

Review article

Evaluating Emergy Analysis at the Nexus of Circular Economy and Sustainable Supply Chain Management

Lojain Alkhuzaim^{a,*}, Qingyun Zhu^b, Joseph Sarkis^c^a Foisie Business School, Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609, USA^b College of Business, The University of Alabama in Huntsville, 301 Sparkman Drive, Huntsville, AL 35899^c Foisie Business School, Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609, USA

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ABSTRACT

Emergy analysis has been gaining attention in its use as an environmental accounting tool. Its relationships and implications to sustainable supply chains and the circular economy are still not well understood, even with initial investigations into the relationship. Emergy analysis can potentially provide additional profound opportunities to advancing these sustainability-oriented fields. Emergy analysis—as a basis for economic, social and environmental performance measurements—uses donor side valuation approaches. We discuss how sustainable supply chain management and circular economy performance measurement methods can be expanded and effectively utilize emergy analysis using a donor-side evaluation. We provide insights into more effective environmentally sustainable supply chain and circularity performance evaluation, accounting, and appraisal using emergy based performance measurements. Our findings show that there is ample room for further application and theoretical development at the nexus of these topics. Practically, the measures and approaches for emergy analysis can help decision makers in organizations and across supply chains in managing material sourcing, supplier selection, and network and circular economy flow designs. A theoretical synthesis and research gaps are introduced to help guide future theoretical developments and practical investigations. This work is valuable for those seeking to advance research on sustainability and performance analysis for organizational and supply chain levels of analysis.

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Introduction

Sustainable production and consumption research have investigated relationships between supply chains and the natural system (Fahimnia et al., 2015; Tian and Sarkis, 2020). As supply chains become increasingly complex and integrated with circular economy (CE) principles, the need to expand related evaluation metrics and measures is also growing (Datta and Diffie, 2020; Narimissa et al., 2020a, 2020b; Nikolaou et al., 2019). There is also need for more accurate, persuasive, and rational approaches to evaluate environmental and sustainable performance in this context (Jabbour et al., 2020). We parlay this need for more effective environmentally sustainable supply chain and CE performance evaluation, accounting, and appraisal with a scientific measure used broadly as an ecological indicator—Emergy with an “m”.

Emergy analysis (EA) uses thermodynamics and general systems theory (Odum 1996). EA can provide variational valuation insights to supply chain performance by incorporating a donor side valuation—giving more weight to nature's contribution to anthropocentric production and consumption systems. Although emergy's conceptual underpinnings are relatively straightforward, its implications are potentially profound. EA quantification is based on an energetic foundation of ecosystem goods and services. Existing sustainable supply chain management (SSCM) and CE performance measurement methods estimate the value of ecosystem inputs from an anthropocentric perspective. Emergy seeks to provide an ecocentric value derived from a theory of energy flow and its relationships with systems ecology (Liu et al., 2016).

EA originated in the early 1980s to examine various systems such as ecological, industrial, economic, and astronomical systems (Odum, 1995 a,b, 1996; Brown and Ulgiati, 1997, 2002; Lagerberg and Brown, 1999). Yet EA has not been applied and investigated as broadly outside a relatively small circle of academic environmental communities. This neglected application of EA—despite its promising relevance to private organizations, supply chains, and

* Corresponding author

E-mail addresses: Lalkhuzaim@wpi.edu (L. Alkhuzaim), Q.zhu@uah.edu (Q. Zhu), jsarkis@wpi.edu (J. Sarkis).

government—may be due to inadequate communication of its potential application and insights along with an absence of a clear connection to business and consumer disciplines.

SSCM and CE are each strategically significant topics that can pique the interest of economic and business disciplines to EA as a performance accounting method. The complementary nature of EA and its potential application in supply chain sustainability and circularity research can be a fertile research area requiring further exploration and to catalyze broader industry and business community acceptance. This acceptance is critical if true deeper sustainability and strong sustainability efforts (Schröder et al., 2019) are to gain a stronger foothold in our industrial and social systems.

Our objective is to review and evaluate various EA features and build connections between energy, SSCM, and circularity concepts. We seek to generally analyze the current intellectual structure to evaluate the feasibility of applying EA to SSCM and CE as a performance appraisal and measurement tool. Establishing the links between EA and its related thermodynamic concepts to sustainability and circularity is essential and critical for widening the use of EA. EA can also help advance sustainable supply chain and CE disciplines. We believe this mutual benefit of the two fields can greatly enhance overall sustainability beyond organizations and their supply chains.

The next section sets some of the foundation for an analysis of future research directions. We briefly review several related literature streams including SSCM, CE, and EA. The conceptualizations and associated performance indicators and measurements within each field are also introduced in section 3—for general sustainable supply chain and CE performance. Section 4 provides insights specifically for EA performance and its relationships to the sustainable supply chain and CE. A theoretical synthesis and research gaps are presented in section 5 to help guide future theoretical developments with identified research questions. Section 6 summarizes and concludes this study.

Literature Review

This section provides a foundational review of SSCM, CE, and EA. It also provides a disambiguation of the terms.

Sustainable Supply Chain Management

Originating as a popular business concept during the early 1980s, supply chain management seeks for organizations to manage material, financial and information flows for product or service delivery. It is organized through operational processes linking upstream and downstream tiers of a supply chain network (Lambert and Enz, 2017). The field has exponentially grown; addressing various topics over the past several decades. Sustainability has arisen as a key supply chain management subject incorporating a multiplicity of environmental and social issues.

SSCM encompasses all supply chain activities and includes environmental, economic and social performance outcomes. The goal is to meet stakeholder specifications regarding environmental practices while achieving anticipated economic performance and maintaining elevated social and ethical standards. Integrating sustainability practices within the supply chain has become a priority in SSCM design and execution (Kusi-Sarpong et al., 2019). Production and consumption systems are designed and evaluated using sustainability performance such as resources and energy usage efficiency, manufacturing effectiveness and reliability, transportation and consumption carbon footprints, waste management, and reverse logistics valuations (Sarkis and Zhu, 2018).

However, in the extant literature, economic sustainability has been dominantly addressed in both academic and practical investigations. Limited attention has been directed to social and environmental issues (Dempsey et al., 2011; Kusi-Sarpong et al., 2019; Seuring, 2013). For instance, cost minimization is the main element of change for organizations seeking to improve their sustainability performance (Seuring, 2013). Economic terms are usually tangible; environmental and social supply chain performance may be fuzzier and with limited consensus—these latter social measures exhibit polysemous characteristics.

To achieve unique long-term sustainability performance, the three sustainability pillars—economic, environmental, and social dimensions—should be incorporated (Ahi and Searcy, 2013). Supply chain sustainability performance is a relatively recent area of study but has gained significant importance (Hervani et al., 2005); nevertheless, more work and development are still necessary as the field continues to emerge (Ahi and Searcy, 2015).

Circular Economy

As supply chains become more complex, CE has taken a foothold in helping address environmental sustainability concerns. CE models focus on reducing waste and improving resource utilization to improve economic performance (Ghisellini et al., 2016). CE has been interpreted to be a business model that seeks greater resource utilization—through materials and components remaining within a closed loop commercial system (Webster, 2017). CE focuses on reusing end-of-life materials and waste to produce new components to maximize environmental and economic benefits (Murray et al., 2017). These practices may include industrial symbiosis and upcycling waste byproducts for further revenue generation.

Although we provide a fundamental CE perspective, we are aware that there exist various CE definitions. Its core conceptualizations remain contested and polysemous (Korhonen et al., 2018). Several reasons make it challenging to advance its theoretical consensus. First, CE may mean different priorities at different analysis levels for successful implementation. At the micro level, CE practices focus on production and consumption systems within a single organization, for instance, eco-design, product recycling and reuse. At the meso level, CE is implemented using practices such as industrial symbiosis. Joint efforts concerning resources utilization and optimization are carried out within business communities and eco-industrial parks (Murray et al., 2017). At a macro level, CE has a much broader scope – regional and global – for instance, eco-cities and sharing economies. Performance evaluations at this level can focus on, for example, collaborative municipal consumption and zero waste programs (Liu et al., 2018). Fuzziness in performance indicators and measurements of CE practices also make its implementation and advancement slow and relatively inchoate (Schröder et al., 2019).

The intersection between SSCM and CE literature resulted in important findings and a fertile field for future research (Genovese et al., 2017). SSCM and CE are investigated using similar paradigms theoretically and practically (Liu et al., 2018)—and extant studies are applying SSCM performance measurements to evaluate CE activities; yet, tensions and contradictions may arise. SSCM may not always align with CE advancement. For example, much of the sustainable supply chain literature explicitly seeks environmental performance improvement; CE may still be considered effective even if environmental performance is not improved. There remains a research gap to develop a unique and effective performance measurements to measure circularity while still differentiating it from sustainability—but in many situations, investigators seek to do both simultaneously.

Table 1
Performance Measurements in the Circular Economy

Performance Measurements	Data Objective	Sources
Life Cycle Assessment	Eco-efficiency assessment; Life cycle inventory; Life cycle impact assessment; Life cycle sustainability assessment; The use of materials and by-products; Product sustainability assessment	(Laso et al., 2018; Martin et al., 2017; Mendoza et al., 2019; Niero and Olsen, 2016; Zhou et al., 2019)
Material Flow Analysis	Material flow cost accounting; Resource-efficiency assessment; Waste management	(Cordova-Pizarro et al., 2019; Haupt et al., 2017; Pagotto and Halog, 2016)
Sustainable Performance Assessment	Sustainable product development; Social network analysis; Sustainable supply chain performance	(Gbededo et al., 2018; Han et al., 2017; Sehnem et al., 2019)

Performance Measurements in Sustainable Supply Chain Management and Circular Economy

The recent few decades have witnessed increases in individual, organizational and governmental awareness for sustainable and circular practices, setting the foundation for policy and pressure for business sustainability transitions (Taticchi et al., 2015; Soderstrom and Weber, 2020). Understanding the importance sustainability and circularity practices has encouraged practitioners and scholars to develop related management measures and metrics for enhancing supply chain stakeholder environmental standards.

Organizations have developed and implemented performance measures to evaluate supply chain sustainability by managing sustainable and circular practices and their consequent related strategies (Bai et al., 2019; Kazancoglu et al., 2018). The ultimate goal is to not only improve environmental performance, but also to gain competitive advantages—as posited by building capabilities in a resource-based view and dynamic capabilities perspective (Khan et al., 2020).

SSCM required an evolution in performance measurement—evolving from organizational to supply chain to sustainable supply chains—adding more complexity as inter-organizational and expanded non-business performance dimensions were added. This evolution resulted in additional challenges for practical management in addition to scholarly research (Bai, et al., 2019; Nudurupati et al., 2011). In this environment evidence increased for the significance of incorporating multi-dimensional performance measurements to assess overall supply chain performance with tangible and intangible measure for continual sustainability development (Taticchi et al., 2015).

Due to many factors—including competitiveness and stakeholder pressures—performance measurement development has evolved through different stages from a traditional and conventional viewpoint to a more balanced contemporary and strategic perspective (Schaltegger and Burritt, 2014). Traditional economic measures such as return on investment (ROI) and gross margin (Van Hoek, 1998) are merely directed to evaluate financial performance, their strategic and socio-ecological feasibility is limited especially for ‘strong sustainability’ (Nikolaou et al., 2019). Traditional measures can prevent anticipated progress and practical strategic planning usefulness, hence more comprehensive performance measures were required (Jabbour et al., 2020; Tian and Sarkis, 2020).

More contemporary balanced performance metrics include both financial and non-financial measures to eventually assess supply chains (Taschner and Charifzadeh, 2020). Eventually there was an expansion to economic, environmental and social associated assessment indicators; each including a broader variety of performance measurements. Studies that are linking and integrating sustainability and circularity performance—although evidenced in the literature—remain relatively limited (Taticchi et al., 2015). This lack of sustainability metrics and measures at the micro or organizational level of CE studies is even more evident as research has identified it moving away from traditional sustainability indica-

tors (Kristensen and Mosgaard, 2020). Table 1 summarizes a list of widely used performance measurements of CE.

Environmental supply chain performance measures concern the ecological effect of various supply chain activities and processes for producing a product or service (Shokravi and Kurnia, 2014). Greenhouse gas (GHG) emissions during supply chain activities are an example (Nidhi and Pillai, 2019). Environmental performance measurements can support research or practice. Outcome measures such as water and energy use, land footprints, waste generation and toxic releases, and food security measures exemplify the potential variety in environmental performance measures (Ardito and Dangelico, 2018; Kucukvar and Samadi, 2015; Park et al., 2016; Tian et al., 2020).

Each organizational function—operations, engineering, marketing, finance, human resources, information systems, accounting—can be concerned with a distinct environmental effect that requires a specific performance measure (Hong, et al., 2019). Given that the supply chain is usually interacting or managed by multiple functions, the number of measures can become extensive. According to Mollenkopf et al. (2010) environmental performance measurements are widely addressed within green supply chain management literature however further developments are needed.

One popular supply chain measurement and planning system is the supply chain operations reference (SCOR) model, introduced by the Supply Chain Council (1999). SCOR evaluates supply chain performance with respect to its four business processes—plan, source, make and deliver (Bai and Sarkis, 2014). The SCOR model has been expanded to perform a more holistic supply chain process and environmental performance evaluation (Bai et al., 2012; Ntate et al., 2015).

In some techniques, environmental performance measurements rely on expressing current performance in the form of incurred cost equivalent measures (Bai and Sarkis, 2014). For example, life cycle costing assessment (LCCA) is applied as a tool for decision-making processes which transforms environmental issues into monetary terms by evaluating product and service life cycle cost based on environmental consequences (Bennett and James, 1997; Gluch and Baumann, 2004).

The environmental challenges facing supply chains may also be designated to different levels of analysis including local, regional and global boundaries (Acquaye et al., 2017; Bai and Sarkis, 2014). Environmental performance measurements within SSCM and CE need to incorporate multiple scales to improve not only organizational sustainability but potentially industrial and global symbiosis as well.

The life cycle perspective for environmental performance measurement is also important and popular. As an example, researchers measure carbon footprint to evaluate the environmental impact in a product life cycle (Laurent et al., 2010). For this life cycle perspective, life cycle assessment (LCA) can be valuable for SSCM corporate environmental performance measurement (Gold et al., 2010). LCA is known to be a “standardized” measure and usually used as a SSCM tool to mitigate environmental impacts

caused during product and/or process life cycle (Lundin and Morrison, 2002). LCA provides a comprehensive approach incorporating multiple environmental impacts related to the product life cycle, not exclusive to causes of climate change (Laurent et al., 2010). Predominantly, LCA has been integrated with other tools such as System Dynamics (SD) and EA (Gala et al., 2015; Onat et al., 2016) to give a more inclusive evaluation of the investigated system. Additionally, when investigating complex business models such as CE, LCA is capable of evaluating circular activities and eventually extending product lifecycles (Colley et al., 2020; Hoffmann et al., 2020; Tseng et al., 2020).

In summary, a majority of environmental performance measures focus on the user-side evaluation perspective ignoring the contribution of the donor-side (nature). The contribution of nature represents the cornerstone of economic or human dominated system. Consequently, more investigation is needed to develop performance measurements from the donor-side perspective.

Emergy Analysis

EA was introduced using thermodynamics and general systems theory (Odum, 1996). The concept of emergy was known in the early 1980s as “embodied energy” it was later modified and introduced as emergy Odum and Odum (1980). EA has been applied in SSCM and CE primarily as an environmental accounting tool that quantifies the accumulative available energy directly or indirectly consumed when producing a service or product (Ren et al., 2010; Song et al., 2012). Researchers describe emergy as energy memory to help in visualizing the energy consumption mechanism (Brown and Herendeen, 1996).

The main difference distinguishing EA from other environmental assessment tools and performance measures is its characteristic of quantifying the work of nature—sun, wind, geothermal heat and rain—in addition to labor within production systems. EA focuses on the donor-side value contributed by the ecosystem to operate various commerce and social systems. The determining factor is the value of something and how much goes into an item, as opposed to its value after use (Brown and Herendeen, 1996). The main difference between a user-side model and a donor-side model is the source of perceived value. In a user-side model, the value is determined in terms of the amount of money paid or pollutants emitted. Whereas donor-side models base value on the amount of required inputs from the environment. Thus, it is a more objective—rather than human dominated—performance assessment tool.

EA transforms energy flows into solar emjoules (sej). This capability overcomes a significant limitation in the extant environmental assessment tools with respect to having different units and flows; which affects conducting necessary comparative analyses when evaluating different production and consumption systems (Corcelli et al., 2018; Song et al., 2014). Natural energy such as solar energy is typically used as a unique measuring unit to normalize different inputs and outputs of materials, products and services (Odum, 1996). A more detailed foundational review of EA is presented in the following subsections.

Performance Measurements in Emergy Analysis

Existing performance measurements and methodology from emergy accounting are introduced in the following sub-sections: transformity, unit emergy value, emergy based indicators, emergy diagram, and emergy evaluation and accounting procedure.

Transformity or Unit Emergy Value

When evaluating complex economic systems, EA utilizes specific measurements called transformity or unit emergy values (UEV) which is used as a conversion unit to unify different energy

and material flows. Transformity is the solar emergy used in producing one joule of a product or service (Odum, 1988, 1996). It also implies the geo biospheric contribution to used resources or the support intensity provided by the ecosystem to the final service or product (Brown et al., 2011). Transformity equals the total emergy divided by the actual available energy consumed in the investigated system.

Total emergy aggregates all energy flows contributing to the creation of a service or a product. The unit of measurements for the total emergy and transformities are solar emergy joules (sej) and solar emergy joules per joule of product (sej/J), respectively (Brown and Ulgiati, 1997). A high value of transformity indicates more energy and environmental activities are needed in a production process.

Emergy Based Indicators

EA offers a set of indicators useful for evaluating different systems targeting various sustainability aspects. The significance of emergy based indicators relies on the support they provide to processes of policy-making at different levels. Tian and Sarkis (2020) summarized a list of SSCM indicators which can also be utilized in CE systems evaluation. Some of the popular ones are detailed in this section.

The environmental loading ratio (ELR) quantifies the environmental burden produced by industrial processes or the investigated system. ELR is the ratio of the sum of local non-renewable resources (N) and purchased (imported) emergy (IM) to the renewable resources (R) (Odum, 1996). The higher the ELR is the greater the environmental pressure placed on the ecosystem.

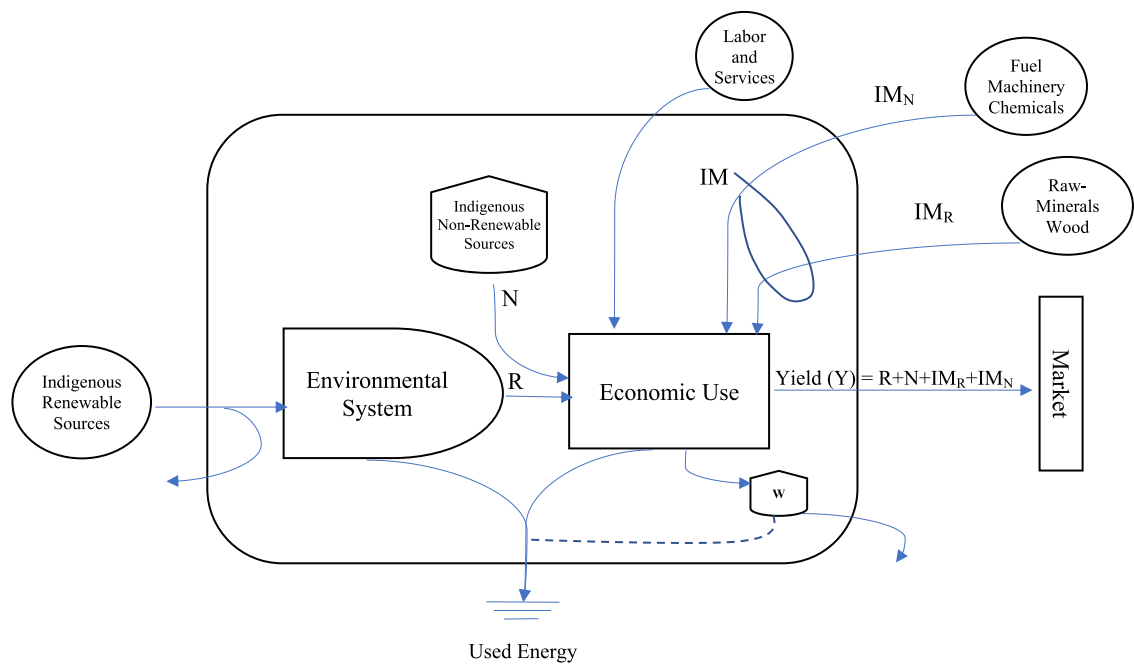
The environmental yield ratio (EYR) measures the process's effectiveness of utilizing local resources by using non-local resources. EYR is the product of dividing the total used resources in the production processes—renewable (R), non-renewable (N) and imported (I)—to the imported emergy (IM) (Odum, 1996).

The emergy sustainability index (ESI) is an important sustainability indicator as it is a direct indicator of a system's sustainability performance from a donor-side perspective. ESI provides an aggregate understanding of the investigated system as it combines two important indicators: EYR and ELR. It is the ratio of the system's contribution to the local economy to the environmental loading ratio (Brown and Ulgiati, 1997).

The emergy investment ratio (EIR) represents the “utilization level” of exploited emergy (Ren et al., 2015). It is computed by dividing the imported emergy (IM) by the sum renewable and non-renewable natural inputs.

Percent renewable (%R) is also an indicator of the sustainability performance which measures a system's ability to endure economic pressure (Brown and Ulgiati, 2004; Cavalett et al., 2006). %R divides the sum of renewable resources ($R + IM_R$) by the total emergy (U). Thus, when evaluating the sustainability of different systems, the one with the highest percentage is the most sustainable option.

Many of these metrics have been developed over the years to help link various elements of social, economic, environmental, and technological systems together. The applications have the measures and their evolution continues. This may also mean a special evolution, over time, for CE and SSCM measures. Emergy based indicators has a potential to assess circularity and sustainability from a donor perspective as they require the identification of resources' origin (Marvuglia et al., 2018). Despite the limited literature, some indicators have been developed and modified to assess circularity of complex systems. For instance, Ren et al. (2010) developed a circularity indicator to determine the ratio of the total output that can be circulated. Furthermore, Brown and Buranakarn (2003) provided a number of emergy indicators for recycling processes that are useful as circularity measures. Other initial



Note: Energy sources include (1) local (indigenous) Renewable Sources (R) such as sun, wind, rain and solar radiation; (2) local (indigenous) Non-renewable Sources (N) such as ground water and biomass and topsoil; (3) imported (purchased) resources (IM) including renewable (IMR) and non-renewable (IMN) flows imported from outside the boundaries of the system of interest such as fuel, raw minerals ,wood, machinery and chemicals; (4) direct labor (L) and indirect labor in the form of services (S); and (5) waste (W).

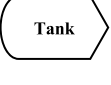
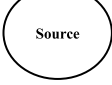
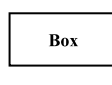
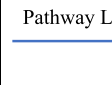
					
Stores energy within the system	Collects and transforms energy quality	An outside energy source	Label for generic unit or function symbol	A flow of energy	Used energy

Figure 1. An Exemplary High-level Energy Analysis Diagram.

measures can serve useful purposes for current CE and SSCM practices, but care needs to be taken in their application as described later.

The Emergy Systems Diagram

EA typically utilizes a system diagram to visualize energy consumed during the creation of a service or product. Figure 1 shows the main components of an exemplary emergy system diagram. The diagram is an initial step for conducting an EA. It identifies interactions between system components including the production of the final product. Emergy system diagram symbols and their descriptions are also presented.

As shown in Figure 1, the diagram is constructed using specific symbols to illustrate sources, flows, storages, interactions and transactions (Brown, 2004). These components are placed within the system's boundary to show interactions between energy, materials and information.

Emergy Analysis Evaluation and Accounting Procedure

Assessments performed by EA extends to not only environmental evaluation, but also monetary assessment. Emergy offers a several ecologically based monetary indicators that can be used for

a comprehensive evaluation. To create an EA evaluation system, three major phases need to be performed (Tian and Sarkis, 2020). First, setting boundaries of the system under study in preparation for creating an emergy diagram. This phase includes determining primary components—material and energy flows—of the system in addition to their relationships.

Second, converting input flows of the system—matter, energy and capital—into solar equivalent values by multiplying each flow by a respective transformity (UEV). Moreover, emergy of labor and services require further analyses depending on the system boundary (Ulgiati and Brown, 2014). For more consistent emergy calculations, some scholars encourage the use of the geobiosphere emergy baseline (GEB) (Brown et al., 2016) to improve the efficiency of emergy evaluations (Campbell, 2016).

Third, calculating emergy indicators—see Table 2—to investigate the performance of the system and provide better understanding for proper environmental and economic assessment. With the limited applications of EA as a supply chain performance assessment tool, databases for practical business analyses are still limited. However, an emergy database is available publicly and categorized to cover several regions worldwide with detailed information about their resources and activities.

Table 2
Emergy Analysis in sustainable supply chain and circular economy literature

Level of Analysis	Sustainability Dimension			Papers
	Environmental	Economic	Social	
Industrial park	✓	✓		(Ren et al., 2010)
Industrial park	✓			(Geng et al., 2010)
Regional	✓	✓		(Song et al., 2014)
Supply Chain	✓			(Markussen et al., 2014)
Supply Chain	✓			(Ren et al., 2015)
Industry	✓			(Jamali-Zghal et al., 2015)
Industry	✓			(Park et al., 2016)
Supply Chain	✓	✓		(Asamoah et al., 2017)
Regional	✓	✓		(Fang et al., 2017)
Regional		✓		(Huang et al., 2018)
Regional	✓	✓	✓	(Xue et al., 2018)
Supply Chain	✓			(Corcelli et al., 2018)
Industry	✓			(Pan et al., 2019)
Supply Chain	✓			(Tian and Sarkis, 2020)
Supply Chain	✓	✓		(Cai et al., 2020)
Supply chain	✓			(Krishnan et al., 2020)
Regional	✓			(Wu et al., 2020)

The National Environmental Accounting Database (NEAD) initially designed in 2003 and updated in 2014 help researchers and scholars advance emergy as a methodology and a theory (Viglia et al., 2018). The NEAD database¹ provides emergy data at the national level organized in forms of tables. Additionally, some calculations and indicators are performed based on emergy units. The database provides three different tables with flows, scores, and indicators. It also includes a flow diagram. Researchers use these databases to help set values for various levels of analyses—national, regional, municipal, eco-park, and supply chains.

Methods

This section conducts a comprehensive review of EA in SSCM and CE literature streams. A detailed review methodology and results are presented in the following subsections.

Review Methodology

The review process follows the procedure of the preferred reporting items for systematic reviews and meta-analysis (PRISMA) developed by Moher et al (2009). Google Scholar was used as the primary database. Using keywords including "emergy", "circular economy", "supply chains" and "sustainability", the initial results yielded 271 publications. The search covered all published articles with no specification of time ranges. But we did find that the earliest articles that fit our keyword criteria only started to appear in 2010. Therefore, the articles span from the years 2010 to 2020. Only those written in English were included. Books, publications from non-scientific journals, conference proceedings, and book chapters are excluded from the review. Content analysis was then conducted for the remaining 210 papers. Only 17 papers have explicitly applied emergy analysis in a circular economy or sustainable supply chain management context. The detailed steps are presented in Figure 2.

Literature Synthesis

In the extant literature, EA has been conducted globally to evaluate the total environmental performance and circularity of business systems from both natural and economic perspectives. Table 2 demonstrates its current applications across multiple investigation levels and different business orientations. Results show

that most emergy-related studies focus on the field of environmental sciences and ecology at the supply chain level; with a relative paucity of multiple dimensions including economic and business decisions.

EA is currently regarded as an emergent environmental assessment tool within the general environmental and ecological indicators research community; expanding it to include SSCM and CE is only a recent phenomenon and has yet to reach the attention of the broader business community. Its inclusion in sustainable consumption and production at the supply chain and organizational level is only starting receive any minimal importance. A recent review of emergy applications did not even mention supply chain management in the review (He et al., 2020). Also many limitations still exist—some of which are described later in this paper.

SSCM and CE performance indicators and measurements may overlap but also differ. Sustainable practices and circularity initiatives both typically seek to advance economic, social and environmental performance but with various viewpoints. SSCM primarily focuses on pro-environmental and socially responsible business activities while economic performance can be an overarching drive. Circularity's early underlying principles are based on economic policy development while alleviating environmental and resources challenges. Extant studies have conducted at the nexus of SSCM and CE, but uncertainty and controversies exist in the linkages (De Angelis et al., 2018; Liu et al., 2018). Emergy can be an effective ecological indicator to analytically link these fields—an integrated performance measurement system—for these two concepts.

In the following sections we identify general research findings, directions, and a summary of research questions based on theoretical lenses for using EA in the CE and SSCM perspectives.

Results

EA provides a holistic measurement from integrated sustainability and circularity dimensions by assessing complex systems from the donor side value. In this section we set the stage with identifying current applications of EA for SSCM and CE by returning to Table 2 and identifying gaps in the literature.

EA integrates different flows of energy, materials, and labor with different units into one measurable unit (solar emjoules) (sej). It considers different kinds of resources including natural resources, imported resources, labor and information (Brown and Buranakarn, 2003). EA is a very comprehensive technique that can support measuring the three sustainability dimensions includ-

¹ The database is available at: <https://cep.ees.ufl.edu/need/>

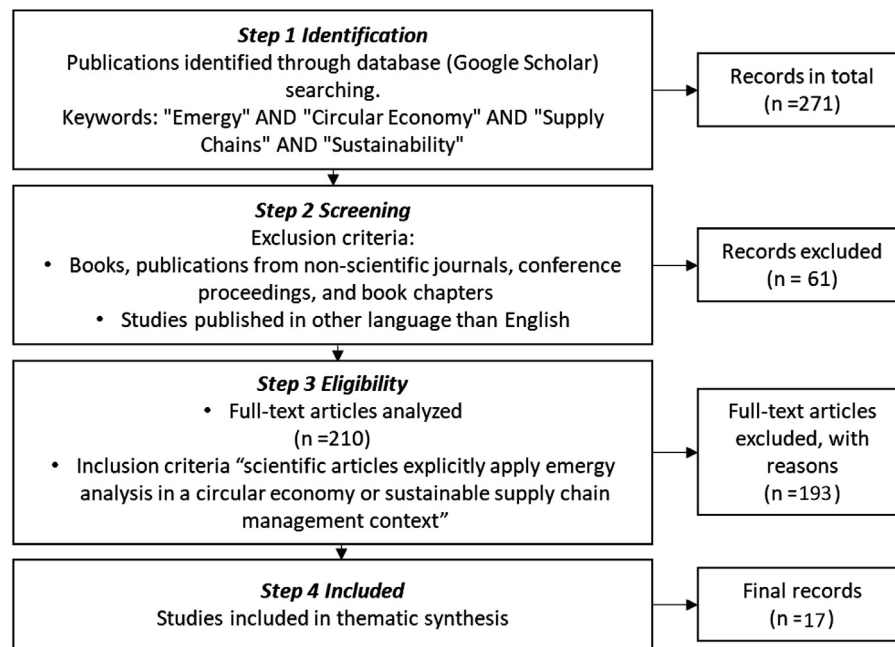


Figure 2. Literature Review Methodology

ing social – labor – economic concerns and the natural environment.

From a practical perspective, EA is suitable for measuring regional sustainability because it accounts for a multiplicity of resources locally available within a certain geographical boundary. For instance, comparisons between developed and developing regions in terms of sustainable practices can be made clear using EA and its various indicators (Khan, 2019; Khan et al., 2017b).

From a supply chain context, EA is capable of performing proper evaluations based on the structure of the supply chain. In other words, emergy offers a number of indicators that are specifically suitable for circular systems along with other linear system emergy indicators (Marvuglia et al., 2018). Another important aspect of emergy is its ability to measure the amount of work accumulated to generate information. This aspect is especially useful in supply chain network evaluations as information is an integral part in defining the degree of circularity. Although not extensively studied, to some extent, emergy also identifies activities in intra and inter organizational flow values.

EA and SSCM has been considered—albeit lightly—at multiple levels of analysis. Macro level analyses is the dominant focus for a majority of published supply chain work (Liu, et al., 2018). A few papers had a narrower scope of the supply chain with an operational and managerial focus (Tian and Sarkis, 2020). Existing emergy data is at a broader level analysis—national and regional—making it easier to evaluate at the macro analysis level (Tian and Sarkis, 2020). Some EA applications do occur at the industrial park or meso level. At this level emergy based indicators evaluate and analyze these meso-level interorganizational system's eco-efficiency and sustainability (Geng et al., 2010). Few organizational and individual studies integrated EA in their evaluations.

Although the EA application has not been intensively performed within the supply chain level of analysis, some studies provide significant future directions. For instance, Cai et al. (2020) built an emergy model to investigate the sustainability of outsourcing machining resources to support improved resource consumption efficiency. They created several emergy models namely, production quality emergy, production time emergy, production logistics cost emergy, and production resources consumption emergy. The results and metrics supported the feasibility of emergy in opera-

tional and supply chain performance evaluation—in this case the outsourcing decision. Next section provides a broad discussion of some future directions for EA application in SSCM and CE.

Discussion

While many emergy studies seek to evaluate economic, social, and ecological performance, the social dimension is relatively neglected (Chen et al., 2017). More emergy social related indicators can be developed from the interaction between humans and human systems and their surrounding environment. For instance, sustainable practices such as recycling and waste treatment techniques may improve the quality of life and human welfare in a particular region (Eichner and Pethig, 2001). Future studies can focus on applying emergy based indicators to evaluate socio-ecological systems at macro, meso and micro levels of analysis.

Empirical research—especially broad-based survey study—methodology is limited in emergy assessment and application (Hau and Bakshi, 2004). Empirical findings are essential to a wider acceptance and application of emergy. Emergy can offer practical implications to policymakers and managers to identify the space, time and natural resources for production and consumption systems. EA performance measurement can be utilized in empirical analytics such as system dynamics, non-parametric and parametric modeling and evaluation. For example, emergy may be applied in supply chain design and evaluation practices by incorporating emergy indicators with green and sustainable supply chain criteria and other assessment approaches such as LCA, ecological footprint and input-output analysis (Fruegaard and Astrup, 2011). The combination of EA with other methods will be the long-term direction of future emergy-related studies.

Theoretical linkage and development—especially within supply chain and CE research in EA is relatively neglected. EA has taken a slow and challenging path to become an accepted ecological indicator methodology within the scientific community including sustainability and circularity fields. In order to effectively apply emergy to supply chain management and circularity research, various missing theoretical linkages provide opportunities for future research. Systems theories and thermodynamic theoretical principles form the major underlying theoretical perspectives

Table 3

Theory-based Future Directions for Emergy Analysis in Sustainable Supply Chain and Circularity Research

Level	Theory	Conceptualization	Potential application	Research questions
Macro	Ecological modernization theory (EMT)	EMT states the achievement of industrial development without environmental degradation through continuous technological innovation and development (Spaargaren, 2000).	Comparisons between developed and developing economies/regions can be addressed from an ecological modernization perspective using EA as a technological development tool; Whether ecological modernization results hold can be determined through technological and economic EA measures. Research can evaluate if these measures vary in terms of theoretical expectations. Ecological Modernization in CE has been investigated (e.g. Park et al., 2010).	Can EA provide a macroscopic evaluation based on technological development and innovation?
	Institutional theory (IT)	IT posits that regulative, normative and cultural-cognitive factors may lead to coercive, normative, and mimetic mechanisms in organizational social behaviors (DiMaggio and Powell, 1983; Richard, 2001).	EA can uniquely evaluate social systems although emergy social indicators are still inchoate measures.; EA may be used to help evaluate whether norms or mimetic activities are influencing organizations within supply chains and across international borders (Tian et al., 2018).	Can elements of IT change supply chains decisions when using EA evaluations?
	Stakeholder theory (ST)	ST illustrates that individuals and social groups affecting or being affected by the organizational business activities represent organizational stakeholders (Freeman, 1984).	Stakeholder influence can be investigated using EA in conjunction with other tools to perform a comprehensive assessment within CE and supply chains (Jakhar et al., 2019). For example, emergy shifts in resources due to CE or supply chains practices may consider social and equity impact. For example, packaging design using emergy may influence supply chain and CE practices, but influence stakeholders differently (Meherishi, et al., 2019).	Can stakeholders' pressure be evaluated with an input-based model (EA)?
	Natural resource dependence theory (NRDT) ;	NRDT extends the traditional perspective of RDT and states that organizations are directly and indirectly dependent on natural resources (Tashman, 2011).	NRDT is still an emerging theoretical concept needing general CE and supply chain evaluation.;	How does EA as an environmental assessment tool play a role on supply chains especially those that depend more directly on natural resources?; Can EA evaluate ecological impact on organizations, organizational impact in natural system and dependency on natural resources?; Can NRDT constructs be integrated as a circularity measurement using EA?

(continued on next page)

Table 3 (continued)

Level	Theory	Conceptualization	Potential application	Research questions
Meso	Resource based view (RBV)	Resources that are valuable, rare, inimitable and non-substitutable can build organizational competitive advantage (Barney, 1991).	EA can provide unique evaluations of organizational performance considering the origins of valuable, rare, inimitable and non-substitutable resources.	Can evaluations performed by EA give supply chains and partners a competitive advantage in designing their valuable, rare, inimitable and non-substitutable resources?; Can CE principles, as evaluated using EA, be sources of competitive advantage for organizations and partners?
	Natural resource-based view (NRBV)	NRBV extends RBV by emphasizing organizational competitive advantage can be achieved through building relationship with natural environment (Hart, 1995), (i.e. pollution prevention, waste management and sustainable development).	Global supply chain diffusion and evaluation of various pollution prevention or environmental resources with EA.	Can EA broaden the perception of environmental policy such as CE used by policy makers by adding a donor-side perspective?
	Resource dependence theory (RDT)	RDT states that inter-organizational relationships affect organizational capabilities of obtaining resources from the environment (Pfeffer, 1977).	Resource dependence across organizations or regions (Deslatte and Stokan, 2019) may vary depending on EA, a comparative analysis with other metrics and tools; EA can bring new insights affecting the ability to obtain critical resources necessary for organizational survival (see for example, Schnittfeld and Busch, 2016; to extend RDT across market environments and supply chains).	Can inter-organizational relationships be evaluated using an input-based model (EA)?
Micro	Theory of industrial symbiosis (TIS)	TIS integrates separate industries through a collective approach to gain collaborative competitive advantages through physical exchange of materials, energy, water and byproducts (Chertow, 2000).	To some extent, using EA as a strategic tool for geographical and design considerations of industrial symbiosis can ensure the successful application of such establishments (e.g. Geng et al., 2014).	Would industrial symbiosis activities be more or less sustainable with EA? Which symbiotic relationships would be selected using EA?
	Systems theory (ST)	Organizations can be reviewed as dynamic systems through interactions with products and services; (Von Bertalanffy, 1968).	EA is suitable to be integrated with tools originated from systems theory (i.e. system dynamics) adding more depth to systems within a micro level. Macro and Meso level systems have been evaluated.	Can EA be used as micro-level evaluation measurement in supply chain and circularity performance?
	Social exchange theory (SET)	SET indicates inter-organizational relationships can be built upon cost-benefit evaluations amongst potential alternatives (Emerson, 1976).	EA uses nature's contribution for environmental, economic and social system evaluations. Thus, it has the ability to provide an objective assessment for inter-organizational relationships.	Can EA be integrated as an assessment tool for inter-organizational relationships?
Individual	Theory of production frontiers (TPF)	Production frontier represents the maximum output with given inputs and other technical considerations (Aigner et al., 1977).	Supply chain and CE based organizational analysis to help determine production frontier expansion as natural resources are considered.	Can EA give different insights to the theory of production frontier by including a donor-side perspective to the equation?
	Theory of reasoned action (TRA)	TRA states that individual behavior patterns are formed by individual's internal and external beliefs (Fishbein and Ajzen, 2011; Osterhus, 1997).	This will require that individuals are able to comprehend EA. For example, ecological footprint analysis can be conducted at individual level to evaluate the impact of individual economic behavior corresponds to natural energy consumed or occupied (Bastianoni et al., 2004).	How can emergy promote environmental norms and further affect green purchasing behavior?
	Acquisition-transaction utility theory (ATUT)	ATUT depicts that individual evaluation of a product is collectively determined by the acquisition utility, or the transaction utility (i.e.: expenditure), and the perceived product value (Thaler, 1983).	EA can be integrated to extend individual acquisition utility and transaction utility functions. These can also be traced to CE activities such as recycling or purchasing circular products and services.	Can EA be used to evaluate individual level transactions and alter individual actions?
	Theory of planned behavior (TPB)	TPB indicates that individual behavior follows a rational choice model where intention is the direct psychological antecedent (Ajzen, 1991).	EA may help in assessing individual behavior and utility maximization when it comes to adopting of CE and SSCM practices.	How can EA be used to explain the individual intention in engaging in sustainability and circularity programs?

for emergy (Odum 1996); with emergy itself considered as a theory (Amaral, et al., 2016). Expanding consideration and evaluation of emergy theory from organizational, economic, sociological, psychological and policy theories can expand acceptance and application. This issue is similar to issues related to sustainability practices such as eco-innovation (Hazarika and Zhang, 2019).

EA—as mentioned—can be considered from other conceptual theoretical lenses, such as institutional theory, organizational theory, individual motivation theory (see how these theories have been utilized for in CE and sustainable supply chains in Liu et al., 2018). Table 3 summarizes the potential theory development and future research directions of EA from a supply chain sustainability and circularity nexus—using the various theoretical lenses. In each case we can consider using EA as an indicator for measurement or theorizing, or consider how theories may help explain adoption or lack-thereof of EA.

Table 3 is divided into multiple levels of analysis, macro-, meso-, and micro- dimensions. Although we place some theories into a given level, each may have more than one level of analysis—we provide an example at each. The theory and a definition of the theory is provided with supporting references. Specific research questions are also included. In many cases, the basic assumption or research question is that the level of EA granularity exists or would need to be developed for the theory. For example, EA at the individual level may require that products and materials, or practices, that individuals buy or adopt exist at those levels. We view this as a meta-question of whether EA can be brought down to the lower levels of analysis when most of the data exists at the national or regional level.

Some of the theories presented are quite popular based on the CE and SSCM literature. We do note again that most emergy research and use of EA has been relatively non-theoretical from an organizational and economic perspective. The numerous theories and research questions we present in Table 3 are only meant to be exemplary and as a starting point. We feel that these three fields have much to offer business and economic research that covers sustainability and CE practices.

Based on our review, we identify a number of limitations with regard to integrations between EA, SSCM and CE. First, much of the available data is at a very broad level—high granularity—that is not suitable for the organizational supply chain or individual levels of analysis (Tian and Sarkis, 2020). Careful consideration and examination are necessary to disaggregate available solar equivalent data to organizational, product, or supply chain levels (He et al., 2020). Consequently, some issues may arise from data disaggregation. For example, disclosing of materials sourcing may be ambiguous to some extent for proprietary reasons. Furthermore, calculations and conversions of inputs into emergy values might not be recently updated or available for some regions. Even the current regional and national databases are under continuous review and updating (e.g. Brown and Ulgiati, 2010; 2016).

Second, the results of EA are not easily interpreted and explained (Amaral et al., 2016). To be able to properly calculate the emergy value of a certain product, EA extends from resource formation of all raw materials used in the production stage to the creation of the final product. This also foils broader practical business application of EA. In other words, adjusting business systems to be compatible with performing an emergy evaluation may entail substantial efforts. For example, organizations may undertake major systems' adjustments to link enterprise resource planning (ERP) systems with bills-of-material to manage products (Tian and Sarkis, 2020).

From a CE perspective, it is not clear if the emergy of even the same material is equal as it may be affected by different spatial characteristics (Wang et al., 2020). Imagine a metal that has undergone many cycles of processing, recycling, and remanufactur-

ing, the allocation becomes blurred and difficult to maintain since a material could have gone through multiple life cycles after extraction. Is it fair for the first usage to get the full allocation of a resource if the resource is reused, if it is recycled and reused, will the original emergy valuation for a product be adjusted? These are some concerns that still require research and modeling (He et al., 2020).

Conclusion

SSCM and CE require effective performance measurement to help them progress. Some of the techniques currently used have limitations which are outlined. As an emergent and potentially effective social-ecological performance evaluation tool, EA differentiates from other conventional measures (e.g. financial payback analysis) in its capability of quantifying the work of ecosystems in solar equivalent values. EA provides alternate evaluation performance insights as it incorporates the donor-side value of the environment.

Advancements in EA to be applied to the micro-level analysis of SSCM and CE is required to make EA more effective in these situations. Given the early stages of emergy applications in SSCM and CE, a number of limitations are identified in this paper. First, much of the available data is at a very broad level—high granularity—that is not suitable for the organizational supply chain or individual levels of analysis. Second, the results of EA may not be easily interpreted and explained. For broader practical business application of EA these issues and interpretations need investigation. From a CE perspective, it is not clear if the emergy of even the same material is equal. These are many concerns that still require research and modeling.

We have also observed that organizational, economic, and consumer theory and EA linkages can be studied. Theory can support EA becoming more accepted as a performance measurement tool for businesses, industry, and supply chains. Integrating EA as a research tool can benefit a more complete and sustainable understanding of economic, business, and sustainability efforts, especially sustainable supply chains and CE practices.

In summary, EA is an emergent and valuable technique that can be used in sustainability and circular development at various levels. More research is needed to logically integrate it into the organizational supply chain and individual level. More practical applications of EA will eventually help in emphasizing the significance of such a holistic tool not only for ecological assessment but also broader managerial and operational evaluation and individual decision making. This paper reviews and evaluates various EA features and build connections between emergy, SSCM, and circularity concepts. We seek to generally analyze the current intellectual structure to evaluate the feasibility of applying EA to SSCM and CE as a performance appraisal and measurement tool. This paper helps set the foundation for much needed additional research in these fields.

Declaration of Competing Interest

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

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