How can the circular economy-digitalization infrastructure support transformation to strong sustainability?

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Abstract
How can the evolving nexus of circular economy with digitalization infrastructure support transformation to strong sustainability? In this perspective paper we seek to advance the discourse from a systems perspective by suggesting research questions that may lead to new insights and conceptualizations. We begin by framing the sustainability discourse in terms of a long-standing debate over the treatment of technological solutions, and by briefly describing the systems perspective we employ in outlining potential research questions that can advance this discourse. Specifically, we take three main layers of systems (patterns, structure, and mental models) and describe how they can help investigate and support circular economy-digital infrastructure transitions to stronger sustainability.

1. Introduction
Ecological modernization theory postulates that economic growth can decouple environmental degradation from economic growth (Buttel 2000). In fact, technology’s function as a counterbalance to environmental impact from population and affluence growth is central to the ‘IPAt’ equation—where environmental impact (I) is a function of population (P), affluence (A), and technology (T) (Chertow 2000).

This perspective has been further intimated with studies evaluating how Industry 4.0 and blockchain technology—along with other multi-stakeholder digital technologies—further environmental and social sustainability (Beltrami et al 2021). Others have been more restrained, taking the other side in a long-running debate over the treatment of technological solutions, arguing that narrowly promoting them offers false hope for sustainability if it lacks adequate assessment of the human responses to changing impacts (Chertow 2000) (Sterman 2012) and technological advances (Sarkis 2019). Such responses can be counterproductive to achieving strong sustainability in the long run. Optimists would counter that scientific findings about solutions to urgent sustainability problems can be safely disseminated in a narrow assessment, as facilitated by models like IPAT.

This debate and consideration is important for the sustainability community especially because reconciling the philosophical divergence in these viewpoints requires more evidence and development. In this perspective paper we seek to advance the discourse with potential research questions and a brief agenda to aid this reconciliation. Specifically, we focus on the circular economy (CE) concept and whether a digital infrastructure can make it more environmentally sustainable—achieving strong sustainability (Schröder et al 2019).

We rely on a systems thinking perspective to outline concerns and research questions that may lead to new insights and conceptualizations. Systems’ patterns, structure, and mental model layers (Goodman 2002) help to generally identify research questions related to investigating the CE-digitalization infrastructure and a transformation to strong sustainability.

But first, let us provide a brief foundation. CE has numerous definitions which depend on context for its evaluation and support (Kirchherr et al 2017). It may be an economic policy, an operational concern, a business model, or a sustainability philosophy. These perspectives feed into concerns and the discourse on why CE may not be sustainable. Issues include lack of a social sustainability focus, potential inequities associated with CE
practices and policies, and countercyclopedic CE practices that generate more waste or use additional resources to maintain CE operations (Korhonen et al. 2018, Schröder et al. 2019).

Many times, CE studies describe the eventual system rather than how to get there. Stopping us from overshooting planetary boundaries—a strong sustainability perspective—requires making enduring game-changing system changes that move toward sustainability in a timely, appropriately-scaled, and balanced manner (Elkington 2018, Serman 2012). System change lays a critical foundation for transitioning to CE that is strongly sustainable, equitable, and inclusive.

We also believe that this foundation can be supported with an effective digital infrastructure. There has been significant discussion around how digital technology helps reduce burdens and provides support for CE operations. Blockchain, the Internet of things (IoT), and other multi-stakeholder technologies and platforms are likely to form the basis of this digital infrastructure (Esmaeilian et al. 2020).

A systems perspective can provide insight into developing a research agenda at the intersection of these powerful but complex ideas—the CE-digital infrastructure linkage. Systems thinkers often talk about system changes, such as digital transformation, in terms of how the change relates to three main layers of systems: patterns, structure, and mental models (Goodman 2002, Meadows 2008). We take each of these layers and describe how they can help investigate and support CE-digital infrastructure transitions to stronger sustainability.

A system’s patterns are the trends in its behavior over time—including challenges such as exponential growth, variability, chronic stagnation, and predictable disruptions. Thinking of systems change in terms of patterns is superior to thinking narrowly in terms of a series of events, each with a single cause. Understanding this layer could suggest many ways to improve a system.

Systems thinkers have observed that a common approach to system improvement is to adjust the responses to trends—similar to adjusting a faucet filling a bathtub to reach the desired level without changing the plumbing. Adjusting flows can bring lasting systems change only if it can reach the critical range that catalyzes beneficial processes at the deeper structure and mental models systems layers (Meadows 2008). This approach of focusing on patterns is analogous to the reductionist perspective of the scientific process. The reductionist perspective will control for all extraneous factors to focus on the pattern. In the CE context, this is similar to singularly focusing on technical closed-loop systems operations.

Greater transformational leverage may occur from managing a system’s causal structure. This layer of systems change would include reconfiguring flows, installing new feedback mechanisms, and rebalancing a system’s positive and negative feedbacks. Depending on the situation, some of these leverage points can disappoint in terms of delivering transition and transformation (Meadows 2008). For CE, causal structure requires considering other innovations, such as sustainable supply chains, stakeholder engagement, and consideration of institutional environments. For example, positive and negative feedback structural elements may include stakeholder response to CE patterns.

We believe the most transformational leverage is found in altering mental models—and by extension making the enduring changes to structure and consequently to behavior patterns—that define the structure and response. Aspects include improving perception accuracy, system rules and goal changes, investing in new experimental structures, showing advantages offered by new paradigms, and even letting go of the need for paradigms, while accepting the inherent uncertainty and ignorance of science (Goodman 2002, Kampourakis and McCain 2020, Meadows 2008).

In CE, new mental models would include emergent perspectives and theories (cf (Beling et al. 2018)), such as degrowth, biocentrism, feminist theory, and post-colonialism and their impact on how CE is perceived and implemented. These are only exemplary potential theoretical perspectives, our recommendation later will be to evaluate general emancipatory theories—theories that provide a perspective that frees thinking—that have not been traditionally viewed from a CE context (Cornelissen et al. 2021).

We now use these systems layers to identify investigatory issues to answer the question—‘How can the CE-digitalization infrastructure support transformation to strong sustainability?’

1.1. Patterns

A central goal in CE design is to eliminate waste and stabilize earth’s resources—an effort that will require several generations to achieve. CE success in meeting this objective hinges on its ability to control waste and resource flows. At the patterns layer, CE may mean directly managing the slowing, narrowing, or closure of material flows (Ranta et al. 2021).

To help meet this multi-generational goal, a CE-digitalization infrastructure needs to be managed with the long-term in mind. Specifically, it can have the most impact if CE-related processes or goals are digitally supported through multi-stakeholder digitalization technology—such as IoT and blockchain. For example, blockchain’s instant information accessibility and traceability—across supply chain partners, consumers, and other actors—are used to improve CE’s responsiveness to evolving global resource and waste situations or
regulatory policies. These regulatory policies may include take-back legislation or evolving standards associated with industries that have circularity developments—for example, the electronics industry is working on electronics circularity standards.

Multi-stakeholder digital technologies may help in the short term. Long term transformations, especially for meeting a strong sustainability vision, need to complement these short-term changes with a sophisticated understanding of system structure and eventually adopting new mental models.

Exemplary pattern-layer research questions include: how do you integrate these multi-stakeholder technologies in a CE system? What major CE practices such as closing the loop, tracing materials, incentivizing organizations and individuals to contribute to CE practices might benefit most from digitalization? How can multi-stakeholder technologies, including integration into artificial intelligence (AI), use models and algorithms to promote linkage of the patterns in ‘big data time series CE data’ to digitalization decision-making and learning at deeper layers? What is the performance of circular systems with and without digitalization? How does a digitalized infrastructure for CE do sourcing, marketing, and waste management?

1.2. Structure

Traditional resource, waste, information, and capital flows have been optimized to promote linear economic growth that can keep pace with accelerating growth in consumption patterns and population. In turn, these patterns are influenced by self-reinforcing cycles or positive feedbacks—where positive is meant in the quantitative sense of amplifying change, rather than a values-based sense of good or bad—whose strength is evidenced in the exponential growth of variables like those described in the literature on the ‘great acceleration’ (Steffen et al 2015).

The structure layer of systems implies a more sophisticated view of CE which recognizes its aims to improve the way material flows are managed. CE changes structure in at least two ways: (1) introducing information flows that initiate organizational responses to minimize waste flows and maximize circular material flow use in a goal-seeking cycle (i.e., closing negative feedbacks that can bring a pattern toward a goal if they can balance out the positive feedbacks); and (2) changing consumption patterns to weaken harmful positive feedback strength.

Implementing multi-stakeholder technologies, such as blockchain, is a specific CE-digital infrastructure transition that can support CE-sustainability achievement by providing transparent, structurally unambiguous and traceable information, known by blockchain scholars as ‘deep transparency’ (Sengupta and Kim 2021). A blockchain’s inherent logical constraints—for example, nothing can be shipped if inventory and receiving are both zero—remove ambiguities in the way information represents material flows and accumulations.

A digital infrastructure characterized by deep transparency will help to overcome existing barriers to integrating CE efforts in government, industry, and research (Geng et al 2019). Over time, providing deep transparency into material flows can make CE’s negative feedback loops stronger as the stakeholders in them can be more confident that a product or material has circularity and meets requirements, and that their involvement—a structural difference—truly impacts material flow structure and patterns.

Industry 4.0 (I4.0) is a broad spectrum of digital technologies. Some are multi-stakeholder, some are organizationally-based. Because it offers capacity for re-designing material flows, I4.0 can theoretically support CE-oriented material flow reforms. To keep up with accelerating waste flow rates, process automation will likely need to prioritize waste flow conversions, waste measurement and handling and be implemented through a holistic view of supply chain boundaries (Sarkis 2012). Experience has shown that, by itself, digitalizing measurement infrastructure does not lead to CE adoption (Ranta et al 2021, Strandhagen et al 2020), and that the most effective CE redesigns are built on a holistic approach to designing digital infrastructure involving measurement, data integration and data analysis capabilities (Ranta et al 2021).

These example structure relationships lead us to exemplary research questions at the structure layer, including: what type(s) of feedback does digital technology offer for CE, to improve or worsen the chances for transitioning to strong (or weak) sustainability? What makes the pre-existing institutional dimensions brought to the fore by a digitalized CE infrastructure more supportive or adversarial to strong sustainability transitions? For example, how does a digitalized CE infrastructure support each phase of the social-benefit market institutional model (Corbett and Montgomery 2017)?

1.3. Mental models

Despite the benefits, CE networks have yet to reach a scale where there is broad popular awareness and sufficient linkage across industries and society (Geng et al 2019). Attracting more interest and action to CE involves modifying mental models—the causal structures found in individual perspectives, theories, business models, professions, ideologies, worldviews, and cultures. Modifying mental models will require demonstrating that a digitalized CE infrastructure is capable of replacing the incumbent linear economy. New mental models provide momentum for CE to overcome these incumbents.
Since mental models develop through experience and socialization, the linear economy is institutionally embedded. While the linear economy is an institutional Goliath, CE is not David and this war of ideas will not be won with a single stone. By uncritically promoting a narrow view of CE—as a new green trend for businesses in wealthy countries—we miss out on the opportunity to develop and apply a more holistic understanding to effectively change global mental models.

Researchers in CE have often relied on an explanatory approach to theory that seeks to build on prior theories rather than develop new ones. To make major advances in CE research, we need to free ourselves of the confines of previous theory, such as ecological modernization theory. Even the IPAT concept may not be sufficiently radical or paradigm-shifting to bring CE digitalization infrastructure to strong sustainability.

For CE, an emancipatory approach to theory (Cornelissen et al. 2021) offers a better lens for perceiving the blind spots of prior theories. Some have advocated for the use of degrowth theory (Schroder et al. 2019), but this may not be emancipatory enough. For scholars to free themselves from traditional mental models, something deeper is needed. Emancipatory theorizing can more fully identify CE-digitalization opportunities. For example, a biocentric or feminist theory may re-imagine the role of CE-digitalization infrastructure research in contributing to strong sustainability.

Exemplary research questions at the mental model layer: what are the blind spots in stakeholder mental models that a digitalized CE infrastructure can enlighten or further obscure? For example, how does a digitalized CE infrastructure support or limit stakeholder engagement in social-benefit markets under different stakeholder orientations (Georgallis and Lee 2020)? As adoption of digitalization grows, does this enable or present further barriers to adoption of CE and inclusiveness? What mental models need to be institutionally embedded such that CE digitalization infrastructure leads to strong sustainability? Should and how can mental models be integrated AI digitization for CE?

2. Discussion

Upgrading to a digital infrastructure offers opportunities to transition from a linear to a CE. But true change requires going beyond pattern and structure-layer thinking toward the adoption of emancipatory mental models.

Digitalization enhances measurement, data collection, and visibility. Monitoring dynamic patterns in the data will make a digitalized CE infrastructure more adaptable to changes in policy and market conditions. Such pattern-layer thinking can identify important questions for the structure layer.

A digitalized CE infrastructure has enhanced potential to satisfy, in theory, the structural conditions for production systems that are sustainable from a strong sustainability perspective. With deep transparency and holistic infrastructure development, digitalization of CE enables changes to structure and enhances learning about the resulting consequences—ultimately improving performance and mental models.

While it is unlikely to fully resolve the debate over the technological solution, research that improves understanding at the patterns layer can clarify the roles for these technologies in the information infrastructure of evolving CE practices and hasten the adoption of best practices. Even if this understanding supports only short term, narrow IPAT, or bullet-list thinking at the structure layer, the patterns layer’s temporal focus can enhance assessment of intended and unintended impacts. At the structure layer, research supports broadening thinking and empowering CE stakeholders to use their CE digital infrastructure to internalize impacts and redesign specific CE practices accordingly. Nevertheless, uncovering worldviews that guide impact responses and correcting biases which inhibit digitalization’s technological advances from making their fullest impact on strong sustainability can only be done when researchers delve to the mental models layer.

CE blends tangible technology innovation with softer intangible social innovation. Digitalization research needs to go beyond old, conceptually-narrow perspectives on developing and applying theory in CE. Current theory is useful, nevertheless new theory is needed to achieve paradigmatic breakthroughs and bring about true strong sustainability. Practical implementation, will require that these theoretical advances involve careful consideration of pragmatic concerns such as sequencing and duration (patterns), feasibility (structure), and culture change (mental models).

Despite the significant potential for expanding research and understanding in CE digitalization, we also understand there are limitations to completing studies on this emerging topic. In addition to normal implementation challenges, the actions taken and the ability to measure impact might be limited in the initial implementation. Where little implementation has taken place, we recommend applying theory in evaluating potentials and recommendations (cf. (Strandhagen et al. 2020)). Where more has been achieved researchers recommend leveraging CE digitalization experiences to promote theoretical understanding (cf, (Ranta et al. 2021)). Where stakeholders lack experience with emancipatory or strong sustainability concepts, researchers may use a specific structural representation of CE in sustainability as an information system (cf, figure 10 in (Sterman 2012)) as a starting point to expand mental models.
3. Conclusion

In conclusion, digitalization has the potential to significantly support CE, and could even be a game-changer for a broad-based transition to a CE. As we progressed through a layers perspective to systems thinking, the research questions become more meta-theoretical from basic hypothesis-testing and reductionist approaches to much broader rethinking of theory in an emancipatory way to truly achieve strong sustainability that is inclusive and equitable for the CE-digitalization infrastructure.

Data availability statement

No new data were created or analysed in this study.

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References

Beling A E, Vanhulst J, Demaria F, Rabi V, Carballo A E and Pelenc J 2018 Discursive synergies for a ‘great transformation’ towards sustainability: pragmatic contributions to a necessary dialogue between human development, degrowth, and buen vivir Ecol. Econ. 144 304–13
Beltrami M, Orzes G, Sarkis J and Sartor M 2021 Industry 4.0 and sustainability: towards conceptualization and theory J. Clean. Prod. 312 127735
Buttel F H 2000 Ecological modernization as social theory Geoforum 31 57–65
Chertow M R 2000 The IPAT equation and its variants J. Ind. Ecol. 4 13–29
Corbett J and Montgomery A W 2017 Environmental entrepreneurship and interorganizational arrangements: a model of social-benefit market creation Strateg. Entrepren. J. 11 422–40
Cornelissen J, Höllerer M A and Seidl D 2021 What theory is and can be: forms of theorizing in organizational scholarship Organ. Theory 2 2631787211020328
Elkington J 2018 25 years ago I coined the phrase ‘triple bottom line’. Here’s why it’s time to rethink it Harv. Bus. Rev. 25 2–5 (https://hbr.org/2018/06/25-years-ago-i-coined-the-phrase-triple-bottom-line-heres-why-im-giving-up-on-it%E2%80%8B)
Esmaeilian B, Sarkis J, Lewis K and Behdad S 2020 Blockchain for the future of sustainable supply chain management in Industry 4.0 Resour. Conserv. Recycl. 163 105064
Geng Y, Sarkis J and Bleischwitz R 2019 How to globalize the circular economy Nature 565 153–5
Georgallis P and Lee B 2020 Toward a theory of entry in moral markets: the role of social movements and organizational identity Strateg. Organ. 18 50–74
Goodman M 2002 The Iceberg Model (Hopkinton, MA: Innovation Associates Organizational Learning)
Kampourakis K and McCain K 2020 How uncertainty makes science advance Uncertainty: How it Makes Science Advance (New York: Oxford University Press)
Kirchherr J, Reike D and Hekkert M 2017 Conceptualizing the circular economy: an analysis of 114 definitions Resour. Conserv. Recycl. 127 221–32
Korhonen J, Honkasalo A and Seppälä J 2018 Circular economy: the concept and its limitations Ecol. Econ. 143 37–46
Meadows D H 2008 Thinking in Systems: A Primer (New York: Chelsea)
Ranta V, Aarikka-Stenroos L and Väisänen J-M 2021 Digital technologies catalyzing business model innovation for circular economy—multiple case study Resour. Conserv. Recycl. 164 105155
Sarkis J 2012 A boundaries and flows perspective of green supply chain management Supply Chain Manage. 17 202–16
Sarkis J 2019 Sustainable transitions: technology, resources, and society One Earth 1 48–50
Schröder P, Bengtsson M, Cohen M, Dewick P, Hofstetter J and Sarkis J 2019 Degrowth within—aligning circular economy and strong sustainability narratives Resour. Conserv. Recycl. 146 190–1
Sengupta U and Kim H M 2021 Meeting changing customer requirements in food and agriculture through the application of blockchain technology Front. Blockchain 4 5
Steffen W, Broadgate W, Deutsch L, Gaffney O and Ludwig C 2015 The trajectory of the anthropocene: the great acceleration Anthropocene Rev. 2 81–98
Sterman J D 2012 Sustaining sustainability: creating a systems science in a fragmented academy and polarized world Sustainability Science: The Emerging Paradigm and the Urban Environment (Berlin: Springer)
Strandhagen J W, Buer S-V, Semini M, Alnæs E and Strandhagen J O 2020 Sustainability challenges and how industry 4.0 technologies can address them: a case study of a shipbuilding supply chain Prod. Plann. Contr. Special Issue: Supply Chain Management in Construction and Engineer-to-order Industries (Forthcoming) 1–16