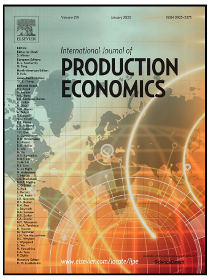

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Expanding Green Supply Chain Performance Measurement through Emergy Accounting and Analysis

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Expanding Green Supply Chain Performance Measurement through Emergy Accounting and Analysis

Abstract:

Emergy accounting has existed for decades. Emergy evaluates the donor side contribution of nature at region or country, macro-level analyses. It has been rarely applied and considered for organizational or supply chain management. In this study we provide an introduction and background on how emergy accounting analysis can be adjusted and applied at the supply chain level. Supplier selection is the example supply chain application for which actual emergy measures are used. The purpose of this study is to introduce the concept as a valuable tool for investigation by operations and supply chain management scholars and practitioners. The application provides some initial insight. This work at the nexus of sustainable supply chains and performance measurement is an initial study with significant future opportunities. These opportunities include effectively internalizing environmental and resource externalities for more thoughtful business models and evaluations. Implications and future research directions are summarized for this important, yet understudied field. It contributes by expanding the supplier performance measurement field.

Keywords: Green Supply Chain Management; Emergy Accounting; Eco-design; Sustainability, Supply Chain Management

1. Introduction

Evaluating the performance of green supply chains has been a concern from early research on greening supply chains (Hervani et al., 2005). In this environment, standard business approaches and metrics attempt to incorporate both economic and environmental performance metrics. These measurements and indicators have limitations in that they typically use ‘user-side’ or ‘demand-side’ indicators such as energy that emits carbon emissions (Kharrazi et al., 2014). To help expand the field of green supply chain performance measurement we argue that ‘donor-side’ or supply side metrics may give a more accurate picture of the overall green performance of supply chains; and it is time to consider these emergent environmental indicators in these evaluations. Donor-side metrics concern how much natural work expended for the resources and activities used by human systems. More on this issue is discussed in later sections.

One of the most popular approaches for evaluating ecological and human systems indicators from a donor-side perspective is through Emergy accounting (Brown and Ulgiati, 2004; Odum, 1996).

Emergy (with an 'm') is called the memory of energy. It is the available energy previously used to directly and indirectly generate a service or products (Odum, 1996). It seeks to value multiple resource types -- energy, raw materials, finished goods, and human services -- in the same measurable units, the solar emjoule (seJ) (Odum, 1988, 1996).

Although limitations exist with Emergy analysis (Raugei, 2011), introducing the concept to organizational and supply chain management research can advance both fields. It further develops application of Emergy to the business and supply chain unit of analysis, and expands supply chain performance measurement into using the latest knowledge in environmental measurement and accounting. Introducing emergy analysis into the supply chain management field is an important initial step and innovation.

Emergy accounting analysis, because of data availability, typically focuses at national or regional levels of analysis. Some recent efforts have tried to focus measurement at finer granular levels such as products or processes for given industries or at eco-industrial parks level of analyses (Ren et al., 2010; Wang et al., 2005; Zhang et al., 2011). These works though have presented the evaluation and development from a non-managerial and non-operations perspective, with a focus on broader environmental policy implications. Our goal is to apply emergy accounting analysis for green supply chain evaluation from a business and managerial perspective.

Emergy accounting principles for the supply chain management researcher and practitioner are introduced in this paper. How emergy is used to model performance of supply chains is overviewed. The example illustration is based on conceptual perspectives for a supplier selection problem. We also recognize the limitations of emergy within this context, with the primary limitation being the need for more detailed data granulation such that individual processes, products, and materials; this is for more accurate portrayal for contingent situations.

The concept of emergy based supply chain management performance measure especially for green supply chain management (GSCM), fills a need for a standard performance measure to link both environmental and economic measures with minimal transformation (Beske-Janssen et al., 2015; Hassini et al., 2012). Although relatively intuitive, emergy analysis requires nuanced explication for improving researcher and practitioner awareness and acceptance. Some details of these nuanced considerations occur within this study.

In this paper, we begin by providing background with what we feel is the most closely related topic to this study, green supply chain performance measurement. We then introduce some emergy analysis foundations. In this section emergy terminology and methodology are both overviewed. The next section forms the core of our contribution, which seeks to clearly and closely align emergy analysis at the supply chain level, specifically considering a supplier selection problem using emergy valuations. An analysis of the advantages and limitations of the technique includes further research questions and an agenda.

2. Green Supply Chains and Performance Measurement

Supply chain performance measurement has gained increasing importance as competitive positioning has expanded to include supply chains and processes (Ketchen and Hult, 2007). Performance measurement can be utilized for various supply chain activities including performance improvement, supplier selection, benchmarking, supply chain management research, and project management.

Although growing in importance and investigation, performance measurement in the supply chain is a relatively recent phenomenon in organizational and management research (Akyz and Erkan, 2010). Of particular importance and investigation is the focus on broadening supply chain performance measurement to incorporate green, environmental, factors as well as social factors, when the focus is on the broader sustainability topic. Our focus will be on green supply chain performance measurement, although extensions to social concerns can be completed.

Understanding supply chain processes and relationships is an initial step in green supply chain performance. For example, the Supply Chain Operations Reference (SCOR) model has utilized its various functions and linked performance metrics to supply chain processes such as “plan” and “deliver” processes (Chae, 2009). There have been extensions to SCOR incorporating environmental measures, or green or sustainable SCOR and other initiatives (Genovese et al., 2013; Stohler et al., 2018). These more recent initiatives still require further investigation.

Green and sustainable supply chain performance measures can utilize extensions to traditional business metrics such as cost, quality, flexibility, and time. These types of measures are typically associated with operational capabilities of supply chains. More traditional environmental performance metrics would include various types of emissions from practices. For example, energy and water use, solid waste generated, or carbon emissions are all examples of measurements from tools such as life cycle assessment (LCA).

A number of potential supply chain environmental accounting tools do exist including LCA, materials flow analysis (MFA), and eco-efficiency measures. Limits to these techniques exist. For example, MFA focuses primarily on volume of material flows to evaluate systems. LCA is appropriate for certain products with appropriate data availability, but not so well designed for service. Eco-efficiency is a measure that focuses primarily on resource efficiency. Each of these tools are capable of evaluation on very specific and different scales. Emergy accounting can be integrated with each of these approaches as an evaluation tool.

LCA is focusing on how to identify the impacts. It aims to identify local and regional impacts, such as a production process. It focuses on very specific activities environmental aspects. For example, the goal is to identify activities that have significant emissions or in which step resources are consumed. In this way, a decision maker could make the choice and improve an identified activity; with a focus on human costs. LCA is exploring the impacts of current activities, such as, the emission impacts from a production process over an annual, monthly or daily time period.

Emergy evaluates environmental cost by focusing on the embodied resources invested into a process or activity; from the formation of a resource until current time. For example, let's consider a fossil fuel, petroleum oil. Oil formation requires geologic time and processes. These geologic times and processes means that the embodiment of resources in oil as an energy source is extremely large. Therefore, when oil is used, all the past resources are embodied in it and the embodied environmental cost requires accounting.

LCA and emergy analysis may be considered complementary tools. Emergy is considered an environmental accounting indicator, which is a calculation of the environmental cost. LCA aims to identify the impacts. Emergy is a type of impact; one that arguably more accurately represents embodied environmental costs.

The next section will detail core aspects of emergy accounting analysis (EMA).

3. An Introduction to Emergy Accounting

Human-dominant activities impose pressures on natural ecosystems, especially with rapid development of economic globalization (Brown and Ulgiati, 2001a; Jomo and Rudiger, 2009). In order to identify the interface between economy, environment and society, emergy accounting (EMA) has received particular attention during the past few decades (Amaral et al., 2016; Geng et al., 2013).

Emergy theory was first proposed in the late 1980's emphasizing the importance of applying energy system language for open systems using thermodynamics and general systems theory (Odum, 1996). EMA is recognized as a donor side method, considering the work of the environment. It is regarded as an environmental accounting tool for measuring the contribution of natural resources to economic activities (Brown and Ulgiati, 1999; Brown and Ulgiati, 2001b; Odum, 1996).

Emergy has at least three advantages for environmental accounting and measurement. First, emergy focuses on the donor side; it can identify how input resources from natural systems can contribute to the economic system. Secondly, most other approaches ignore natural economic system contribution; most natural system contributions have been assumed to not vary. Current methods consider resource acquisition convenience but ignore environmental quality contribution.

Finally, emergy provides a single unit of measure that can be integrated effectively and is more environmentally related; whereas most evaluations in business and environment focus on monetary valuations as the single unit. The limitation of monetary evaluations is that many resource systems cannot have accurately assessed true market values. For example, wind and ecosystem services cannot be easily valued into monetary terms. Valuing these resources in emergy is more feasible.

Emergy is advantageous due to supporting tools to convert different input flows in the system into unitary solar energy units. In this way diverse systems are able to be directly compared to each other. These comparative analyses, amongst other factors, can help identify appropriate investment measurement and policy for decision makers, even corporate and organizational decision makers.

Solar emergy attempts to value natural resources that economic valuations do not fully and accurately value. Rain, raw materials from nature, water from rivers, and biodiversity are difficult to monetize and measure economically. It can also value resources that are central to the human economy, mainly fossil fuels and their derivatives including goods and services of industrial economies.

To convert energy inputs and other flows into their solar equivalent, a Unit Emergy Value (UEV) is used. UEVs are an indirect measure of the total environmental support (emergy) needed to generate a unit of product flow or storage. UEVs act as conversion factors. Typical UEV units are solar equivalent joule per gram (sej/g) or solar emjoule per Joule (sej/J). For example, it may require 1000 sej from the sun to make 1 Joule of energy from a piece of coal.

UEV is an expression of the quality of an output. Higher UEVs mean that more emergy is required to make the resource. For example, to acquire 1 Joule of energy from gas may be only 900 sej, while 1 Joule of coal requires 1000 sej of nature's work or effort. Thus, coal can be considered a higher "quality" resource due to a higher emergy value. Although each of these materials provides the same level of energy output of 1 Joule, the amount of effort can be substantially different. The emergy for coal is larger due to the greater effort and time to produce; again having higher quality. This example also shows the difference between a donor-side measure versus a user-side measure. In this situation both the coal and gas have equal user-side measures, but different donor-side values.

UEVs exist for a wide variety of resources, commodities, and renewable energies. UEVs may be found in past research studies, a series of emergy folios, and the National Environmental Accounting Database (NEAD). It is important to note that two types of NEAD can be used. One is the NEAD produced in 2012 by the International Society for the Advancement of Emergy Research (ISAER) – the website is https://cep.ees.ufl.edu/emergy/nead.shtml. The other is NEAD V2.0, which was updated in 2017. This later version updated commodity UEVs using the emergy 2016 baseline. More information can be found on the website http://www.emergy-nead.com/home/about (Brandt-Williams, 2001; Brown and Bardi, 2001; Kangas, 2002; Odum, 1996; Odum and Odum, 2000; Pan et al., 2017; Sweeney et al., 2007; Vilbiss and Brown, 2015).

Here, we use NEAD V2.0 for brief emergy accounting descriptions. The NEAD compiles detailed information for over 213 countries over a 15 year time period from 2000-2014. It contains data on a comprehensive array of resources that underlie economies, including environmental flows (sunlight, rainfall), natural capital stocks (soil, water, forests, fish), mined materials (metals, fuels) and economically transformed goods and services (agricultural commodities, manufactured goods, services). Example data from NEAD V2.0 is shown in Figure 1.

Figure 1 about here

The basic equation for calculating the emergy of a product[1] is described in expression (1).

$$E_p = P \text{ (g or J)} \times UEV_p \text{ (sej/g or sej/J)} \quad (1)$$

E_p is the emergy of a product *p*; P denotes the mass or energy, UEV_p represents the UEV of product *p*.

The EMA includes three general steps. First, the investigated system is presented through an emergy system diagram using a systems diagramming language. This systems diagram shows the interacting systems and their exchanged flows of energy and capital.

Secondly, all matter, energy and capital flows are converted into their solar emergy equivalents by multiplying the available energy or mass by a suitable UEV. This typically involves only mass or energy. Additional analyses may also incorporate items such as the emergy of Labor and Services (L&S, Table 1). L&S may also include both the direct activity performed within the system's boundaries (Labor) and the indirect activity related to the infrastructure. Indirect labor chains make the process possible at the larger scale of an economy, defined as services (Ulgiati and Brown, 2014).

In the third step, emergy indicators are calculated to help evaluate and interpret the performance of the investigated systems. Several basic emergy indicators, which we

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[1] The term product is used here in an emergy sense as the product from solar energy used to make it. The product can be a commodity, material, resource, or service, for example.

will utilize in the exposition for the green supply chain performance illustration, are listed in Table 1. Additional indicators also exist (Odum, 1996), but are not utilized in our exposition and evaluation.

Table 1 about here

EMA has addressed multiple levels of analysis; most of the research focuses on global or regional geographical systems. For instance, EMA has considered the sustainability of regional development at national (Brown et al., 2009; Lou and Ulgiati, 2013; Pulselli, 2010), regional (Cai et al., 2009; Lv and Wu, 2009; Pulselli et al., 2007) and city/municipal (Ascione et al., 2009; Lei et al., 2006; Zhang et al., 2009) levels of analysis.

EMA has been applied to a variety of processes and systems, including: agricultural (Jaklič et al., 2014; Yang and Chen, 2014; Zhang, 2004) and industry level production (Fan et al., 2017; Geng et al., 2010; Yang et al., 2003); cement industry production (Chen et al., 2016); household waste management (Franzese et al., 2008; Mu et al., 2011, Tian, 2016); and energy (Lugaric and Krajcar, 2016) systems. EMA has also focused on specific evaluations, such as buildings (Reza et al., 2014), trade (Geng et al., 2017), natural reserves (Lu et al., 2007) and information (Abel, 2010). Each of these focused on specific environmental issues and concerns – with virtually non-existent business and managerial analyses.

Only a few studies investigate the supply chain level of analysis. The food supply chain in UK farming has been evaluated (Markussen et al., 2014). A general supply chain perspective for a generic farming supply chain is introduced. A retail distribution system level analysis uses a joint emergy and LCA approach in that particular study (Markussen et al., 2014). The study had very limited emergy accounting evaluation from a supply chain management perspective; differences between two generic systems were evaluated.

Another generic emergy accounting supply chain application targets the pulp and paper industry (Corcelli et al., 2018). Three forest management scenarios based on Spruce/Pine, Eucalyptus and Poplar production for raw material supply are evaluated; assessing the sustainability and efficiency of each tree species. This study includes a general comparative resource evaluation. A model introduces some aspects of a pulp and paper supply chain with a focus on transportation and production activities. Findings showed emergy outputs with spruce/pine forest management as the most sustainable wood resources.

Alluvial and underground gold production systems sustainability evaluation from within Ghana also applied emergy analysis at the generic supply chain level (Asamoah et al., 2017). The two production systems differed markedly in raw material extraction stages.

One of the few emergy analytical modeling supply chain applications uses a mixed-integer non-linear Programming (MINLP) model for strategic design of a supply chain (Ren et al., 2015). In this model, the emergy sustainability index of biodiesel supply is employed as a sustainability measure, and multiple feedstock, transport modes, distribution centers and regions for biodiesel production were considered. The situation was a generic design of a various stages of delivery and transport in a supply chain. This study demonstrated that the proposed methodology is feasible for finding the most sustainable design and planning of biodiesel supply chains. Managerial decision making in this situation was not a focus.

Generally speaking these studies focused on the supply chain issues from environmental or resources perspective; with limited business and managerial perspectives. They each provided details on how to quantify the environmental or resource role using EMA for production or transportation processes of a supply chain. These studies lack explanation and investigation on how to link green supply chain business practices with an emergy accounting perspective. For example, benchmarking, supplier management, supply chain managerial activities and functions, and general research for green supply chains, were not included in evaluations or analyses.

These studies can prove helpful, altogether, for investigating the supply chain and organizational level of analysis. Most of them focus on generic supply chains, how supply chain and business managers can utilize these tools and designs is not explicitly developed or studied.

It is difficult for supply chain actors to implement EMA with a more direct business and managerial focus. Thus, no investigation has explicitly considered and evaluated the use of EMA for supply chains from a business perspective (Matteo Mura et al., 2018) for a typical organization or product. In order to advance EMA usage in supply chain management and research, we apply EMA for green supply chain evaluation from a business and managerial perspective. In this case we focus on a supplier selection managerial decision.

4. Emergy Accounting for Green Supplier Management

In this section, we introduce EMA for supply chain and decision analysis. An illustrative example evaluates supply chain performance based on emergy valuation. The analysis links up various supply chain functions within organizations and example calculations for these supply chain functions. The example addresses comparative supplier evaluation and selection.

4.1 An illustrative case study

Many practical managerial dimensions exist when seeking to green supply chains. In this study we use EMA for the supplier selection business decision.

For the supplier selection decision we introduce a hypothetical illustration with four companies. One is the focal company; focusing on beverage production. The three other companies are potential suppliers for the focal company's bottle container needs. The goal is to aid the focal company select a supplier of plastic bottles. Each of the three potential suppliers have different bottle production materials and processes. The general illustrative overview, with supplier descriptions and assumptions appears in Table 2. The location of the selected companies are shown in Figure 2.

<insert Table 2>
<insert Figure 2>

In order to provide an emergy analysis, the system diagram needs to be developed. The major components within the system boundary and the interactions between the different components need to be identified. The general emergy system diagram for the suppliers in this illustrative study is shown in Figure 3. Note – in Table 2 – that the description varies by location, type of energy source, level of automation, labor skill characteristic, transportation considerations, and the transportation type. These variations influence emergy valuations.

In this illustrative study, we assume each supplier has four related departments or core supply chain functions – purchasing, inbound transportation, make, and outbound transport – which are based on value chain processes as well as the APICS SCOR model (Estampe et al., 2013; Huan et al., 2004). These functions provide basic resources and services in order to complete the production and transportation of plastic bottles from a supplier to the focal company. Various energy and resource inputs derive from outside the system boundary. Each of these supplier alternatives requires valuation based on location and type of resource. Emergy valuations tend to differ depending on location.

In this illustrative example the focal company is located in Shanghai, China. We assume the focal company to have 10% of the Shanghai market annual demand for plastic bottles for its beverage.

The legend for the symbols for the emergy system diagram (Figure 3) appears on the right hand side of the diagram. Additional detail on the meanings of each of these symbols has been standardized in previous publications (see Odum, 1996).

<insert Figure 3>

4.2 Supplier Emergy Evaluation

In order to describe an emergy-based supplier selection application clearly, we assume an amount of input resources to the production system for each supplier. The emergy flows of the bottle production system for each supplier summarily appear in Table 3. Please see an example calculation based on various practical assumptions in the note under Table 4; which also details the emergy elements for each company's make process.

<insert Table 3 and Table 4>

Table 3 shows resource inputs and emergy flows by department for each of the three suppliers. This table also presents the type of resource input, such as renewable or non-renewable resources. The focal company can easily view the environmental and resources consumption list in the table. For instance, the supplier could easily see the amount of renewable and non-renewable resources input into the production. In addition, suppliers can be compared to each other. The overall purpose is to determine which supplier can provide the necessary materials in an emergy efficient way; incorporating nature's work value.

Figure 4 provides the total emergy resources used by each supplier. These results show that supplier 1 consumed the largest amount of emergy resources during bottle production and transport processes. Supplier 3 used the fewest emergy resources in those processes. The outbound transport department is the major contributor to resources consumed for each supplier. For each supplier improving outbound transport departments should be a future goal.

When we consider different types of resources consumed by the suppliers, it is shown that supplier 1 consumed the largest amount of non-renewable resources. This result indicates that supplier 1 is the least environmentally and resources friendly.

This information is valuable for the focal company, the buyer, to help them more accurately evaluate environmental burden of activities and materials of their suppliers. It provides a more complete picture for focal companies in evaluating supply chain partners through a holistic internalization of nature's burdens in completing commercial activities. Overall, if the emergy valuation is to be used for supplier selection, Supplier 3 would be the choice in this illustrative example.

5. Discussion, practical and policy implications

In order to improve holistic measurement of green supply chains, we introduce emergy accounting for supply chain evaluation. We illustrated an emergy analysis of three suppliers with differing material, production and transport characteristics. The emergy analysis reveals varying environmental and resources consumption for each supplier.

After an emergy accounting, suppliers and a buying focal company can more holistically understand the resource consumption performance of each supplier and their activities. The example application was for supplier selection allowing for a focal company to select a “green partner”.

In addition to supplier selection, emergy performance measures can be used for other supply chain management reasons. One of these other supply chain management activities is supplier auditing. A supplier audit is a more in-depth descriptive and predictive assessment of the supplier's performance (Wagner and Krause, 2009). Supplier auditing provides information that aids benchmarking and supplier development activities (Narasimhan et al., 2001). Supplier auditing is especially pertinent for managing supply chain sustainability (Seuring and Muller, 2008). Auditing requires participation by both the buyer and supplier in gathering and analyzing information. Suppliers and buyers can help identify materials, processes, equipment, or transportation alternatives to improve environmental performance.

Auditing information – either internally or by a buyer – allows suppliers to adopt alternate activities to address environmental and resources concerns as part of continuous improvement processes. They can adopt these alternatives to be attractive to buyers who use environmental performance criteria. For instance, Supplier 1 consumed a larger amount of non-renewable resources when compared to the other suppliers; this is an example of a benchmarking exercise. They can improve their emergy valuation by shifting to renewable resources. This benchmarking can be completed by Supplier 1. They must have information on how well they compare to other suppliers. In this situation, the focal company can share information to help suppliers improve. Helping suppliers improve is elemental to supplier development activities.

Green supplier development can also use information from supplier auditing (Bai and Sarkis, 2010; Fu et al., 2012). In this situation, greening a supply chain becomes easier because of a holistic and integrative picture offered by emergy analysis. For example, an audit may show that emergy performance in a given process is poor due to non-renewable energy sources. Supplier development include helping suppliers invest in renewable energy sources or finding alternative fuels with lower embodied resources.

We have shown only a dyadic relationship in this selection and supplier development process. Supply chains are usually networks and multi-tiered channels. Expanding this work to multiple channels and tiers – networks – provides a more accurate portrayal of the true supply chain burdens on resource consumption and the environment. In these broader situations, the supply chain boundary and EMA system requires expansion.

In terms of vendors and options for improvement, emergy can prove beneficial for business decisions that influence organizational and supply chain performance. We alluded to selecting other resources and equipment to help improve emergy performance. Transportation is a major burden. Selecting the appropriate transportation alternative is also a critical decision. In fact, most supply chain partners seek third-parties to supply transportation functions. In this situation, the transportation provider selection decision can also benefit from the emergy analysis.

The advantage of emergy accounting is its ability to identify nature's contribution to economic systems. After an emergy accounting, a more complete holistic valuation of input resources can result. For example, if only market economic values are used, the total monetary value for fossil fuel, wood, and corn may be similar in value. Their emergy valuations can dramatically differ, sometimes by magnitudes. Each resource has a quality value that depends on the broader, long term embodied resources invested in it. The company completing an emergy analysis could identify accurate natural resources consumption within the whole process.

The emergy evaluation process is able to distinguish value and impact in multiple ways. For example, the variety of input resources into the transport and making process can be evaluated separately. These details provide buyers and suppliers with improved information to develop a greener supply chain.

5.1 Challenges

Although emergy accounting could provide useful insights into green supply chain management, it has many uncertainties and challenges. One of the limitations and concerns is that not all materials, components and products can be easily traced in emergy analysis. Part of the concern is that there might be missing data either associated with material or location; emergy is heavily dependent on the scientifically developed database.

Specific organizational data associated with products and materials, much of which are focused on economic and costing aspects, may still not be complete. For example, knowing exact labor input into materials that derive from other locations may be based on assumptions. Even in modern accounting systems, knowing the exact direct or indirect labor costs, material usage and scrap, and tracing costs effectively – within organizations – are non-trivial organizational processes replete with variation (Schmitt, 1984; Nachtmann and Needy, 2003). Researchers and organizations propose many competing accounting systems. These systems are characterized with uncertainty and errors, requiring adjustment (Christensen, 2010).

In the example we provided, a number of assumptions were made such as companies were willing to share the types and composition of product materials, the composition of the equipment, and the type of energy used or source. It is difficult to acquire much of this operational and business data; especially across the supply chain.

A practical implication is the need to adjust legacy performance, accounting, and purchasing databases in the company. Many companies utilize enterprise resource planning (ERP) systems. These systems may have bills-of-material (BOM) to help them in their management of resources. These BOM have been linked to life cycle assessment and environmental approaches (e.g. De Benedetto and Klemes, 2010). But these systems are developed as prototypes and have yet to be fully adopted, even in leading firms. Not only are there uncertainties, but a lack of integration exists further hindering traceability of information.

Product engineering and design systems would also need to be integrated and adjusted across organizations. Many organizations are unwilling to provide detailed information on their products and how they are engineered or processed. This proprietary information is what gives some organizations a competitive advantage. Thus, competitive limitations to making this design information transparent and traceable is a major barrier for emergy analysis across the supply chain.

A number of environmentally based modules and information systems would need to be developed and linked to various accounting and production control systems. These systems will need to incorporate emergy data. These environmental management and information systems also have difficulties. Environmental management systems and accounting tools, such as life cycle assessment, are still replete with data uncertainties (Mendoza, et al., 2018). Emergy is likely to be reliant on life cycle assessment systems that trace products and materials throughout their product life cycles. There have been efforts to link life cycle inventories with emergy analysis (e.g. Navarrete-Gutiérrez, et al., 2016; Rugani & Bennetto, 2012). These nascent systems can prove valuable in addressing many supply chain management decisions that will face managers and build decision support tools in the supply chain environment. These emergent tools have many uncertainties, especially given that emergy will likely be linked to legacy environmental accounting systems with their own uncertainties (Londono, et al., 2019).

Thus, basic originating data for product manufacture across the supply chain may be missing due to difficulties in accounting, engineering, production, and environmental management data systems. Information and organizational systems integration within and between organizations will be necessary for better supply chain data traceability. Establishing data sets and bases – such as integration of environmental and purchasing department data -- will be necessary for effective data collection and calculation. This information, will eventually need to be integrated with EMA.

Given the nature of current emergy data, database updates are continuously being made as the methodologies for emergy calculations become more refined. Development of broad-based industry specific tools and databases may prove useful, similar to databases for life cycle analysis (LCA).

Using LCA thinking to operate the company is important for taking full advantage of emergy accounting. Training and education from multiple functional departments will be required for affective adoption and diffusion of the accounting tool. A database of previous product UEV's may also be needed across the supply chains and industries. Updated UEV databases from all countries are needed to more precisely reflect the resources consumption.

5.2 Policy and Supplier Practice Challenges

Focal companies face many complexities when seeking to identify good partners. For example, in this study, we focused on selection from an environmental and resources perspective. Organizations typically select suppliers based on business perspectives and cost. This situation is clearly expected, but many times the only decision factor is cost.

The basic tension is environmentally friendly selections are not always the lowest cost. In practical situations considering focal economic and cost perspectives, while helping them to select an environmental friendly option, is challenging. The question shifts to how to motivate focal companies to make these important supplier selections while considering environmental sustainability as a goal.

There are a number of potential internal – to the organization – and external measures for encouraging integration of environmental dimensions into supplier selection and supply chain management. Externally, governments and public agencies may subsidize specific programs for supporting more environmentally sound technological developments – for example through green public procurement (Cheng et al., 2018) or through public-private partnerships (Lin, 2014). In public procurement governmental agencies can set emergy guidelines for purchased materials. This type of effort can help encourage companies to utilize newer emergy measures and develop systems to meet government requirements. To aid companies build this capability, helping encourage emergy analysis tools and database development through partnerships can advance EMA adoption.

Unfortunately, not all governments have resources, policy, or motivation to make these requirements a reality. Education programs and information regarding true environmental (emergy) costs would require significant effort from agencies.

Other environmentally favorable policies may be to utilize emergy information for penalties or incentives. For example, there may be taxes levied on certain sources of material or resources with high emergy content. These taxes can help internalize externalities associated with high emergy products and materials.

We begin at this broadest level of policy recommendations since the changes in behavior and adoption of new emergy systems will likely require social-economic systems, such as financial and economic systems to adopt this new perspective. We do acknowledge that this transformation will require significant social and organizational effort; which, at this time may seem infeasible or insurmountable. As society evolves and environmental concerns become more prevalent, enlightened adoption of new, emergy based systems may occur.

Broadly, industry and society are still in the early stages of adopting norms and institutions to support sustainable industry and supply chains. To have such systems become established institutions requires significant social, governmental and regulatory effort. These evolutionary changes require external, to the supply chain, effort.

Another external actor used by for-profit organizations, for legitimacy and other reasons, is partnering with non-governmental organizations (NGOS) and civil society. Raising awareness and educating NGOs in emergy accounting and having them partner with for-profit organizations can lead to adoption of emergy in supply chain finance, governance, and performance measurement systems.

Industrial associations and accounting, environmental, and other standards organizations can play a role in the development and diffusion of emergy-based indicators. Guidelines from groups such as the International Standards Organization (ISO) can help to further develop emergy accounting systems adoption.

There are also internal organizational and supply chain measures and activities that can help to evolve these emergy-based measurement and management systems. It is already clear that buyers have many additional business factors to consider in supplier selection decisions (Sarkis and Talluri, 2002). These business factors include cost, material quality, delivery performance, and technological capabilities. Currently, we do not transform the emergy values into costs, but this step of linking the two is possible.

Weighing and measuring emergy valuations against business factors is needed. This balanced approach provides a more complete picture of the various benefits and burdens of supply chain environmental burdens (Tognetti et al., 2015). Investigations on how to transform traditional business factors – such as cost and quality of products and materials – into emergy values, is needed. We describe additional requirements and limitations on emergy accounting for supply chain and green supply chain management in the next section.

6. Future Directions for Emergy Research in GSCM and SCM

As can be seen by the various policy and practice implications of this work, many challenges still exist. Given the relative novelty and early introduction of emergy as a business concept there are many avenues for research to effectively address these government, industry, supply chain and organizational challenges.

There is currently effort and research to further link emergy with LCA and MFA (Li and Wang, 2009; Ohnishi et al., 2017). In order to offer more complete emergy evaluation and analysis in the supply chain, emergy needs to be further linked and improved with these complementary environmental tools. In this way, practitioners and researchers knowledgeable with those tools are in position to more readily accept these changes. Determining the level of validity and boundary definitions, as well as depth of emergy data, may be necessary for different supply chain networks. Research and aggregation for different system boundaries require investigation.

The emergy calculation factor such as UEVs of products and resources requires continuous updating. Given complex supply chain levels, it requires partners in the supply chain to contribute to improving the emergy database. How emergy researchers are able to gather, validate, and adjust data at this level is still to be decided, and then executed.

There are some efforts on transparent supply chain mapping and flows across generic and specific supply chains, but this data and effort is still immature (Tate and Ellram, 2019). Knowing and learning of specific supply chain flows – for example, resources, materials, labor and energy – will need to be completed. Without knowing valid flows, inaccurate estimates would be the norm. It is necessary to develop an emergy UEV database for the supply chain level of analysis.

Operations and supply chain analytic systems require development. These systems are needed to more quickly and effectively generate and monitor emergy accounting flow data. Software and algorithms can be developed to initially parse current regional and national database systems. One promising and current evolution of supply chains is their digitization. Cloud computing, the Internet of Things, Industry 4.0, big data, block chain technology, machine learning, and artificial intelligence, are all tools and systems that can enhance performance measurement and management across the supply chain (Kim and Laskowski, 2018; Lee and Lee, 2015; Wu et al., 2013). Yet, even for traditional data and measures, the digitization of the supply chain is a very difficult task. Add to this difficulty the complexity and issues associated with emergy accounting, and the challenges become larger.

This novelty in digitization also provides an opportunity to work from a greenfield situation where digitization opportunities are just beginning (Saberi et al., 2018). For example, in the blockchain situation, experts can build further and validated information from emergy analysis along the supply chain. A database of various industries, activities, materials, locations, and other emergy focused dimensions can grow as experts and industry specialists jointly evaluate and validate data. This is just one example of a broad-based open system for blockchain emergy analysis. Software developers, such as ERP and cloud computing companies, can develop proprietary systems, which they can sell. These are industry research requirements and the business case benefits of such efforts need to be made clearer to developers.

In terms of adoption, research is needed for determining how well managers, supply chain personnel, and accounting personnel are able to grasp these new techniques. As we have seen even in the limited number of publications; it is not business research that is leading the effort for emergy use in supply chains and business. Research is led environmental and ecological researchers. Expanding management and business related supply chain performance measurement research, as we have done here, is necessary. Comparative analyses with various measurement tools and techniques is another avenue for research. Development of special decision tools, and whether current decision tools will work well, for emergy analysis, requires further evaluation.

The broader perspective of green supply chains also needs to consider and include recycling and closed-loop nature of supply chains. Many green practices fit within a circular economy perspective. Developing and applying circular economic principles into green supply chains is still needed (Liu et al., 2018). Emergy research itself is still considering the issues around diverted emergy; emergy of recycled and reused materials. For example, in calculating some of the valuations for emergy of equipment, there is a dependency and assumption that the equipment over its life will only be used for a given product and that the material utilized by the equipment (e.g. metals) will not be utilized again. This is not necessarily the case. How is the value of the metal that might be recycled at later stages, and many times over, considered? Is accurate discounting over many years or centuries something to consider in the calculations. Emergy considers geological time, while organizations may be considering quarterly or yearly measures. These variations in scale need reconciliation and more accurate integration into various emergy estimations.

One area of research is the application of performance measures and indicators across many tiers of the supply chain (Tuni and Rentizelas, 2018). Emergy analysis, its flexible boundary definition can support this multi-tier evaluation. It also improves the boundary analysis to not only consider physical and organizational boundaries, but temporal boundaries based on earth effort. Further investigation in various boundaries and flows can be included, especially for emergent research in multi-tier sustainable supply chain research (Jabbour et al., 2018).

There are many directions for future development and research, whether they are developing new data, tools, infrastructure, or models, the emergy and supply chain linkage is fertile uncharted territory.

7. Conclusions

In this paper we have introduced the concept of emergy analysis within a business and specifically supply chain context. Using actual data from emergy databases, but using an illustrative example, we provided some insights into how emergy can be used for supply chain business decisions. Emergy provides a comprehensive and more valid approach for helping to evaluate the natural worth of products, suppliers, and business activities. The specific problem environment and example provided in this paper focused on supplier selection. Some nuances of the approach were provided in this illustrative case example.

Clearly, at this point the work is conceptual. To advance this study and research to actual application means additional development and research is required. There are many challenges that exist and we have provided some insights into these challenges. The challenges also provide opportunity for further research, development and integration. Further investigations may include emergy, business, information systems, and modeling approaches, just to name a few areas, separately and jointly.

Overall, we believe there are significant opportunities at multiple levels for future investigation of emergy in business analysis. The supply chain represents an important and necessary first step.

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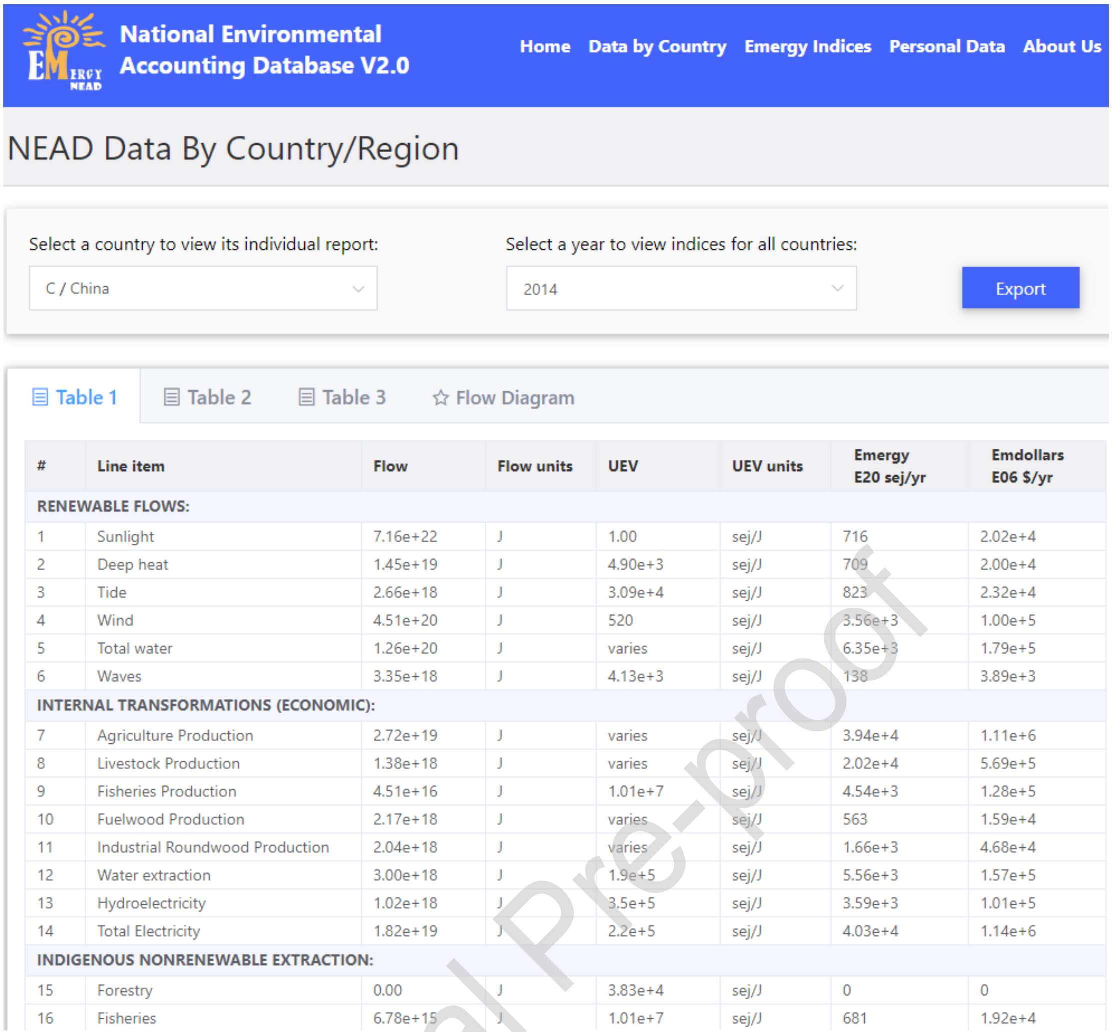

NEAD Data By Country/Region

Select a country to view its individual report: C / China

Select a year to view indices for all countries: 2014

#	Line item	Flow	Flow units	UEV	UEV units	Emergy E20 sej/yr	Emdollars E06 $/yr
RENEWABLE FLOWS:							
1	Sunlight	7.16e+22	J	1.00	sej/J	716	2.02e+4
2	Deep heat	1.45e+19	J	4.90e+3	sej/J	709	2.00e+4
3	Tide	2.66e+18	J	3.09e+4	sej/J	823	2.32e+4
4	Wind	4.51e+20	J	520	sej/J	3.56e+3	1.00e+5
5	Total water	1.26e+20	J	varies	sej/J	6.35e+3	1.79e+5
6	Waves	3.35e+18	J	4.13e+3	sej/J	138	3.89e+3
INTERNAL TRANSFORMATIONS (ECONOMIC):							
7	Agriculture Production	2.72e+19	J	varies	sej/J	3.94e+4	1.11e+6
8	Livestock Production	1.38e+18	J	varies	sej/J	2.02e+4	5.69e+5
9	Fisheries Production	4.51e+16	J	1.01e+7	sej/J	4.54e+3	1.28e+5
10	Fuelwood Production	2.17e+18	J	varies	sej/J	563	1.59e+4
11	Industrial Roundwood Production	2.04e+18	J	varies	sej/J	1.66e+3	4.68e+4
12	Water extraction	3.00e+18	J	1.9e+5	sej/J	5.56e+3	1.57e+5
13	Hydroelectricity	1.02e+18	J	3.5e+5	sej/J	3.59e+3	1.01e+5
14	Total Electricity	1.82e+19	J	2.2e+5	sej/J	4.03e+4	1.14e+6
INDIGENOUS NONRENEWABLE EXTRACTION:							
15	Forestry	0.00	J	3.83e+4	sej/J	0	0
16	Fisheries	6.78e+15	J	1.01e+7	sej/J	681	1.92e+4

Figure 1: The National Environmental Accounting Database V2.0 with Exemplary Emergy Accounting Valuations for China 2014.

Figure 2 The location of selected companies

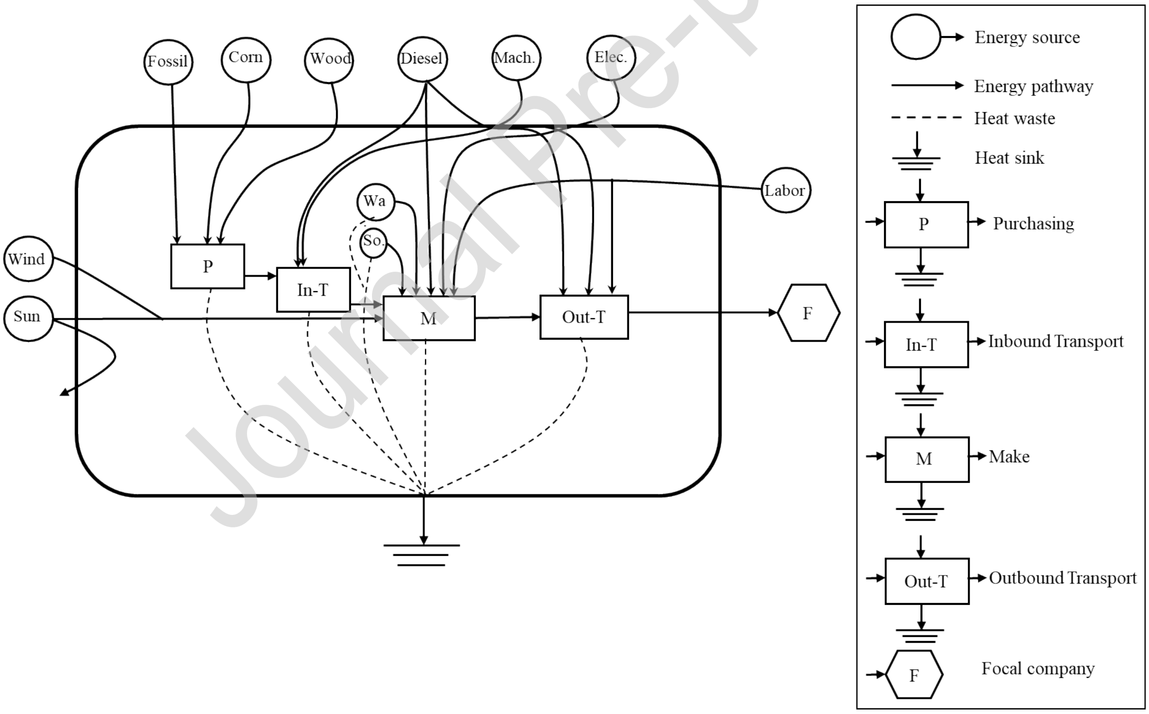

Figure 3 A general emergy system diagram of a typical supplier

(Notes: The boundary is for a supplier organization. Within each supplier's organization, four departmental functions exist. These functions include purchasing or procurement (P), Inbound Transportation (In-T), manufacture or make (M), and outbound transport (Out-T). In order to complete each departmental process, renewable and non-renewable input resources are needed. These items appear as energy resources based on the energy required to produce or move items, such as Wa represents water, So represents soil.)

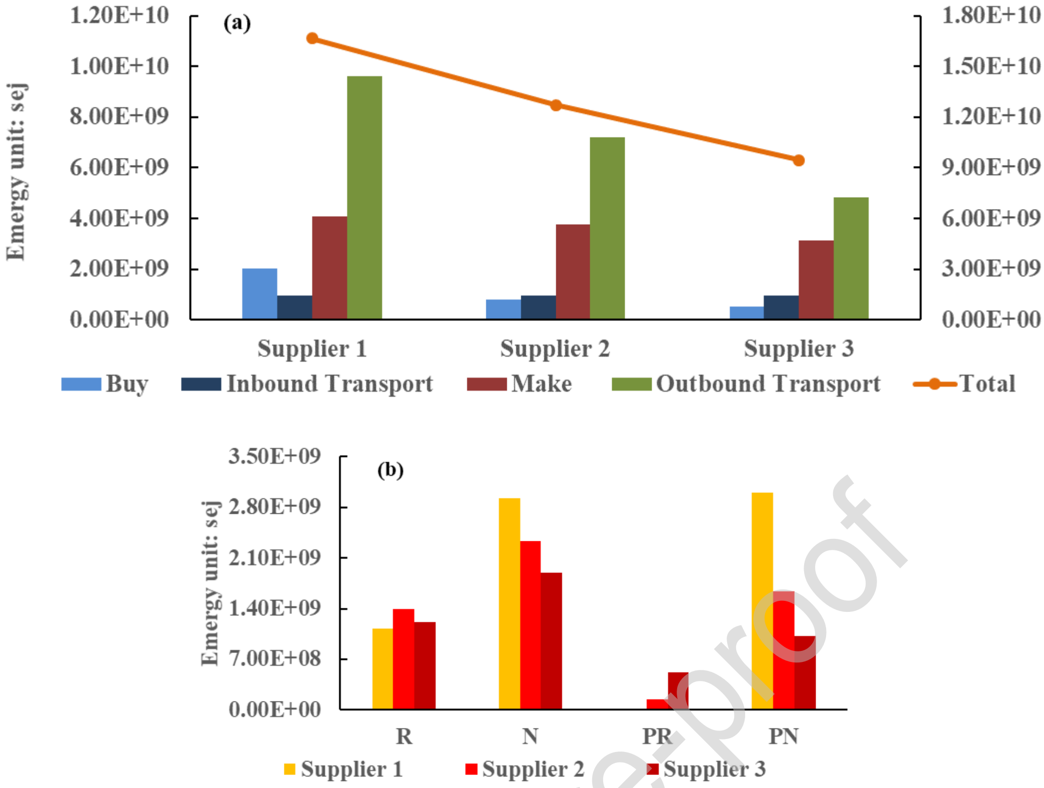

Figure 4 Total input resources of each department of each supplier (a) and the percentages of different type of resources of each supplier (b) (Note: R presents renewable resources; N presents non-renewable resources; PR presents purchase R; PN presents purchase N)

Table 1 Emergy based flows and indicators

Index	Symbol/formula	Description
Locally available renewable resources	R	Emergy of renewable flows directly available to the system, such as solar radiation, wind, rain and biomass on the land, within the boundary of the investigated system.
Locally available non-renewable resources	N	Emergy of local resources characterized by a turnover time much higher than the time in which the investigated process occurs. These resources include slow-renewable resources of soil, groundwater, forest and fishery extraction, while also including non-renewable resources such as fossil fuels and minerals, when locally available.
Imported resources (Purchased resources, F)	I	Emergy of resources that becomes available to the system through trade or other forms of import from outside. Such resources may be primary (fuels, raw minerals, wood) or manufactured (goods and commodities, including refined fuels and minerals).
Purchased Renewable resources	F_R	The portion of the economic resources inputs that are from renewable sources.
Purchased Non-Renewable resources	F_N	The portion of the economic resource inputs that are of non-renewable origin.
Exported resources (Output)	E	Same as the above Imported Resources, applied to resources that leave the system as economic exports.
Labor	L	Emergy value of activities directly displayed within the system, while the process takes place (e.g. hours of cropping in a farm).
Services	S	Emergy value of activities displayed outside the system to extract, process and deliver imported resources and goods (e.g. hours of activity invested to extract oil and refine it into fuels).
Gross domestic product	X	The total economic value of goods and services produced annually within a country.
Total emergy used	$U = R + N + I$	Total emergy supporting a system in the reference time (generally one year).
Emergy-to-money ratio	$EMR = U/X$	The ratio of total emergy U supporting the yearly economy of a country to the gross domestic product of the same country. It expresses how much emergy is needed in a country to generate one unit of GDP.
Per Cent Renewable	$\%R = (R+F_R)/U$	The ratio of the renewable inputs divided by the total emergy of the system. The higher the %R, the more likely the system will survive against the economic stress and the more sustainable the system. The opposite is also true.
Environmental Loading Ratio	$ELR = (I+N)/R$	Represents the ratio of purchased (I) and nonrenewable emergy (N) to locally free environmental emergy (R). ELR is an indicator of the pressure of human activities on the local ecosystem. ELR measures ecosystem stress due to excess exploitation of local non-renewable

		resources or investment from outside, compared with locally available renewable resources.
Emergy Yield Ratio	EYR=U/I=(R+N+I)/I	It is the ratio of total emergy used and exploited by the process (U) to the emergy (I) invested from outside the system. EYR measures the net benefit to the economy, namely the amount of local resources exploited derived from the investment amount. It measures the capability of human processes to exploit local resources.
Emergy Sustainability Index	ESI = EYR/ELR	ESI is the composite ratio of the emergy yield ratio to the environmental loading ratio, indicating the process trade-off between the emergy advantage provided by the process and its environmental pressure. Systems with an ESI lower than 1 is less resource-depleting and high environmental stress. 1 < ESI < 10 implies that the system has good economic viability and good sustainability. ESI > 10 implies the system is undeveloped

Table 2 Supplier Scenarios for Illustrative Emergy-based Green Supply Chain Performance

Company	Description
Focal company	Located in Shanghai, China
Supplier 1	Located in Vietnam. It uses 100% fossil fuel energy to produce bottles; It has a low level of automation, with automation from about 50% machinery for production based on costs, that is, the process is relatively manual. The fuel, diesel inputs into transportation system delivery of materials to the plant are by ship; the electricity inputs into the production system is 100% from coal; the workers are 100% low-skilled labor levels. This supplier will transport its bottle to the focal company by ship.
Supplier 2	Located in Hunan province, China. They use 70% fossil and 30% wood to produce one bottle. 75% automated machinery is used for production. The diesel inputs into the production system are purchased and delivered by railway. The electricity inputs into the production system are 90% from coal. The workers are 75% low-skilled labor. This supplier will transport its bottle to the focal company by railway.
Supplier 3	Located in Shanghai, China. It is a far regional distance from the focal company. They use 70% wood and 30% corn to produce one plastic bottles. They use 90% automated machinery for production, it is a relatively automated less labor intensive process. The diesel inputs into the production system are purchased and delivered by road, or truck transportation. The electricity inputs into the production system are 80% from coal. The workers are 50% low-skilled labor level. This supplier will also transport its bottle to the focal company by road.

Table 3 Emergy flows of various supplier departments and processes (Unit: sej)

		Supplier 1				Supplier 2				Supplier 3			
	Item	Purchasing department	Inbound Transport department	Make department	Outbound Transport department	Purchasing department	Inbound Transport department	Make department	Outbound Transport department	Purchasing department	Inbound Transport department	Make department	Outbound Transport department
Renewable resources	Solar	0	0	6.15E+08	0	0	0	7.65E+08	0	0	0	4.65E+08	0
	Wind	0	0	5.10E+08	0	0	0	6.30E+08	0	0	0	7.50E+08	0
Non-renewable resources	Topsoil loss	0	0	1.19E+08	0	0	0	1.04E+08	0	0	0	9.03E+07	0
	Water, irrigation	0	0	2.81E+09	0	0	0	2.23E+09	0	0	0	1.80E+09	0
Purchase R	Corn	0	0	0	0	0	0	0	0	3.78E+08	0	0	0
	Wood	0	0	0	0	1.42E+08	0	0	0	1.41E+08	0	0	0
Purchase N	Fossil	2.03E+09	0	0	0	6.40E+08	0	0	0	0	0	0	0
	Steel for Machinery	0	9.50E+08	7.87E+06	1.50E+07	0	9.50E+08	1.70E+07	1.50E+07	0	9.50E+08	2.17E+07	1.50E+07
	Diesel by sea	0	1.29E+06	0	1.29E+06	0	0	0	0	0	0	0	0
	Diesel by railway	0	0	0	0	0	9.71E+06	0	9.71E+06	0	0	0	0
	Diesel by road	0	0	0	0	0	0	0	0	0	1.82E+07	0	1.82E+07
	Electricity	0	0	8.29E+04	0	0	0	2.29E+04	0	0	0	4.28E+04	0
Labor		0	0	1.44E+06	9.60E+09	0	0	1.43E+06	7.20E+09	0	0	8.55E+05	4.80E+09

Table 4 Sample of Emergy valuations and calculation for the “make” process for each supplier.

		Supplier 1				**Supplier 2**				**Supplier 3**			
		Amount	Unit	UEV	Emergy	Amount	Unit	UEV	Emergy	Amount	Unit	UEV	Emergy
Renewable	Solar	6.15E+08	J	1.00E+00[a]	6.15E+08	7.65E+08	J	1.00E+00[a]	7.65E+08	4.65E+08	J	1.00E+00[a]	4.65E+08
	Wind	6.38E+05	J	8.00E+02[a]	5.10E+08	7.88E+05	J	8.00E+02[a]	6.30E+08	9.38E+05	J	8.00E+02[a]	7.50E+08
Non-renewable	Topsoil loss	1.26E+03	J	9.41E+04[a]	1.19E+08	1.11E+03	J	9.41E+04[a]	1.04E+08	9.60E+02	J	9.41E+04[a]	9.03E+07
	Water, irrigation	5.85E+04	J	4.80E+04[a]	2.81E+09	4.65E+04	J	4.80E+04[a]	2.23E+09	3.75E+04	J	4.80E+04[a]	1.80E+09
Import	Machinery	3.16E-03	g	2.49E+09[b]	7.87E+06	6.81E-03	g	2.49E+09[b]	1.70E+07	8.70E-03	g	2.49E+09[b]	2.17E+07
	Electricity	3.75E-01	J	2.21E+05[c]	8.29E+04	1.14E-01	J	2.00E+05[c]	2.29E+04	2.25E-01	J	1.90E+05[c]	4.28E+04
Labor		4.50E-08	h	3.20E+13[d]	1.44E+06	3.75E-08	h	3.80E+13[d]	1.43E+06	1.50E-08	h	5.70E+13[d]	8.55E+05
Total Emergy					4.06E+09				3.75E+09				3.13E+09

Note: UEVs sources: a-(Zhong et al., 2018); b-(Geng et al., 2017); c-(Corcelli et al., 2018); d-(Vilbiss and Brown, 2015). All UEVs are based on updated emergy baseline 2016 (Brown and Ulgiati, 2016)

Note: Emergy calculations for the machinery calculation for supplier 1 (3.16E-03 g) are provided as an example to show how practical information is used for these calculations. A series of assumptions based on published numbers are utilized; some assumptions about the illustrative company are also made. Assume 73,000,000,000 plastic bottles of water are sold in China annually (source: https://www.theguardian.com/environment/2017/jun/28/china-informal-army-recyclers-plastic-bottles-landfill). Shanghai’s population is 24,000,000 people. China has 1.386 billion people. The average number of bottles consumed annually per person in China is 52.7 bottles. Proportionally, this means Shanghai consumes about 1.264 billion bottles. Assume the company represents 10% of the plastic bottle market for Shanghai, which means it produces 126 million bottles per year. A lifetime of a machine is 20 years. The company has 4 bottle making machines. That means one machine produces about 632,000,000 bottles over its life. To arrive at the weight of the machine used per bottle manufactured (the amount of metal for which we will assign an emergy value) we must divide the full machine weight by 632,000,000 bottles. A bottle making machine weighs approximately 2 metric tons or 2000 kilograms. Therefore, the weight of machinery per bottle manufactured is 3.16E-03 g (2,000,000g divided by 632,000,000 bottles manufactured over the life of the machine).

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