Hidden in plain sight: The importance of scale in organizations' attention to issues. *Academy of Management Review*, *43*(2), 217–241.

Byrne, D., & Callaghan, G. (2014). *Complexity Theory and the Social Sciences: The State of the Art*. Routledge.

Chertow, M. R. (2000). Industrial Symbiosis: Literature and Taxonomy. *Annual Review of Energy and the Environment*, *25*, 313–337.

Choi, T. Y., Dooley, K. J., & Rungtusanatham, M. (2001). Supply networks and complex adaptive systems: Control versus emergence. *Journal of Operations Management*, *19*(3), 351–366.

Clift, R., Sim, S., King, H., Chenoweth, J. L., Christie, I., Clavreul, J., Mueller, C., Posthuma, L., Boulay, A. M., Chaplin-Kramer, R., Chatterton, J., DeClerck, F., Druckman, A., France, C., Franco, A., Gerten, D., Goedkoop, M., Hauschild, M. Z., Huijbregts, M. A. J., … Murphy, R. (2017). The challenges of applying planetary boundaries as a basis for strategic decision-making in companies with global supply chains. *Sustainability (Switzerland)*, *9*(2), 1–23.

de Jesus, A., & Mendonça, S. (2018). Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. *Ecological Economics*, *145*, 75–89.

Desing, H., Brunner, D., Takacs, F., Nahrath, S., Frankenberger, K., & Hischier, R. (2020). A circular economy within the planetary boundaries: Towards a resource-based, systemic approach. *Resources, Conservation and Recycling*, *155*(December 2019), 104673.

Dewick, P., Bengtsson, M., Cohen, M. J., Sarkis, J., & Schröder, P. (2020). Circular economy finance: Clear winner or risky proposition? *Journal of Industrial Ecology*, *24*(6), 1192–1200.

Farooque, M., Zhang, A., Thürer, M., Qu, T., & Huisingh, D. (2019). Circular supply chain management: A definition and structured literature review. *Journal of Cleaner Production*, *228*(April), 882–900.

Garcia-Torres, S., Albareda, L., Rey-Garcia, M., & Seuring, S. (2019). Traceability for sustainability – literature review and conceptual framework. *Supply Chain Management*, *24*(1), 85–106.

Gaustad, G., Krystofik, M., Bustamante, M., & Badami, K. (2018). Circular economy strategies for mitigating critical material supply issues. *Resources, Conservation and Recycling*, *135*(January 2017), 24–33.

Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. C. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega (United Kingdom)*, *66*, 344–357.

Haslinger, S., Hummel, M., Anghelescu-Hakala, A., Määttänen, M., & Sixta, H. (2019). Upcycling of cotton polyester blended textile waste to new man-made cellulose fibers. *Waste Management*, *97*, 88–96.

Helander, H., Petit-Boix, A., Leipold, S., & Bringezu, S. (2019). How to monitor environmental pressures of a circular economy: An assessment of indicators. *Journal of Industrial Ecology*, *23*(5), 1278–1291.

Holland, J. H. (2006). Studying complex adaptive systems. *Journal of Systems Science and Complexity*, *19*(1), 1–8.

Jabbour, C. J. C., Jabbour, A. B. L. de S., Sarkis, J., & Filho, M. G. (2017). Unlocking the circular economy through new business models based on large-scale data: An integrative framework and research agenda. *Technological Forecasting and Social Change*, *August*, 0–1.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232.

Korhonen, J. (2020). The circular economy as a complex adaptive system. In M. Brandão, D. Lazarevic, & G. Finnveden (Eds.), *Handbook of the Circular Economy* (pp. 28–38). Edward Elgar Publishing Limited.

Korhonen, J., Nuur, C., Feldmann, A., & Birkie, S. E. (2018). Circular economy as an essentially contested concept. *Journal of Cleaner Production*, *175*, 544–552.

Laubscher, M., & Marinelli, T. (2014). Integration of Circular Economy in Business. *Going Green - CARE Innovation 2014*, 1–6.

Levin, S. A. (1998). Ecosystems and the biosphere as complex adaptive systems. *Ecosystems*, *1*(5), 431–436.

Lopes de Sousa Jabbour, A. B., Rojas Luiz, J. V., Rojas Luiz, O., Jabbour, C. J. C., Ndubisi, N. O., Caldeira de Oliveira, J. H., & Junior, F. H. (2019). Circular economy business models and operations management. *Journal of Cleaner Production*, *235*, 1525–1539.

Lüdeke-Freund, F., Gold, S., & Bocken, N. M. P. (2019). A Review and Typology of Circular Economy Business Model Patterns. *Journal of Industrial Ecology*, *23*(1), 36–61.

Manninen, K., Koskela, S., Antikainen, R., Bocken, N., Dahlbo, H., & Aminoff, A. (2018). Do circular economy business models capture intended environmental value propositions? *Journal of Cleaner Production*, *171*, 413–422.

Masi, D., Day, S., & Godsell, J. (2017). Supply Chain Configurations in the Circular Economy: A Systematic Literature Review. *Sustainability*.

Merli, R., Preziosi, M., & Acampora, A. (2018). How do scholars approach the circular economy? A systematic literature review. *Journal of Cleaner Production*, *178*, 703–722.

Miller, E. (2018). *Trash to Treasure: A Multiple Case Study of Finnish Companies That Create Economic Value from Waste Materials* [Aalto University School of Business, Finland].

Monat, J. P., & Gannon, T. F. (2015). What is Systems Thinking? A Review of Selected Literature Plus Recommendations. *American Journal of Systems Science*, *4*(1), 11–26.

Montabon, F., Pagell, M., & Wu, Z. (2016). Making sustainability sustainable. *Journal of Supply Chain Management*, *52*(2), 11–27.

Murray, A., Skene, K., & Haynes, K. (2017). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380.

Parida, V., Burström, T., Visnjic, I., & Wincent, J. (2019). Orchestrating industrial ecosystem in circular economy: A two-stage transformation model for large manufacturing companies. *Journal of Business Research*, *101*(June 2018), 715–725.

Patala, S., Albareda, L., & Halme, M. (2018). Polycentric governance of privately owned resources in circular economy systems. *Academy of Management Proceedings*.

Pathak, S. D., Day, J. M., Nair, A., Sawaya, W. J., & Kristal, M. M. (2007). Complexity and adaptivity in supply networks: Building supply network theory using a complex adaptive systems perspective. *Decision Sciences*, *38*(4), 547–580.

Prendeville, S., Cherim, E., & Bocken, N. (2018). Circular Cities: Mapping Six Cities in Transition. *Environmental Innovation and Societal Transitions*, *26*, 171–194.

Prieto-Sandoval, V., Jaca, C., & Ormazabal, M. (2018). Towards a consensus on the circular economy. *Journal of Cleaner Production*, *179*, 605–615.

Singh, J., & Ordoñez, I. (2016). Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. *Journal of Cleaner Production*, *134*, 342–353.

Skene, K. R. (2018). Circles, spirals, pyramids and cubes: Why the circular economy cannot work. *Sustainability Science*, *13*(2), 479–492.

Sprecher, B., Daigo, I., Spekkink, W., Vos, M., Kleijn, R., Murakami, S., & Kramer, G. J.

(2017). Novel Indicators for the Quantification of Resilience in Critical Material Supply Chains, with a 2010 Rare Earth Crisis Case Study. *Environmental Science and Technology*, *51*(7), 3860–3870.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*.

Strasser, S. (2000). *Waste and Want: A Social History of Trash*. Henry Holt and Company, LLC.

Suárez-Eiroa, B., Fernández, E., Méndez-Martínez, G., & Soto-Oñate, D. (2019). Operational principles of circular economy for sustainable development: Linking theory and practice. *Journal of Cleaner Production*, *214*, 952–961.

Sundkvist, Å., Milestad, R., & Jansson, A. M. (2005). On the importance of tightening feedback loops for sustainable development of food systems. *Food Policy*, *30*(2), 224–239.

Surana, A., Kumara, S., Greaves, M., & Raghavan, U. N. (2005). Supply-chain networks: A complex adaptive systems perspective. *International Journal of Production Research*, *43*(20), 4235–4265.

Tate, W. L., Bals, L., Bals, C., & Foerstl, K. (2019). Seeing the forest and not the trees: Learning from nature’s circular economy. *Resources, Conservation and Recycling*, *149*(April), 115–129.

Troschinetz, A. M., & Mihelcic, J. R. (2009). Sustainable recycling of municipal solid waste in developing countries. *Waste Management*, *29*(2), 915–923.

Urbinati, A., Chiaroni, D., & Chiesa, V. (2017). Towards a new taxonomy of circular economy business models. *Journal of Cleaner Production*, *168*, 487–498.

Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2017). Ease of disassembly of products to support circular economy strategies. *Resources, Conservation & Recycling*, 1–0.

Wang, Y., Hazen, B. T. H., & Mollenkopf, D. A. (2018). Consumer value considerations and adoption of remanufactured products in closed-loop supply chains. *Industrial Management & Data Systems*, *118*(2), 480–498.

Waste2Wear. (2020). *Ocean Plastic Project*.

Wells, P., & Seitz, M. (2005). Business models and closed-loop supply chains: A typology. *Supply Chain Management: An International Journal*.

Whiteman, G., Walker, B., & Perego, P. (2013). Planetary Boundaries: Ecological Foundations for Corporate Sustainability. *Journal of Management Studies*, *50*(2), 307–336.

Wiesner, K., Birdi, A., Eliassi-Rad, T., Farrell, H., Garcia, D., Lewandowsky, S., Palacios, P., Ross, D., Sornette, D., & Thébault, K. (2019). Stability of democracies: A complex systems perspective. *European Journal of Physics*, *40*(1).

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*(August 2016), 825–833.

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*.

Zou, Y., Reddy, N., & Yang, Y. (2011). Reusing polyester/cotton blend fabrics for composites. *Composites Part B: Engineering*, *42*(4), 763–770.